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A DECISION SUPPORT TOOL TO IMPROVE BINATIONAL WATER QUALITY PLANNING AND MANAGEMENT IN THE LOWER RIO GRANDE/ RÍO BRAVO

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Abstract

A Decision Support Tool to Improve Binational Water Quality Planning and Management in the Lower Rio Grande/Río Bravo

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This dissertation describes the development of a decision support tool designed to facilitate and enhance collaborative binational decision making associated with integrated transboundary water quality planning and management in the Lower Rio Grande/Río Bravo. The Lower Rio Grande Water Quality Initiative Decision Support System (LRGWQIDSS) is the result of a multidisciplinary effort to integrate the results of qualitative social science research and traditional and novel engineering and geographic information systems (GIS) methods associated with the modeling, analysis, and visualization of watershed, water quality and natural resources data. The LRGWQIDSS incorporates information currently used by urban planning and natural resource management organizations working along the Texas-Mexico border area and provides a means to analyze and display the information in a way that is useful to institutional and noninstitutional actors involved in transboundary water quality planning efforts. The analysis of the institutional arrangements currently in place to protect water quality in the Lower Rio Grande/Río Bravo played an important role in the design and development of the LRGWQIDSS and its successful application. The tool's development represents a case study in the importance of the role of institutional analysis in the successful development of decision support systems for transboundary water quality management.

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List of Acronyms

ABM	- Agent-based Modeling
ADB	- Asian Development Bank
AHP	- Analytic Hierarchy Process
APAZU	- Alcantarillado y Saneamiento en Zonas Urbanas
ASAE	- American Society of Agricultural Engineering
BECC	- Border Environmental Cooperation Commission
BEHI	- US-Mexico Border Environmental Health Initiative
BEIF	- Border Environmental Infrastructure Fund
BPUB	- Brownsville Public Utility Board
BPT	- Best Practicable Technology
BTWG	- Binational Technical Work Group
BOD	- Biochemical Oxygen Demand
$CBOD_5$	- 5-Day Carbonaceous Biochemical Oxygen Demand
CBNRM	- Community Based Natural Resources Management
CCN	- Certificate of Convenience and Necessity
CCNR	- Central Commission for Navigation on the Rhine
CEAT	- Comisión Estatal del Agua de Tamaulipas
CHR	- International Commission for the Hydrology of the Rhine Basin
CIAP	- Coastal Impact Assessment Program
CILA	- Comisión Internacional de Límites y Agua
CFR	- Code of Federal Regulations
CFU	- Colony Forming Units
COMAPA	- Comision Municipal de Agua Potable y Alcantarillado
CONACYT	- Consejo Nacional de Ciencia y Tecnología
CONAGUA	- Comisión Nacional del Agua
CWQMN	- Continuous Water Quality Monitoring Network
DANUBIS	- Danube River Information System
DEM	- Digital Elevation Model

DO	- Dissolved Oxygen
DQO	- Demanda Química de Oxígeno
DBO_5	- Demanda Bioquímica de Oxígeno de 5-días
DPRP	- Danube Pollution Reduction Program
DRPC	- Danube River Protection Convention
DSF	- Decision Support Framework
DSS	- Decision Support System
EAM	- Estadísticas del Agua en Mexico
EDSS	- Environmental Decision Support System
EIS	- Executive Information Systems
FGP	- Fuzzy Goal Programing
FloRiAn	- Flow Risk Analysis Tool
GADS	- Gate Assignment Display System
GDSS	- Group Decision Support System
GIS	- Geographic Information Systems
GWP	- Global Water Partnership
HIMA	- Human Integrated Management Approach
HUC	- Hydrologic Unit Code
IAD	- Institutional Analysis Development
IBWC	- International Boundary and Water Commission
ICPDR	- International Commission for the Protection of the Danube River
ICIS	- Integrated Compliance Information System
ICPR	- International Commission for the Protection of the Rhine against Pollution
IMTA	- Instituto Mexicano de Tecnología del Agua
INEGI	- Instituto Nacional de Estadística, Geografía, e Informática
IRB	- Institutional Review Board
IRC	- Institutional Rational Choice
ISD	- Independent School District
ITER	- Integración Territorial
IWRM	- Integrated Water Resources Management

JAD	- Junta de Agua y Drenaje
kg	- Kilograms
km	- Kilometers
km^2	- Square Kilometers
KS	- Knowledge System
lbs	- Pounds
LDEQ	- Louisiana Department of Environmental Quality
LiDAR	- Light Detection and Ranging
LRG/RB	- Lower Rio Grande/ Río Bravo
LRGWQIDSS	- Lower Rio Grande Water Quality Initiative Decision Support System
LRGWQIPRP	- Lower Rio Grande Water Quality Initiative Policy Research Project
LULC	- Land Use Land Cover
LUPE	-La Union del Pueblo
LS	- Language System
L/s	- Liter Per Second
MAAU	- Multi-attribute Adaptive Utility
MCDSS	- Multi-criteria Decision Support System
MDSS	- Multi-participant Decision Support System
Mex$	- Mexican Pesos
MIS	- Management Information Systems
mg/L	- Milligrams per Liter
ml	- Milliliters
MAV	- Multi-variate value
MOA	- Memorandum of Agreement
MPN	- Most Probable Number
MRC	- Mekong River Committee
MRLC	- Multi-Resolution Land Characteristics Consortium
MW	- Megawatt
NAFTA	- North American Free Trade Agreement
NASQAN	- National Stream Quality Accounting Network

NADB	- North American Development Bank
NBI	- Nile Basin Initiative
NBDSS	- Nile Basin Decision Support System
NELAP	- National Environmental Laboratory Accreditation Program
NGO	- Non-governmental Organization
NHD	- National Hydrographic Dataset
NH_3-N	- Ammonia Nitrogen
NOAA	-National Oceanographic and Atmospheric Administration
NPDES	- National Pollutant Discharge Elimination System
NTD	- Neural Tube Defect
ODSS	- Organizational Decision Support System
OSSF	- On-Site Sewage Facility
OST	- Office of Science and Technology
OSU	- Oregon State University
PAIRS	- Productivity, Agility, Innovation, Reputation, Satisfaction
PDSI	- Palmer Drought Severity Index
PM	- Participatory Modeling
PRODDER	- Programa de Devolución de Derechos
PROFEPA	- Procuraduría Federal de Protección al Ambiente
PS	- Presentation System
PPS	- Problem Processing System
PTAR	- Planta de Tratamiento de Aguas Residuales
QUAL-TX	- State of Texas version of the QUAL water quality modeling software
SADC	- South African Development Council
SAITL	- Simulador de Flujos de Agua de Cuencas Hidrográficas
SAR	- Special Administrative Region
SBR	- Sequence Batch Reactor
SDSS	- Spatial Decision Support System
SEDUMA	- Secretaría de Desarollo Urbano y Medio Ambiente
SEMARNAT	- Secretaría de Medio Ambiente y Recursos Naturales

SPSS	- Statistical Packaging for the Social Sciences
SSI	- Survey Sampling International
SST	- Sedimento Suspendido Total
STATA	- Software for Statistics and Data Science
SUD	- Special Utility District
TAC	- Texas Administrative Code
TCEQ	- Texas Commission on Environmental Quality
TDS	- Total Dissolved Solids
TDSHS	- Texas Department of State Health Services
TGLO	- Texas General Land Office
TMDL	- Total Maximum Daily Load
TN	- Total Nitrogen
TNMN	- Trans National Monitoring Network
TNRCC	- Texas Natural Resource Conservation Commission
TOR	- Terms of Reference
TP	- Total Phosphorus
TPDES	- Texas Pollutant Discharge Elimination System
TSS	- Total Suspended Solids
TWDB	- Texas Water Development Board
UNDP	- United Nations Development Programme
UNECE	- United Nations Economic Commission for Europe
UNEP	- UN Environment Programme
US	- United States
USC	- United States Code
USDA-RD	- United States Department of Agriculture – Rural Development
USEPA	- United States Environmental Protection Agency
USFWS	- United States Fish and Wildlife Service
USGS	- United States Geological Survey
USIBWC	- United States Section of the International Boundary and Water Commission
WBP	- Watershed Based Plan

WSC	- Water Supply Corporation
ZAMCOM	- Zambezi Water Course Commission
ZAMTEC	- Zambezi Water Course Commission Technical Committee
ZAMWIS	- Zambezi Water Resources Information System

CHAPTER 1: ADDRESSING WATER QUALITY DEGRADATION IN THE LOWER RIO GRANDE/RÍO BRAVO

1.0 Introduction

The Rio Grande, known as the Río Bravo in Mexico, is an important transboundary water resource for both the United States (US) and Mexico. In recent years, this iconic river has become seriously threatened by the border region's growing population and rapid industrialization. In addition to water availability issues, several persistent water quality problems threaten to limit the beneficial uses of the river. While water quantity is inextricably linked to water quality in the river, the primary focus of binational management efforts in the Rio Grande/Río Bravo has historically been on the apportionment of its water between the two countries. Recently, however, the federal governments of the United States and Mexico have initiated a series of collaborative efforts aimed at addressing water quality problems, which are recognized by both countries as impediments to sustainable development along the border region on both sides of the river.

Among the most common water quality problems faced by the Rio Grande/Río Bravo are elevated levels of bacteria, such as fecal coliform, *E. coli* and Enterococcus, which are commonly monitored as indicators of fecal contamination in surface water bodies. Another common water quality problem in the Rio Grande/Río Bravo is increasing salinity due to high levels of dissolved salts entering the river. In addition to these common water quality impairments, the Rio Grande/Río Bravo also suffers from a long list of other water quality problems and concerns, including elevated levels of metals, such as mercury, in fish tissue, unexplained ambient toxicity, elevated levels of nutrients and low dissolved oxygen.

Recognizing the diversity of water quality problems plaguing the Rio Grande/Río Bravo, the federal governments of the United States and Mexico agreed to collaborate on a binational pilot project to study water quality problems in the portion of the river between Falcon Dam and the Gulf of Mexico, a section of the river where poor water quality affects a disproportionately high number of people living in the riparian areas of the river and its tributaries. The pilot project, named the Lower Rio Grande/Río Bravo Water Quality Initiative (LRGWQI), was formally authorized under the US-Mexico Water Treaty of 1944 (i.e., Treaty on the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande, 1944) and was initiated in September of 2013.

A unique feature of the LRGWQI is that, unlike other binational projects involving the United States and Mexico, this initiative did not originate as a result of bilateral interactions between the federal governments of the two countries. Instead, the LRGWQI was initially conceived and proposed by the Texas Commission on Environmental Quality (TCEQ). The project subsequently evolved as a result of interactions between state and federal institutional actors on both sides of the border.

1.0.1 INSTITUTIONAL INTERACTIONS WITHIN THE UNITED STATES

In 2007, the TCEQ began holding official discussions with the US Environmental Protection Agency (USEPA) and the US Section of the International Boundary and Water Commission (USIBWC) regarding persistent water quality problems in the Rio Grande/Río Bravo. Through these discussions, the TCEQ hoped to clarify the specific responsibilities of the three agencies under US federal law. While the federal Clean Water Act clearly specifies the roles of the federal government and of sub-federal governments (i.e., states, territories, and Native American tribal lands) in the protection of surface water quality within the United States, the statute is less clear about the roles and requirements of these governmental entities with respect to transboundary water bodies such as the Rio Grande/Río Bravo.

In the United States, the federal Clean Water Act gives the USEPA the power to regulate the release of pollutants into the environment. For example, in 1972 the USEPA published rules that required industrial facilities and municipalities to obtain a permit to discharge treated wastewater into navigable surface waters. Discharge requirements for wastewater permits are specified under the USEPA's National Pollutant Discharge Elimination System (NPDES) authorized under Part 122 of Title 40 of the United States Code of Federal Regulations. The federal Clean Water Act also allows the USEPA to delegate permitting authority to US states, territories and tribal governments. The State of Texas was granted such authority in 1998 through the creation of the Texas Pollutant Discharge Elimination System (TPDES), which gave the state the authority to issue wastewater discharge permits in all waters of the state, including the Rio Grande. With this permitting authority came the responsibility of ensuring that wastewater discharges allowed under the TPDES program did not cause or contribute to the degradation of surface water quality in the state. As a condition for delegation, the USEPA routinely scrutinizes the state's permitting programs and can withdraw NPDES delegation if it deems the state is not adequately protecting water quality in surface waters within the state's jurisdiction.

In addition to outlining wastewater discharge permitting authority and associated responsibilities, the federal Clean Water Act also requires US states, territories and tribal governments to monitor the quality of their surface waters and to assess compliance with specific surface water quality standards and criteria. Under section 303(d) of the act, sub-federal governments must also compile, and submit to the USEPA biennially, a list of surface water bodies of the state that do not meet the criteria specified in their surface water quality standards (i.e., lists of "impaired" water bodies) along with a schedule for establishing "Total Maximum Daily Loads" for each impaired water body placed on the lists. Total Maximum Daily Loads (TMDLs) are essentially caps on the amount of a particular pollutant allowed to be discharged into a surface water body or allowed to wash into a surface water body from urban rainfall runoff.

Under the institutional framework established by the federal Clean Water Act, the responsibility for protecting and restoring water quality in surface waters of the United States is placed first and foremost on the federal government. However, under the regulatory framework established by the USEPA, the burden of achieving these goals is placed on the governments of US states, territories and Native American tribal lands. States and other sub-federal governments that are unwilling or unable to comply with the regulatory requirements promulgated in the implementing regulations associated with the federal Clean Water Act (40 C.F.R. Parts 104-108, 110-117, 122-140, 230-233, 401-471, and 501-503) risk losing control, to the USEPA, of wastewater permitting decisions as well as other aspects of environmental management associated with surface water bodies within their sub-federal jurisdictional boundaries (33 USC §1251 et seq. 1972). However, the clear institutional demarcations established by USEPA regulations are much less clear with respect to water bodies that cross state boundaries or are shared among states and the regulations are especially unclear with respect to transnational water bodies, such as the Rio Grande/Río Bravo.

The State of Texas has conducted water quality monitoring in the Rio Grande since 1969 and, following the requirements of the federal Clean Water Act and its implementing regulations, the state has assessed water quality in the river since 1988. The results of these assessments, along with official requests from the USEPA, prompted the TCEQ and its predecessor state agencies to include the Rio Grande in every list of impaired water bodies it has submitted to the USEPA (TCEQ 1992-2014). However, fearing that the burden of restoring water quality in the Rio Grande would fall entirely on Texas stakeholders, the lists submitted by the State of Texas have not been accompanied by a schedule to establish TMDLs for the river. For its part, the USEPA has not placed much regulatory pressure on Texas to establish TMDLs on any portion of the Rio Grande because it recognizes that a substantial amount of the pollutant loads impairing the river emanate from Mexico and there is currently no comprehensive binational agreement between the United States and Mexico to cooperatively control pollutant loadings to the river.

The lack of coordinated binational efforts to control pollutant loads entering the Rio Grande/Río Bravo has likely helped perpetuate water quality problems in the river. However, it would be inaccurate to state that the Rio Grande/Río Bravo lacks any institutional controls designed to protect water quality in that water body. In fact, the TCEQ adheres to a de facto, self-imposed cap on the loading of certain pollutants entering the river from wastewater treatment facilities in Texas. In 1995, the State of Texas estimated the assimilative capacity of the river for specific pollutants using a deterministic model of water quality it developed for the river (QUAL-TX). The state's intent was to limit the pollutant loading allowed for Texas wastewater dischargers to half of the assimilative capacity calculated using the QUAL-TX model. In 1998, the Texas Natural Resource Conservation Commission (TNRCC), a predecessor agency of the TCEQ, proposed, to the USEPA, this approach for determining wastewater discharge permit limits for Texas facilities discharging to the Rio Grande. The USEPA concurred with the method proposed by the TNRCC and the two agencies signed a Memorandum of Agreement (MOA) agreeing to this permitting policy for the Rio Grande (MOA between the US Environmental Agency, Region 6 and Texas Natural Resource Conservation Commission Concerning the National Pollutant Discharge Elimination System, March 5, 1998). The policy remains in effect to this day.

The TCEQ recognizes that there are serious flaws associated with the unilateral approach to water quality management described above, the most obvious of which is its inability to control pollutant loads from Mexico. Even if the assumption is made that Mexican regulatory measures to control pollutant loads entering the river are adequate, the current lack of binational coordination with respect to water quality management casts serious doubts on the central assumptions of the policy. First, it is difficult to evaluate whether the assimilative capacity estimated by the TNRCC for the Rio Grande/Río Bravo in 1995 is accurate, given the lack of data and physical information about the river available at the time the model was developed and the changes in flow that have occurred over the intervening 24 years. There is no guarantee that any Mexican estimates of assimilative capacity of the river would coincide with, or even be similar to, those of the TNRCC's. Second, there is no guarantee that Mexican regulators would also limit the loadings of pollutants from Mexican dischargers to half of the assimilative capacity of the river. Mexican regulators have not estimated the assimilative capacity of pollutants of concern to the Río Bravo officially (J.A. Rojas, personal communication, May 26, 2015). The uncertainties associated with the unilateral approach currently used to set wastewater discharge permit limits in the Rio Grande/Río Bravo render the approach inadequate for the protection of water quality in the river, even if the approach is better than no approach at all.

The State of Texas' motivation to restore, or at least improve, water quality in the Rio Grande/Río Bravo is not based on federal pressure to comply with the federal Clean Water Act or any other federal law or regulation. The Rio Grande is an important natural resource for Texas stakeholders in the border region. The government of State of Texas is keen to mitigate the degradation of the river's quality, which is why the TCEQ initiated discussions with the USEPA and USIBWC in 2007 to explore the establishment of a binational approach to protect water quality in the river. The State of Texas' motive for clarifying the specific responsibilities of the three agencies (i.e., USEPA, USIBWC, and TCEQ) with regard to water quality management in the Rio Grande/Río Bravo was ultimately to enlist the help of these federal agencies in dealing with pollution sources on the Mexican side of the river. During the interagency discussions, the TCEQ pointed to Section 102(c) of the federal Clean Water Act, which states:

> It is further the policy of Congress that the President, acting through the Secretary of State and such national and international organizations as he determines appropriate, shall take such action as may be necessary to insure that to the fullest extent possible all foreign countries shall take meaningful action for the prevention, reduction, and elimination of pollution in their waters and in international waters and for the achievement of goals regarding the elimination of discharge of

pollutants and the improvement of water quality to at least the same extent as the United States does under its laws.

It should be noted that the IBWC is one of the agencies administered by the US State Department.

During the aforementioned discussions, the TCEQ proposed to the USEPA and USIBWC that a collaborative binational initiative be established to study and address water quality impairments in the portions of the river that affected the most critical uses of the water body. The official discussions between the TCEQ, USEPA and USIBWC resulted in a commitment by all three agencies to explore the establishment of a binational agreement with the Mexican government to develop a collaborative pilot project in a portion of the Rio Grande/Río Bravo of mutual interest to both countries. The agencies envisioned a pilot project that would form the basis for wider binational cooperation between the two countries in addressing transboundary water quality problems and to serve as a model for addressing binational water quality issues elsewhere in the Rio Grande/Río Bravo.

The TCEQ, USEPA and USIBWC agreed to propose to the Mexican government that the pilot study of water quality be conducted in the portion of the river downstream of Falcon Dam. The rationale was that: (1) the severity of the bacteria impairment was highest in the lower portions of the river at the time; (2) more monitoring data and physical information was available for the portion of the river downstream of Falcon Reservoir; and (3) the beneficial uses of the river were highest and most varied in the portion of the river flowing through the Rio Grande Valley of south Texas.

The TCEQ also began committing internal resources to the pilot project and solicited financial support from another Texas state agency, the Texas General Land Office (TGLO). Since the Lower Rio Grande flows directly into the Gulf of Mexico and its watershed includes a portion of the coastal plain of South Texas, the TGLO suggested the TCEQ apply for funding under the Coastal Impact Assessment Program (CIAP), which was an environmental protection program funded by the US Fish and Wildlife Service (USFWS) and administered at the state level by the TGLO. In 2011, the TCEQ submitted a proposal to TGLO for funding of the project under the CIAP program. The TGLO, in turn, submitted the project to USFWS and was awarded $1,000,000 for the project in 2012. In 2013, the TCEQ signed a sub-recipient agreement with the TGLO for funding of the Lower Rio Grande Water Quality Initiative (LRGWQI) Pilot Project.

1.0.2 INSTITUTIONAL INTERACTIONS WITHIN MEXICO

Unilateral efforts to protect water quality in the Rio Grande/Rio Bravo are not limited to the efforts by US governmental entities, Mexican state and federal government agencies also have programs in place, which are designed to protect surface water quality in Mexican national waters, including the Río Bravo. Since 2003, Mexico's Comisión Nacional del Agua (CONAGUA), the country's national water agency, has targeted the Río Bravo river for detailed study and has included the river in its list of priorities for water quality protection (E. Gutierrez, Personal Communication, May 25, 2015). Like the United States' federal Clean Water Act, Mexico's Ley de Aguas Nacionales specifies the legal responsibilities, as well as the regulatory powers, of the Mexican federal government with respect to the protection of water quality in Mexican surface and subsurface water bodies. Unlike its US counterpart, however, the law also grants the Mexican federal government the power to apportion surface water rights and create irrigation districts. In combination with Mexico's Ley Federal de Derechos, the Ley de Aguas Nacionales also grants broad powers to the Mexican federal government (and to CONAGUA in particular) to develop regulations designed to protect water quality in the country's surface water bodies. Also, in contrast to the United States' regulatory framework, the responsibility for implementing CONAGUA's water quality regulations is placed on the Mexican federal government (CONAGUA, SEMARNAT, and PROFEPA). Although many of CONAGUA's functions were decentralized in 2004 through the creation of regional basin authorities known as Organismos de Cuenca, implementation of water quality policy and resource allocation remain in the domain of CONAGUA's central office in Mexico City.

Wastewater treatment facilities in Mexico must obtain a permit from CONAGUA to discharge their effluent to surface waters in Mexico. Under Mexican federal law, all wastewater treatment facilities must be designed, constructed and operated so as to treat wastewater to a level that will meet minimum federal criteria based on the "best available technology economically achievable," referred to commonly as Best Practicable Technology (BPT). The criteria are specified in the country's federal regulation NOM-001-SEMARNAT-1996, which establishes the maximum permissible levels of contaminants in wastewater discharged to national surface waters according to the type of water body receiving the discharge and its established uses. This approach to wastewater permitting is known as a technology-based performance standard and is applied to entire categories of wastewater treatment facilities.

In addition to technology-based performance standards, Mexican federal law provides for the establishment of individual discharge permits that stipulate effluent concentrations and flow limits for individual wastewater treatment facilities based on their effect on the water body receiving the discharge. This more advanced approach to wastewater permitting is known as water quality-based performance standards. It is commonly employed in situations where technology-based effluent limitations are deemed to be insufficient to adequately protect water quality in water bodies receiving wastewater treatment plant effluent. The establishment of water quality-based effluent limits for individual facilities is often preceded by the development of a "Declaratoria de Clasificación," which, among other things, includes a study of the pollutant assimilative capacity of the receiving water body. In 2012, CONAGUA committed internal agency resources towards developing a Declaratoria de Clasificación for the Lower Río Bravo (referred to subsequently herein as the "Declaratoria" when in reference to the Lower Río Bravo). In 2013, CONAGUA applied for, and was granted, funding from Mexico's Consejo Nacional de Ciencia y Tecnología (CONACYT) to fund the bulk of the Declaratoria study on the Lower Río Bravo. Depending on the results of the study, CONAGUA could begin issuing individualized permits for new and existing wastewater treatment facilities discharging to the Lower Río Bravo following the completion and promulgation of the Declaratoria. The Declaratoria, is scheduled to be completed by the end of 2019.

To carry out the technical work associated with the Declaratoria study, CONAGUA enlisted the help of the Instituto Mexicano de Tecnología del Agua (IMTA), a Mexican federal institute that specializes in the practical application of advanced water technology in the Mexico. CONAGUA signed a contract with IMTA in 2013 for the technical work associated with the Declaratoria. The most important deliverable of the contract between CONAGUA and IMTA was the draft Declaratoria document itself. In addition to IMTA's services, CONAGUA also enlisted the help of the government of the Mexican State of Tamaulipas, securing a pledge of logistical and field operations support for the Declaratoria study from Tamaulipas' state water commission, the Comisión Estatal del Agua de Tamaulipas (CEAT), and Tamaulipas' secretariat of development and the environment, Secretaría de Desarollo Urbano y Medio Ambiente (SEDUMA).

A scientific study, such as a Declaratoria de Clasificación, necessarily involves the compilation and analysis of historical physical, chemical and biological information available for the subject water body and its associated watershed. While much of the historical data and information needed for assimilative capacity studies, such as Declaratorias de Clasificación, are available from public sources, certain critical data and information are not accessible without special permissions (e.g., detailed flow diversion records, wastewater treatment facility discharge monitoring reports, etc.). Access to these critical data usually requires the cooperation of a number of natural resource agencies and involves the navigation of significant bureaucratic hurdles. This is especially true of transboundary water bodies, such as the Rio Grande/Río Bravo, where important data and information may not be available from entities inside a researcher's national boundaries.

Data collection efforts are also commonly part of the technical tasks associated with studies of assimilative capacity, especially if large data gaps are identified during the compilation of historical information. Efforts to organize and coordinate data collection efforts in transboundary water bodies, such as the Rio Grande/Río Bravo can be even more challenging than acquiring historical information from foreign data sources. In order to help facilitate access to US historical data and information and also to coordinate anticipated data collection efforts associated with the Declaratoria study, CONAGUA and IMTA researchers enlisted the help of the Comisión Internacional de Agua y Límites (CILA), which is the Mexican Section of the IBWC.

1.0.3 Binational Institutional Interactions

Having come to agreement with its US federal partner agencies (USEPA and USIBWC) to propose, to the Mexican government, a binational pilot study of water quality in the portion of the Lower Rio Grande/Río Bravo downstream of Falcon Dam and with funding for the project awarded by the USFWS through the TGLO, the TCEQ drafted a proposal for the pilot project. The draft proposal underwent a number of revisions resulting from deliberations among the US partner agencies on the scope and language of the proposal before the USIBWC sent the proposal to CILA. CILA had already been in discussions with CONAGUA about securing US cooperation for CONAGUA's Declaratoria study on the coincident portion of the river.

CILA's favorable response to the US proposal led to a series of binational meetings that included representatives of the TCEQ, CONAGUA, USEPA, CEAT, SEDUMA, CILA and USIBWC. The meetings, which were held under the auspices of the International Boundary and Water Commission, culminated in a preliminary verbal agreement by all parties to establish a binational initiative to study the river and to develop a plan to improve and protect water quality the Lower Rio Grande/Río Bravo between Falcon Dam and the Gulf of Mexico. Subsequent binational meetings served to reach binational agreement on the geographic scope and goals of the project and led to the development of Terms of Reference (TOR) for the initiative (Appendix A). The TOR document listed the participants, identified their roles, defined the processes and procedures that were to be followed, and described the results expected of the initiative. Of note regarding the TOR, was the addition of language referencing the solicitation of participation by the Border Environmental Cooperation Commission (BECC) and the North American Development Bank (NADB), whose expertise in infrastructure investments on both sides of the US-Mexico border was deemed to be beneficial to the initiative. Both the BECC and NADB subsequently agreed to participate in the initiative in a consultative role.

On September 10, 2013, the governments of the United States and Mexico conducted an official Exchange of Letters which established the LRGWQI. The agreement was signed by the Principal Engineers of the US and Mexican Sections of the International Boundary and Water Commission (USIBWC and CILA, respectively). The agreement committed both countries to the procedures, scope, collaborative efforts and goals specified in the TOR for the LRGWQI. Although the LRGWQI TOR does not specify the manner in which an agreement resulting from the LRGWQI is to be institutionalized, it lays out three possible institutional mechanisms available under the US-Mexico Water Treaty of 1944: (1) a treaty Minute, (2) a Joint Engineering Report and (3) an Official Exchange of Letters.

1.0.4 THE LOWER RIO GRANDE/RÍO BRAVO WATER QUALITY INITIATIVE (LRGWQI)

From the perspective of the US participants in the LRGWQI, the pollutants of concern to be addressed by the initiative were the ones listed in the 2012 Texas Integrated Report of Surface

Water Quality (TCEQ, 1992-2014); these pollutants are shown in Table 1-6 (page 39). In addition to the water quality impairment and concerns included in Table 1-6, the US and Mexican LRGWQI Partners agreed to investigate sources of salinity in the river upstream of the Gulf of Mexico's tidal influence on the river (i.e., upstream of TCEQ Segment 2301). In addition to the Declaratoria, Mexican interest in participating in the LRGWQI is also linked to the results of Mexican water quality monitoring, which showed elevated levels of fecal coliforms and chemical oxygen demand (Spanish acronym is DOC) in portions of the Lower Río Bravo.

The TOR for the LRGWQI specify: (1) the legal framework and process under which the LRGWQI project would be conducted, (2) the IBWC decision-making process, (3) the general and specific objectives of the initiative, (4) the organization and management procedures to be used, (5) the communication and information sharing policies and protocols for the initiative, and (6) the performance measures for the initiative's outcomes. Cited, in the TOR, as the general objective of the LRGWQI is "to explore border sanitation issues and water quality management with potential binational benefits" (page 4 of the LRGWQI TOC document) and the first specific objective cited in the TOR is to "Address current and future water quality issues of the Lower Rio Bravo/Rio Grande" (page 4 of the LRGWQI TOC document). Beyond these statements, the LRGWQI TOR do not specify the water quality "issues" that are to be "addressed" by the initiative.

Seven agencies are named in the LRGWQI TOR, two US federal agencies (USIBWC and USEPA), two Mexican federal agencies (CILA and CONAGUA), one US state agency (TCEQ) and one Mexican state agency (CEAT). The BECC is alluded to in the TOR, but only as participating in an advisory capacity. Under the LRGWQI TOR, representatives of these agencies are to work under the LRGWQI Joint Cooperative Process shown in Figure 1.1 of the LRGWQI TOR (page 3 of the LRGWQI TOC document).

The structure of the LRGWQI Joint Cooperative Process is designed to incorporate the objectives of stakeholders from both countries into the diplomatic process developed by the IBWC/CILA as part of the 1944 US-Mexico Water Treaty. However, the TOR does not specify the precise mechanism by which these stakeholders are to be included in the process. The structure of the LRGWQI includes separate national "Core" groups of individuals that ostensibly represent the respective interests of their national stakeholders. The following agencies make up the US and Mexican LRGWQI Core Groups:

US Core Group

- US Section, International Boundary and Water Commission (USIBWC)
- US Environmental Protection Agency (EPA)
- Government of Texas, through the Texas Commission on Environmental Quality (TCEQ)

Mexican Core Group

- Mexican Section, International Boundary and Water Commission (CILA)
- Commisión Nacional del Agua (CONAGUA)
- Government of the State of Tamaulipas, through the Commisión Estatal del Agua de Tamaulipas (CEAT)

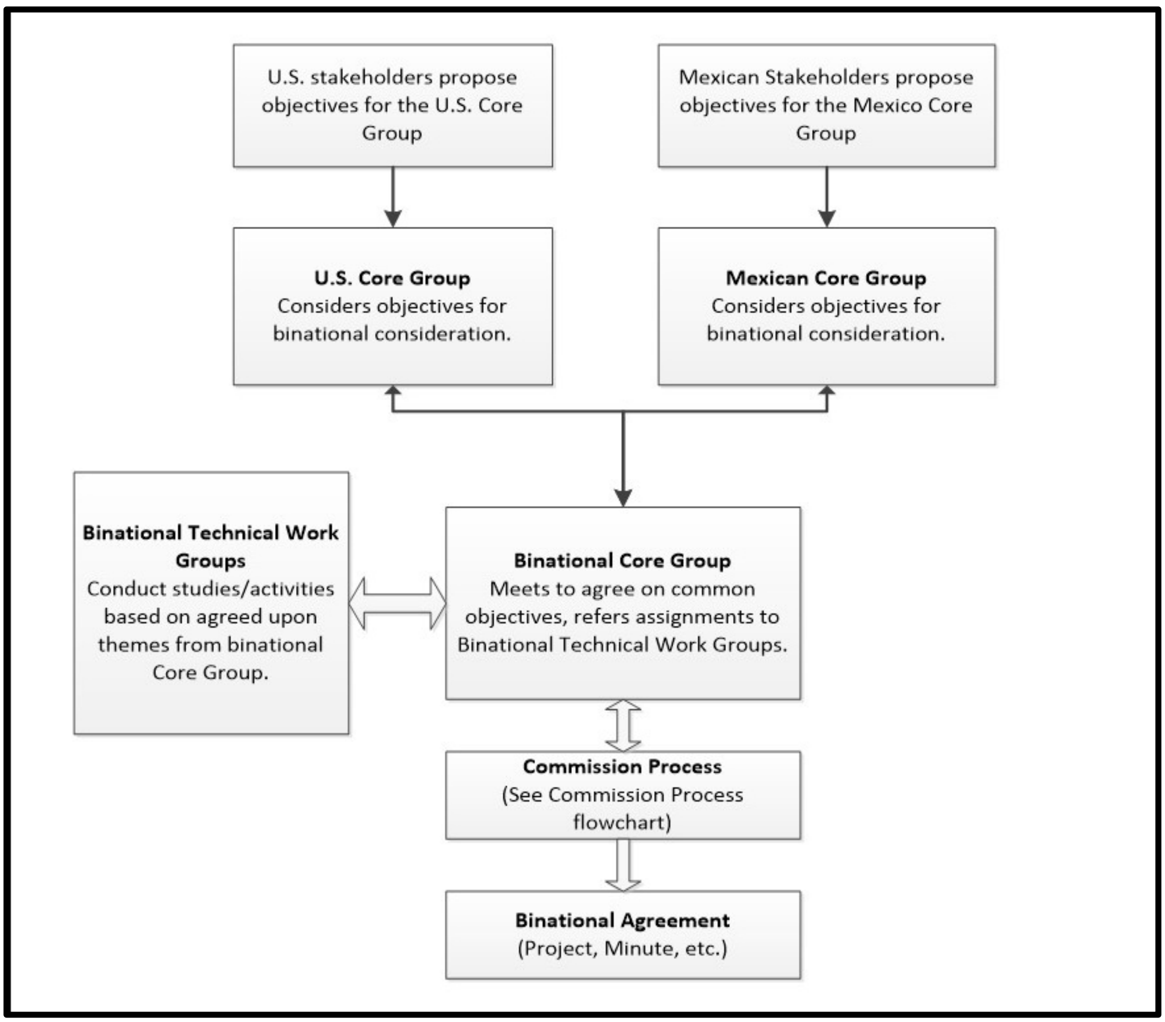

Figure 1-1. The LRGWQI Joint Cooperative Process as Specified in the Lower Rio Grande/Río Bravo Water Quality Initiative Terms of Reference.

According to the LRGWQI TOR, representatives of the respective national Core Groups provide specific objectives to a Binational Core Group. The task of the Binational Core Group is to agree on common objectives for managing and protecting water quality in the Lower Rio Grande/Río Bravo and to assign technical tasks to a Binational Technical Work Group (BTWG), which is to conduct studies and carry out other technical tasks, thereby providing input back to the Binational Core Group. The objectives agreed to by the representatives of the Binational Core Group are to be detailed in a draft agreement that is to be subjected to an institutionalization processes detailed in the 1944 US-Mexico Water Treaty and/or one of its pertinent treaty Minutes. Minutes to the 1944 US-Mexico Water Treaty are annexes that can be made to the treaty through consensus agreement between the two countries without the need for re-ratification of the treaty.

The procedural structure of the LRGWQI, as defined in the TOR, and the lack of specificity of objectives of the LRGWQI affordes the participants of the Initiative the flexibility to jointly define the final objectives of the pilot project in the Lower Rio Grande/Río Bravo. The specific objective of "addressing water quality issues" is worded in this way intentionally with the expectation that the water quality issues ultimately addressed by the LRGWQI will be agreed upon binationally during the course of the pilot project. The US proposal for the pilot project was included as an Annex to the TOR. The proposal contains details about the technical approach proposed by the US LRGWQI Partners, which included: (1) historical data review; (2) identification of data gaps; (3) data collection; and (4) data analysis and modeling. This approach was followed by the BTWG, which also agreed to limit the period of record for historical data compilation and analysis to 2000-2015.

1.0.5 PROBLEM STATEMENT

Perceptions of poor water quality in the Lower Rio Grande/Río Bravo have been common for many years among the local population living within the river's watershed as well as in the general population of the United States and Mexico (e.g., Satija, 2013). While objective, evidence-based, assessments of water quality in the river have, in fact, revealed water quality impairments impacting the beneficial use of the river (IBWC, 1998; TCEQ, 1992-2013), these assessments have consistently failed to corroborate the types of water serious quality problems often publicized in the news media, such as contamination by toxic chemicals (e.g., Oko, 2002).

Instead, the only consistent impairments identified by official water quality assessments conducted since 1992 have been due to excessive concentrations of fecal bacteria (TCEQ, 1992-2014, USEPA, 2016a), which have affected the "contact recreation" use of the river at several locations. A binational analysis of pollutant sources in the Lower Rio Grande/Río Bravo watershed conducted in 2017 points to faulty and/or inadequate wastewater infrastructure as the main culprit, identifying several notable sources of raw and poorly treated sewage located along the river. These sources are in urban and rapidly developing areas on the Mexican side of the watershed and at several sites in the United States (Miranda & Harper, 2017).

In addition to high levels of fecal bacteria, past assessments of water quality in the Lower Rio Grande/Río Bravo have identified concerns associated with other pollutants in the river, including mercury in fish tissue, excessive algal growth and low dissolved oxygen. None of these concerns have ever risen to the level of an impairment affecting a beneficial use of the river (TCEQ, 1992-2014). Nevertheless, analyses of water quality trends have identified an upward trend in the concentration of chloride and total dissolved solids, which contribute to an increase in the overall salinity of the river (IBWC, 2013; Miranda & Harper, 2017). Increasing salinity of the Lower Rio Grande/Río Bravo has been an issue of great concern to local water users since, at least, the early 1960s. In a stakeholder focus group conducted in 2016, agricultural producers and irrigation district managers identified increasing levels of salinity in the river as the highest water quality concern among members of agricultural sector in the Lower Rio Grande Valley (Texas A&M AgriLife Research, 2016).

1.0.6 STUDY AREA[1]

The Rio Grande/Río Bravo defines over half of the international border between the United States and Mexico. In its 3051-kilometer journey from the southern Rocky Mountains of the United States to the Gulf of Mexico, the Rio Grande, known in Mexico as the Río Bravo, provides a vital life line to approximately 5.5 million people living in the Texas-Mexico Border Region (TCEQ, 2016). The fifth longest river in the United States and among the top twenty longest

[1]Some of the content of this Sub-section of Chapter 1 was excerpted from the 2017 report titled "Watershed Characterization Report: Lower Rio Grande/Río Bravo Water Quality Initiative," authored by Roger M. Miranda and Heidi E. Harper"

rivers in the world, the Rio Grande has a watershed that covers an area of approximately 924,300 km^2 (IBWC, 2016). The river begins in the portion of the Rocky Mountains known as the San Juan Mountains, which are located in the southern portion of the US State of Colorado. The river flows south, through central New Mexico, and then flows southeast as it becomes the southernmost portion of the interstate boundary between the United States of New Mexico and Texas. The Rio Grande then becomes the international border between Mexico and the United States before it reaches the Gulf of Mexico (Figure 1-2).

Flow in the upper portions of the river is sustained by snowmelt from the Rocky Mountains and inflow from the Pecos River and Devils River in the United States. The Río Conchos in Mexico provide over two thirds of the water in the river flowing between the US State of Texas and Mexico. In addition to supplying drinking water to more than 5.5 million people, the Rio Grande supplies enough water to irrigate approximately 2 million acres of agricultural land (IBWC, 2016). It is also the principle water source for many multinational industrial facilities, known as Maquiladoras, which are located along the Texas-Mexico border.

In the United States, due to the river's interstate nature, the Rio Grande Compact of 1938 was put into place to allocate water use and regulate interstate water sharing between the US states of Colorado, New Mexico, and Texas. In 1944, the United States and Mexico signed the "Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande," also known as the US-Mexico Water Treaty of 1944, which allocates water in the three transboundary rivers flowing between the two countries, including the Rio Grande/Río Bravo (IBWC 2016a). In 1948, the Pecos River Compact was signed between New Mexico and Texas to apportion the water of the Pecos River, an important US tributary of the Rio Grande/Río Bravo, between the two US states. In addition to the water sharing agreement, the Pecos River Compact also contains provisions to facilitate the development of water-saving construction initiatives on the river.

The Lower Rio Grande/Río Bravo is the 450 km stretch of the Rio Grande that begins just downstream of Falcon International Reservoir Dam and ends in the Gulf of Mexico (Figure 1-3). This portion of the river of creates the southern boundary of three US counties in the state of Texas (Starr, Hidalgo, and Cameron) and the northern boundary of eight Mexican municipios in the state of Tamaulipas (Mier, Miguel Alemán, Camargo, Gustavo Díaz Ordaz, Reynosa, Río Bravo, Valle Hermoso, and Matamoros).

Figure 1-2. Study Area (Modified from Wikipedia, 2015).

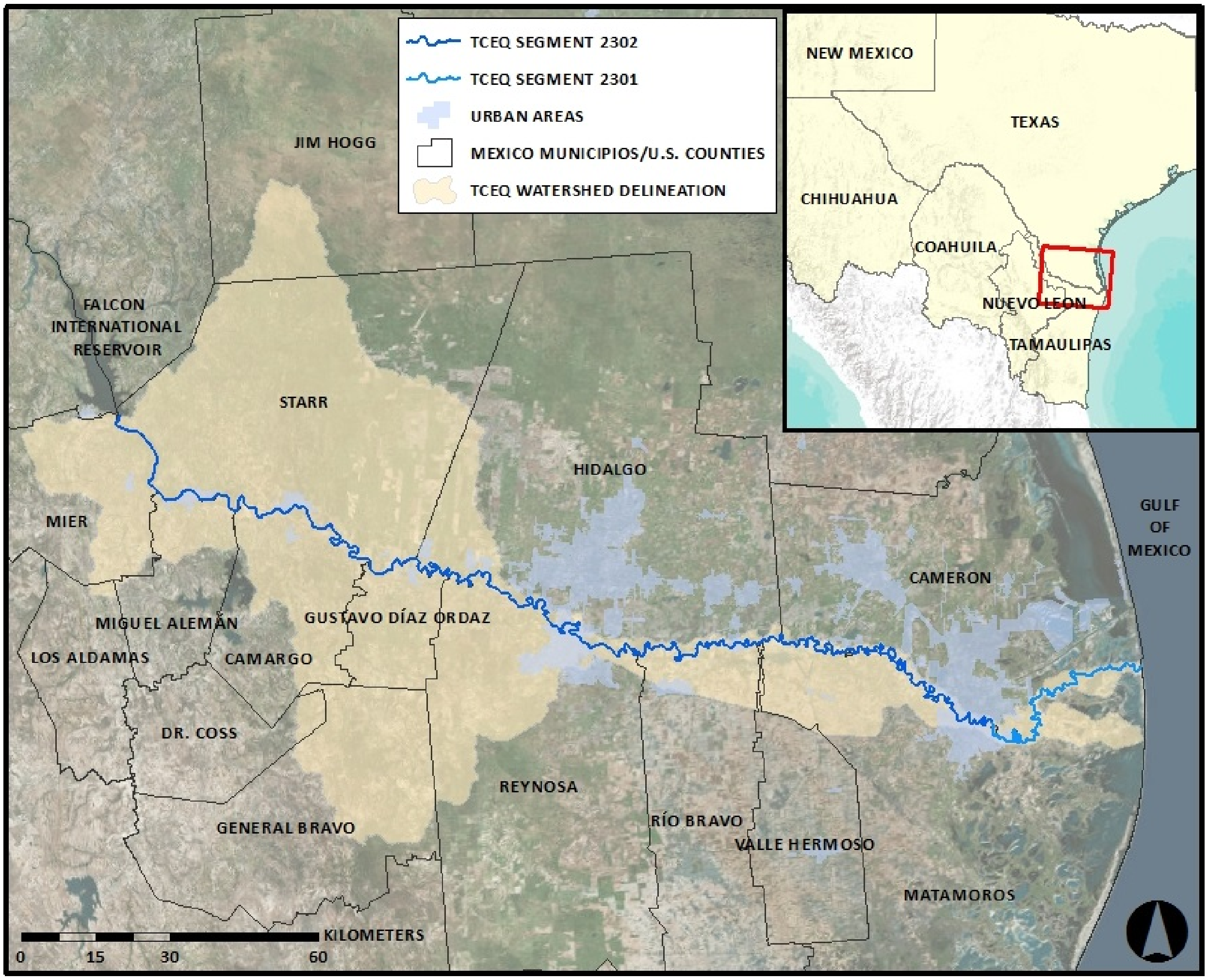

Figure 1-3. The Lower Rio Grande/Río Bravo and its Watershed.

In Texas and northern Tamaulipas, the region surrounding this portion of the river is commonly known as the Lower Rio Grande Valley, el Valle del Rio Bravo in Spanish. Several major "sister cities" are located in the Lower Rio Grande Valley. These are urban areas located directly across the river or in close proximity across the international boundary from each other, including Reynosa-McAllen and Matamoros-Brownsville. Several other smaller sister cities are also located in the upper portions of the Lower Rio Grande/Río Bravo, including Camargo-Rio Grande City, and Miguel Alemán-Roma (Figure 1-4). The maps in Figures 1-3 and 1-4 also show the extent of the Lower Rio Grande/Río Bravo watershed as delineated by the LRGWQI. The total transboundary watershed area of the Lower Rio Grande/Río Bravo watershed is approximately 7316.5 square kilometers (km^2).

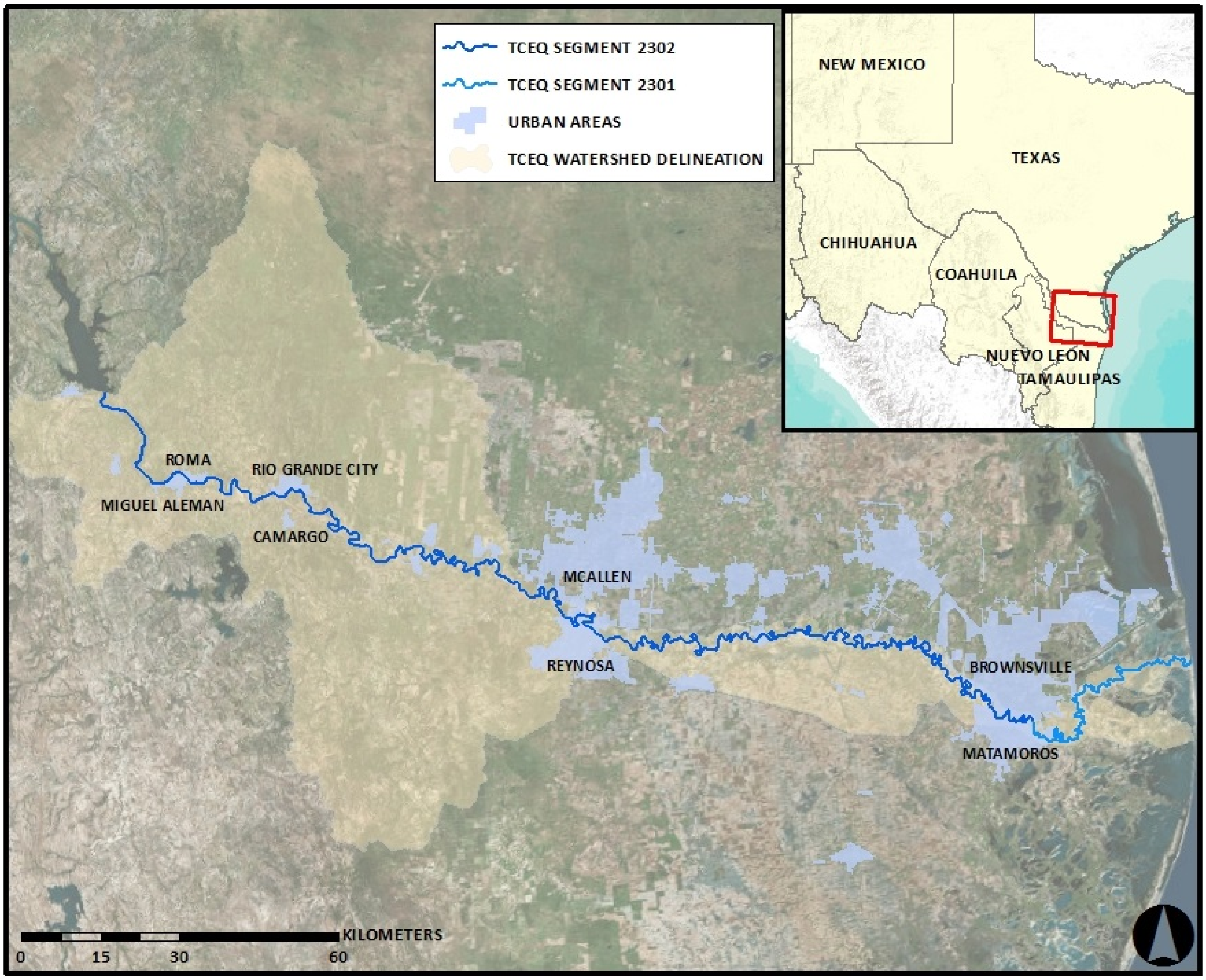

Figure 1-4. Major "Sister" Cities in the Lower Rio Grande/Río Bravo Watershed.

The upper portion of the watershed is defined by Falcon Dam. The headwaters of the two largest tributaries, the Río Alamo and the Río San Juan, are located in the mountains of the northern Mexican states of Nuevo Leon and Coahuila, respectively. Therefore, even with the northern boundary of the watershed set at Falcon Dam, the natural watershed of the Lower Rio Grande/Río Bravo extends deep into the interior of Mexico (Figure 1-1). However, both the Río Alamo and the Río San Juan are impounded by dams located within 20 kilometers (km) of the Lower Rio Grande/Río Bravo. The resulting reservoirs, Las Blancas on the Río Alamo and Marté R. Gómez on the Río San Juan, provide a reliable source of fresh water to the northern portion of the Mexican state of Tamaulipas. These Reservoirs also provide a western limit of the Lower Rio Grande/Río Bravo watershed on the Mexican side. The western watershed limit on the US side is defined by the natural catchment, which runs primarily along the western boundary of Starr County in south Texas. The resulting transboundary watershed is an area with similar areal extent on both sides of the river, 4032 km^2 on the US side and 3285 km^2 on the Mexican side.

1.0.6.1 Climate and Meteorology

The Lower Rio Grande/Río Bravo watershed is located in a subtropical region of North America with hot, usually dry, summers and mild winters (Parcher, 2010). The annual average high temperature in the watershed is 34.17 ^{o}C, the highest average temperatures typically occur in the month of August. Average annual low temperatures range from 7.78 ^{o}C near Rio Grande City to 10.61 ^{o}C near Brownsville (NOAA, 2017). Occasional artic and pacific cold fronts bring short-term freezing temperatures to the watershed. The climate in the Lower Rio Grande/Río Bravo watershed is classified as semi-arid to arid. Annual average rainfall ranges from 410.4 mm in the upper portion of the watershed near Falcon Reservoir to 649.7 mm near Brownsville (NOAA, 2017).

PRECIPITATION

Average annual precipitation varies significantly from one portion of the Lower Rio Grande/Río Bravo watershed to the other, increasing by approximately 40% from the headwaters near Falcon Dam to mouth of the river near Brownsville/Matamoros (Figure 1-5). Tropical storms and hurricanes in the Gulf of Mexico and the Mexican Pacific Coast strongly influence yearly rainfall and climate patterns in the watershed. The hurricane season lasts from June 1, until November 30 (Parcher, 2013). During this portion of the year, storms can generate extreme amounts of precipitation in short periods of time, sometimes causing severe flooding in the watershed. Figure 1-6 shows average annual rainfall totals measured in the Rio Grande Valley of south Texas.

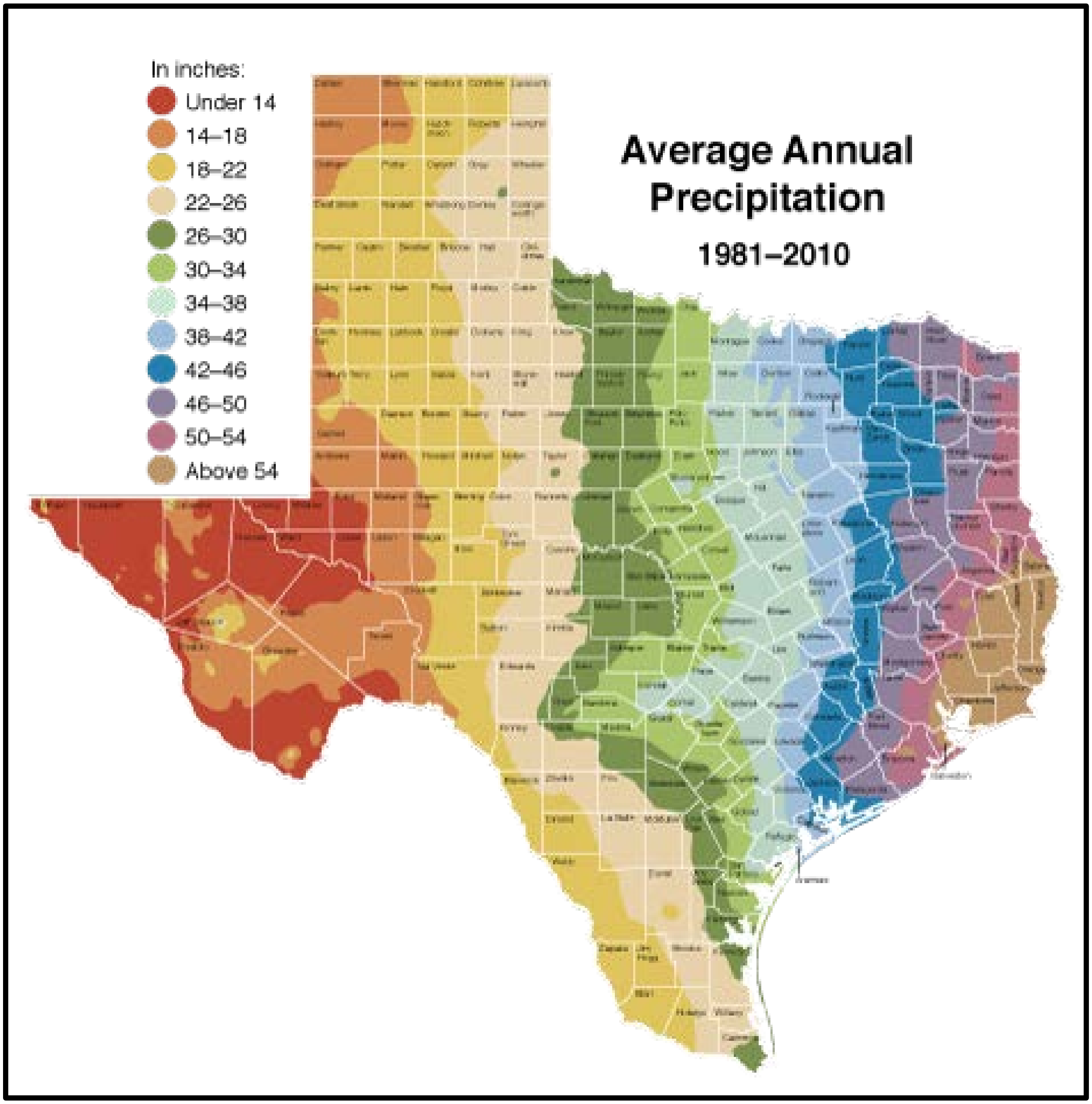

Figure 1-5. Average Annual Precipitation in the State of Texas, 1981-2010. Source: Texas Historical Association (http://texasalmanac.com).

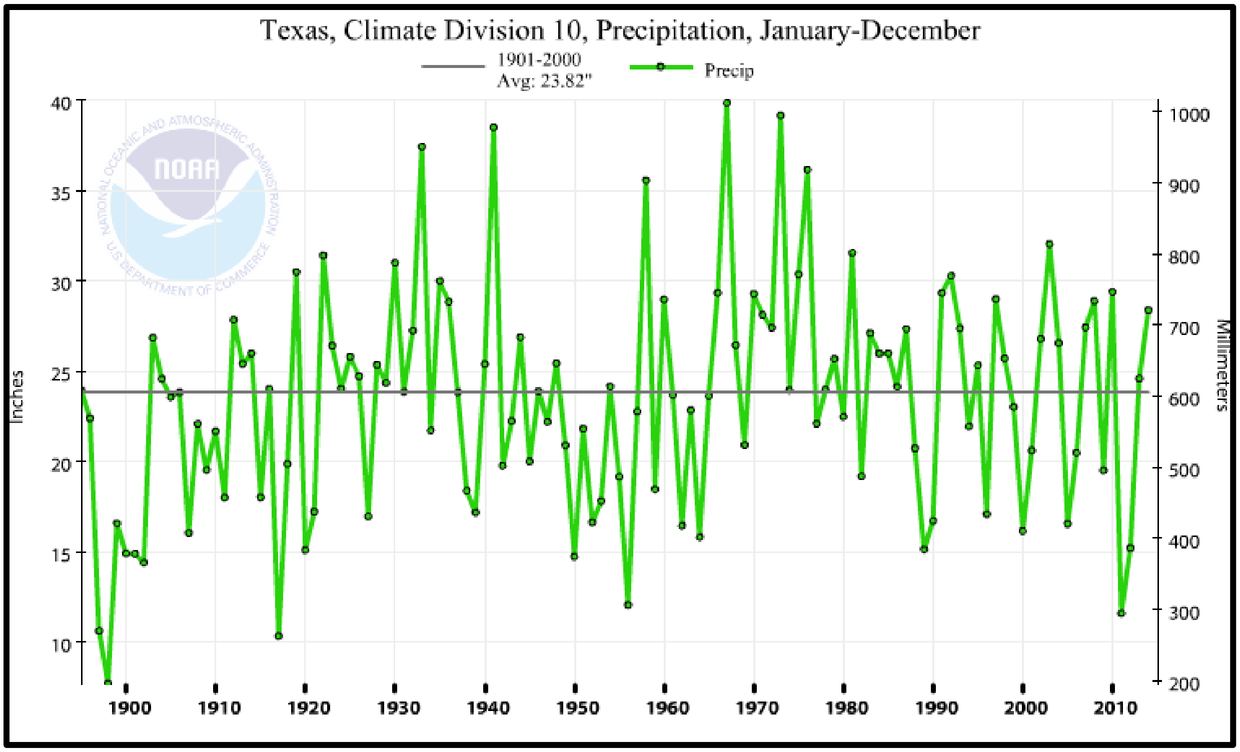

Figure 1-6. Average Annual Rainfall in the Rio Grande Valley, South Texas.

Despite an average annual rainfall exceeding 600 mm, the Lower Rio Grande/Río Bravo watershed is subject to prolonged periods of drought. The Texas Water Development Board defines drought conditions as those in which evapotranspiration rates are higher than precipitation rates causing overall water loss in a region. Decreases in rainfall and/or increases in temperature can cause this to occur leading to lower levels in the reservoirs and in river channels (Parcher, 2013). The Palmer Drought Severity Index (PDSI) is a measure of drought that has a scale from -6.0 (extremely dry) to +6.0 (extremely moist) with zero being "normal" moisture for the area. On this scale, the Rio Grande Valley has an annual average of 0.5 below the normal (Figure 1-7). This means that, on average, the area has experienced more dry periods than wet periods and has typically been below normal moisture conditions since 1895. Since 1994, alone, a series of droughts in the region has caused major economic loss on both sides of the border due to water shortages. Besides economic loss, water shortages can impair biodiversity and damage the ecological health of a watershed.

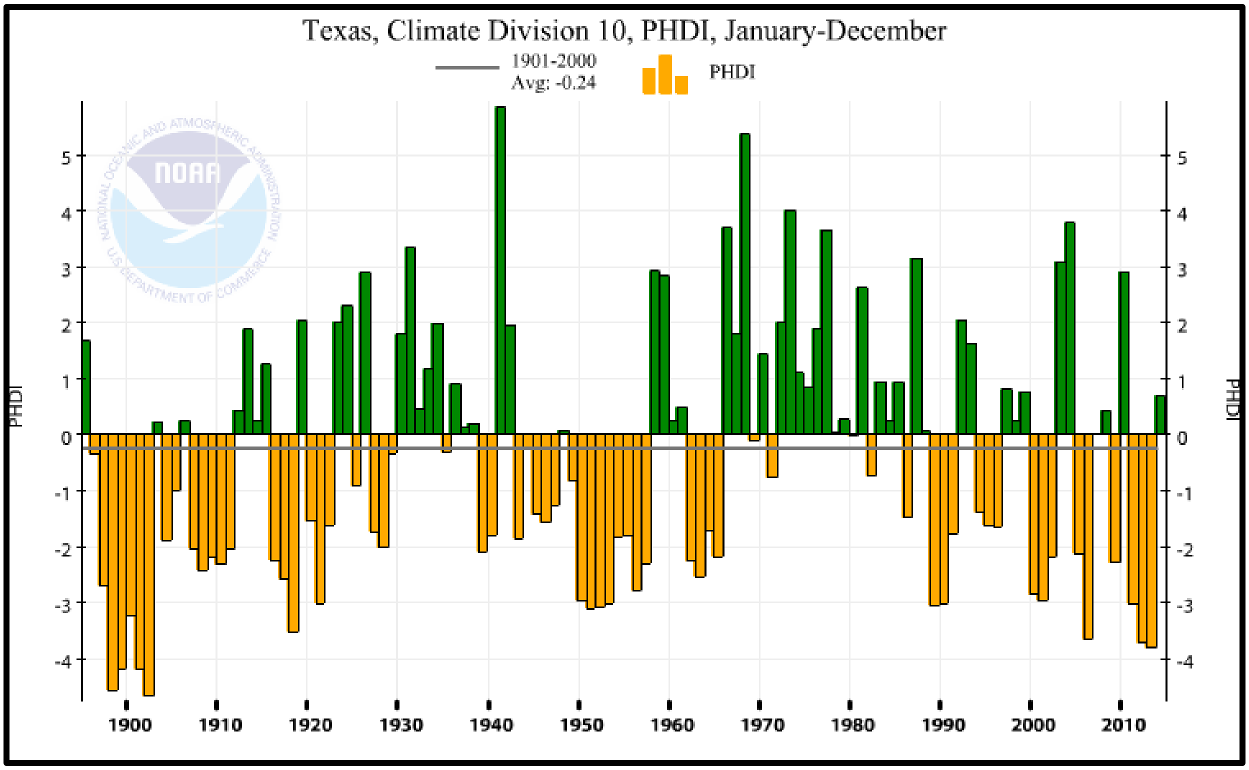

Figure 1-7. Palmer Hydrologic Drought Index (PDHI) for Hidalgo and Cameron Counties. Source: National Climatic Data Center (2007).

1.0.6.2 Land Use and Land Cover

Figure 1-8 shows land use and land cover in the Lower Rio Grande/Río Bravo watershed. The seamless binational land cover dataset displayed in Figure 1-8 was developed jointly by the US Geological Survey (USGS) and Mexico's Instituto Nacional de Estadística, Geografia, e Informática (INEGI) as part of the US-Mexico Border Environmental Health Initiative (BEHI). The BEHI was a collaborative effort between US and Mexican natural resource and health agencies to help examine, analyze and understand the linkages between environmental and human health along the US-Mexico Border. Led by the USGS, the BEHI produced integrated geospatial datasets and documents depicting environmental quality along the US-Mexico border. The BEHI binational land cover dataset combines the United States' Multi-Resolution Land Characteristics Consortium (MRLC) land use/land cover classification scheme (a modified Anderson level I and II at a scale of 1:100,000) with INEGI's Uso de Suelo y Vegetación Serie III classification (1:250,000).

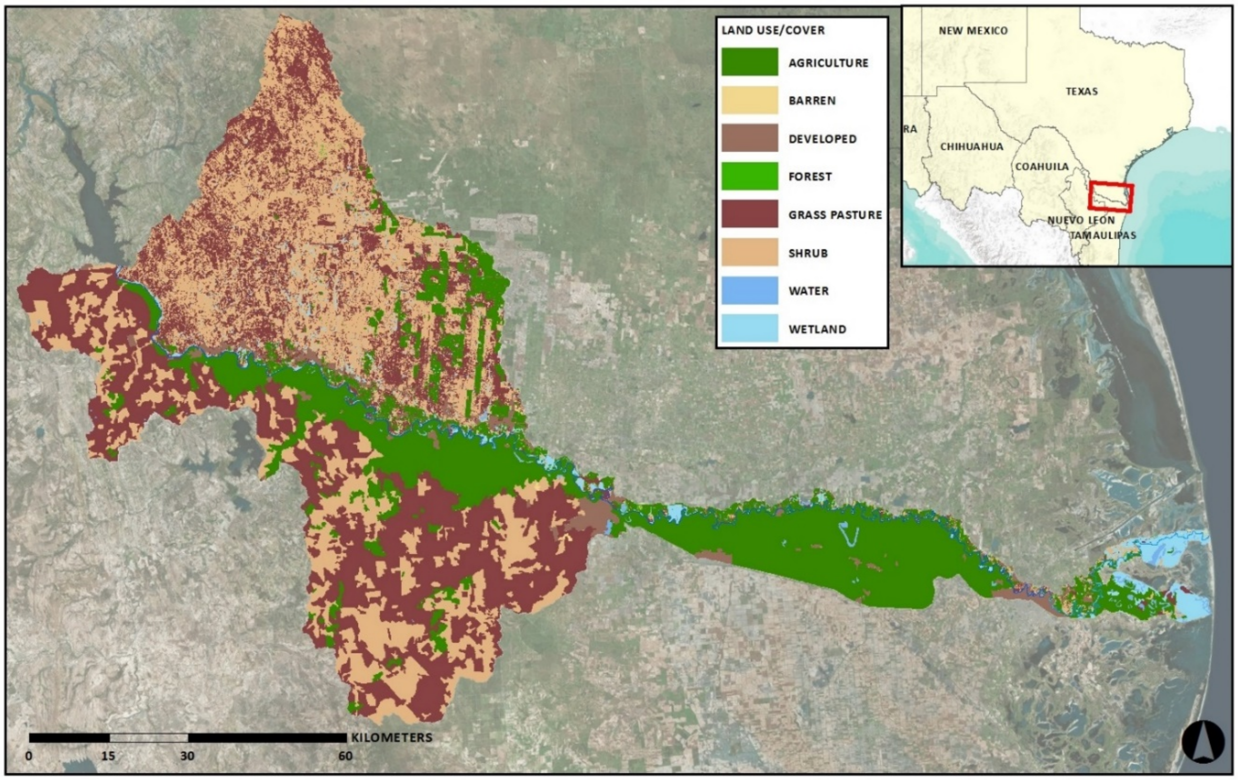

Figure 1-8. Land Use and Land Cover in the Lower Rio Grande/Río Bravo Watershed.

The resulting land use/land cover (LULC) classes are consistent across the international border and are comprised of eight different LULC classifications: developed, agriculture, forest, shrub, water, barren, grass/pasture, and wetland. The source of the data are Landsat 5 and 7 images taken in 2001. Overall, 4.72 percent of the Lower Rio Grande/Río Bravo watershed is classified as developed or built-up urban land and 24.29 percent is used for agriculture (Table 1-1). Approximately 35 percent of the land cover in the watershed is composed of pasture, hay, or grasslands and 33 percent is composed of shrub or scrublands. Wetlands comprise only 2 percent of the total watershed area. Tables 1-2 and 1-3 provide country-specific detail regarding land use and cover in the Lower Rio Grande/Río Bravo watershed.

Table 1-1. Land Use and Land Cover in the Lower Rio Grande/Río Bravo Watershed (US and Mexico)

Land Cover Category†	Area (km^2)	Percent of Total Watershed Area (%)
Agriculture	1,776.88	24.29
Barren Land	14.26	0.19
Developed/Urban	345.07	4.72
Forrest	16.05	0.22
Pasture Hay/Grasslands	2,548.82	34.84
Shrub/Scrub	2,418.43	33.05
Wetlands	156.26	2.14
Water	40.68	0.56
Total	7,316.45	100.00

†Modified MRLC classification

Table 1-2. Land Cover in the Mexican Portion of the Lower Rio Grande/Río Bravo Watershed

Land Cover Category†	Area (km^2)	Percent of Watershed on Mexican Side (%)	Percent of Total Watershed Area (%)
Agriculture	1,344.01	33.34	18.37
Barren Land	2.82	0.07	0.04
Developed/Urban	106.28	2.64	1.45
Forrest	0.03	<0.01	<0.01
Pasture Hay/Grasslands	1,572.77	39.01	21.50
Shrub/Scrub	945.43	23.45	12.92
Wetlands	37.40	0.93	0.51
Water	22.94	0.57	0.31
Total	4,031.67	100.00	55.10

†Modified MRLC classification

Table 1-3. Land Cover in the US Portion of the Lower Rio Grande/Río Bravo Watershed

Land Cover Category†	Area (km^2)	Percent of Watershed on US Side (%)	Percent of Total Watershed Area (%)
Agriculture	432.88	13.18	5.92
Barren Land	11.44	0.35	0.16
Developed/Urban	238.79	7.27	3.26
Forrest	16.05	0.49	0.22
Pasture Hay/Grasslands	976.05	29.71	13.34
Shrub/Scrub	1,473.00	44.84	20.13
Wetlands	118.87	3.62	1.62
Water	17.74	0.54	0.24
Total	3,284.81	100.00	44.90

†Modified MRLC classification

1.0.6.3 Geology, Topography, and Soils

The geology, topography and soils in a river's watershed influence the physical, biological and ecological properties of the river. The following is a summary of the geology, topography, soils, hydrology and biology of the Lower Rio Grande/Río Bravo watershed.

GEOLOGY

The Lower Rio Grande/Río Bravo watershed is located in the western Gulf of Mexico coastal plain at the base of outcropping tertiary geologic units of the Goliad, Catahoula, Frio and Vicksburg formations, which are composed mainly of Miocene sandstones and clays. In the northern and western portions of the watershed coarser fluvial sedimentary formations of the Eocene Jackson and Wilcox groups are found, along with Oligocene conglomerates (Figure 1-9). Quaternary alluvial sediments and terrace/floodplain deposits dominate the riparian areas surrounding the river and its tributaries.

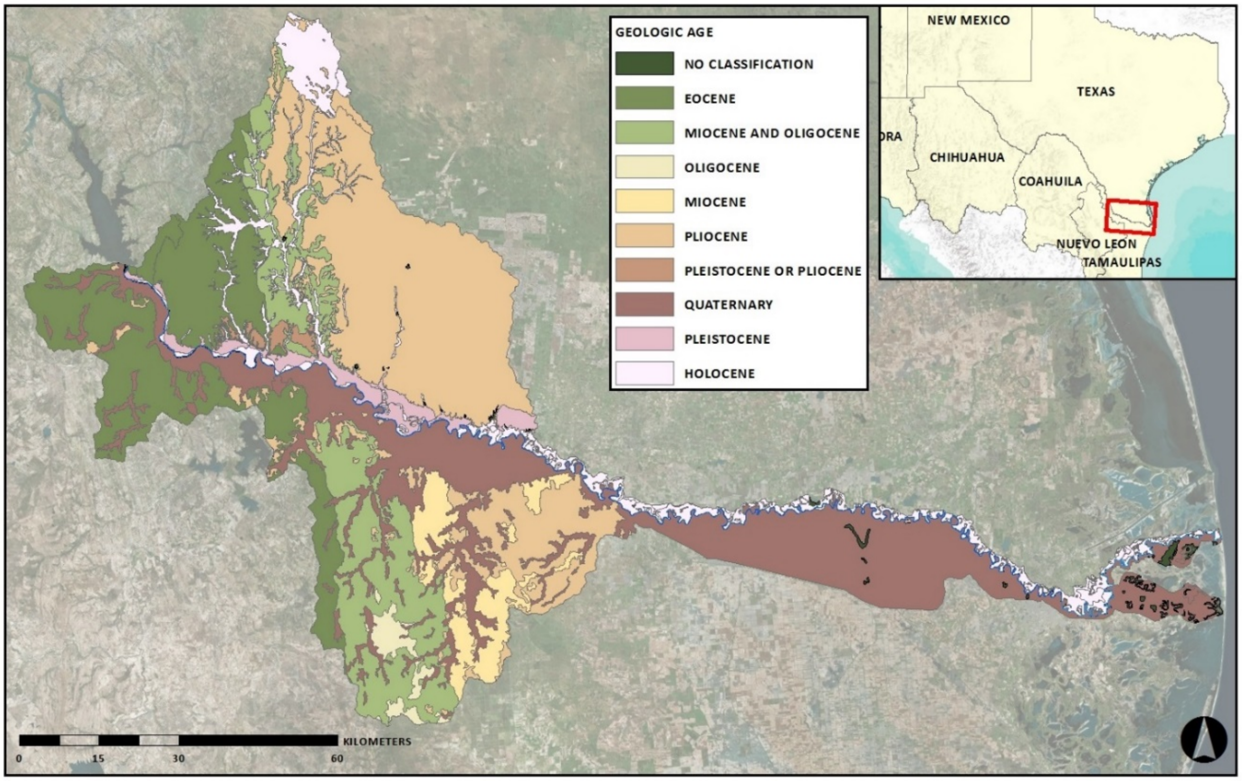

Figure 1-9. Geologic Rock Formations in the Lower Rio Grande/Río Bravo Watershed.

TOPOGRAPHY

The southern and eastern portions of the Lower Rio Grande/Río Bravo watershed lie in the ecological region classified by the USEPA as the Lower Rio Grande Alluvial Plain, while the northwestern parts lie in the Texas-Tamaulipan Thorn Scrub region. The terrain is generally level and low in most of the watershed. The elevation of the watershed varies from sea level at the Gulf Coast to approximately 300 meters (m) above mean sea level at its highest extent, with an average slope of only 40 cm/km, or 0.04% (Figure 1-10).

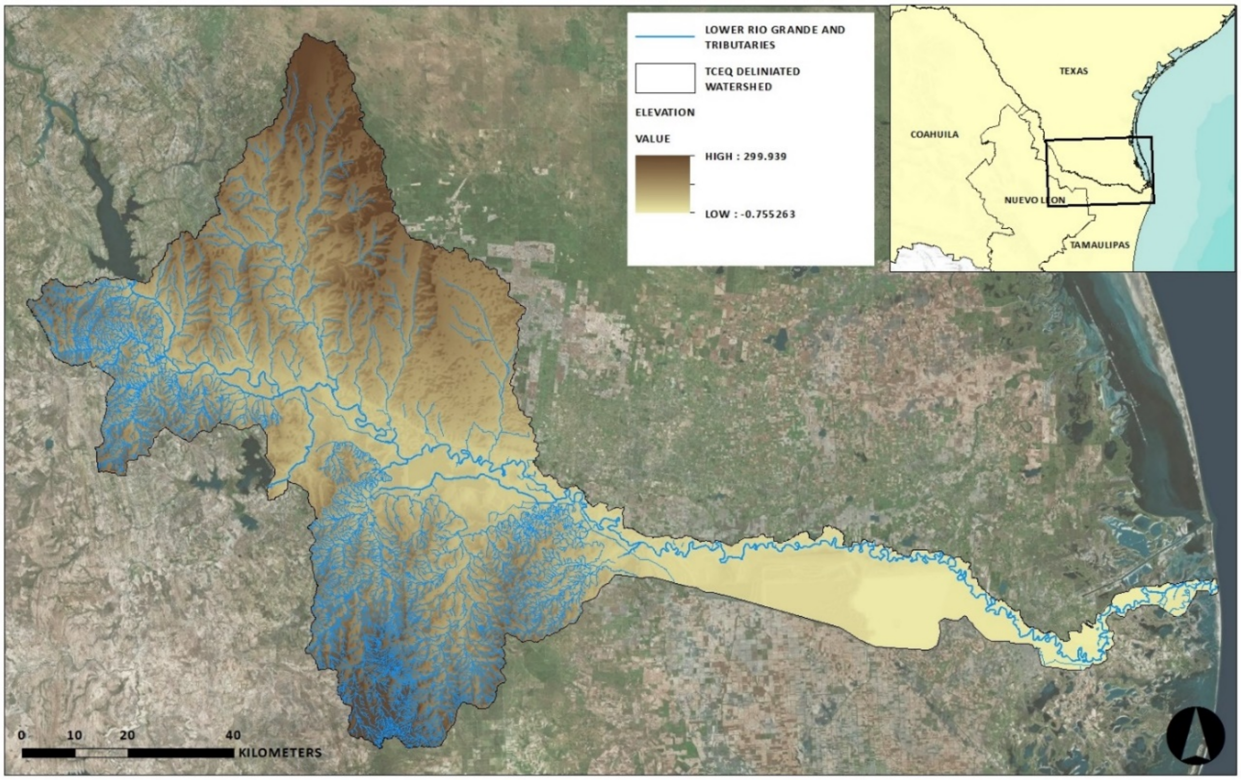

Figure 1-10. Topography and Hydrology in the Lower Rio Grande/Río Bravo Watershed.

SOILS

Figure 1-11 shows the predominant soil types in the Lower Rio Grande/Río Bravo watershed. For the most part, soils in the watershed are primarily fine-textured and well drained. Aridisol and entisol soil types dominate the northern and western portions of the watershed, while vertisols are prominent in the southern and eastern portions of the watershed.

Limited leaching in aridisol soil types often results in one or more subsurface soil horizons in which suspended or dissolved minerals have been deposited, including silicate clays, sodium, calcium carbonate, gypsum or other soluble salts. Accumulation of salts on the surface can result in soil salinization. Vertisol soil types in the southern portion of the watershed can have high water holding capacity, and very slow water permeability. Together with the low and level topography, these soil properties give rise to scattered marshes and wetlands in the coastal portion of the Lower Rio Grande/Río Bravo watershed.

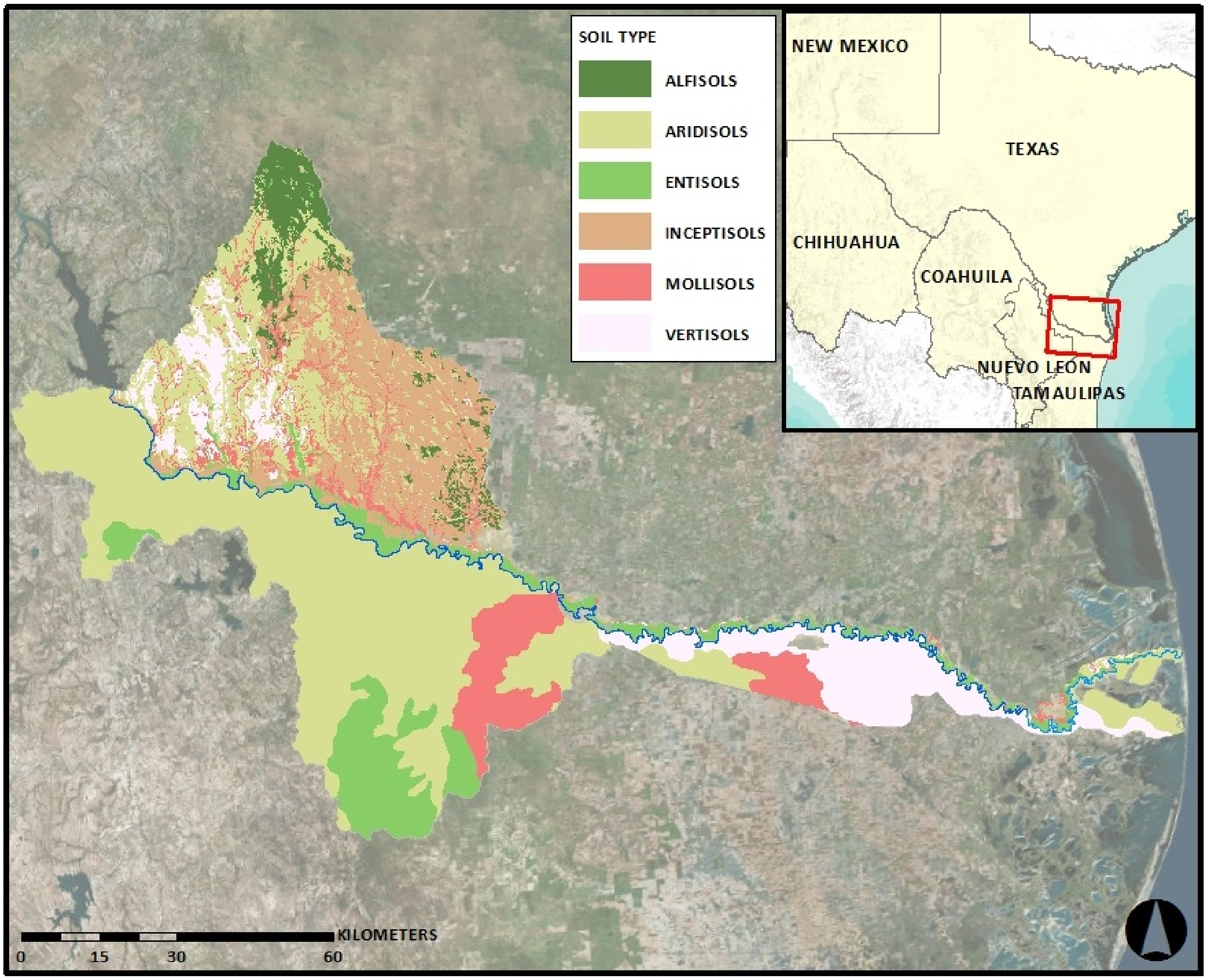

Figure 1-11. Soil Types in the Lower Rio Grande/Río Bravo Watershed.

1.0.6.3 Hydrology

The mainly fluvial hydrology of the Lower Rio Grande/Río Bravo is characterized by its coastal-deltaic nature. For most of its length, the Lower Rio Grande/Río Bravo fluvial system meanders through large areas of relatively flat land, with a mean change in elevation of approximately 40 meters over a distance of 100 km (Figure 1-10). As is the case with most large rivers approaching sea level, the coastal plain of the Lower Rio Grande/Río Bravo forms a natural web of distributary channels and oxbow lakes, which intensify in number and size as the riparian areas of the river enter the deltaic plain. Many of these channels and lakes, known locally as "resacas," are used for conveyance of water from the river for municipal and agricultural use.

Perennial contributions to flow in the Lower Rio Grande/Río Bravo are rare, with the only measurable natural tributary inflows coming from the Río Alamo and the Río San Juan. In recent years, the natural flow from these two tributaries has diminished due to the relatively recent impoundments of these two contributing rivers into the Las Blancas and Marte R. Gómez reservoirs, respectively, and also to an increase in agricultural water use from these reservoirs. Flow contributions to the Lower Rio Grande/Río Bravo, from base flow, are likely, although the exact amount of these base flow contributions has not been well studied. The Lower Rio Grande/Río Bravo also receives seasonal flow contributions from several large drains which carry return flows from irrigated agricultural land primarily on the Mexican side of the watershed.

The final 79 km stretch of the river, prior to its confluence with the Gulf of Mexico, is influenced by tidal forcing and becomes increasingly brackish in a downstream direction. The flow of seawater upstream is dependent on tidal conditions as well as on the flow conditions of the river. Often in this portion of the river, the water column becomes highly stratified with fresh to brackish water near the surface flowing over strongly saline water at the bottom of the river channel. The upstream extent of tidal influence is artificially halted near the eastern edge of the Matamoros-Brownsville urban area by a concrete block weir used, among other things, to increase the depth of the river on the fresh water side. The El Jardín weir, as it is known, is the site of the last major irrigation district pump on the US side.

1.0.6.4 Biology

The Lower Rio Grande/Río Bravo watershed is home to a diverse array of wildlife including nearly 700 species of vertebrates and 1,200 plant species (Schmandt, et al., 2002). Vegetation cover in the Lower Rio Grande/Río Bravo watershed is dominated by native Tamaulipan Brushland, characterized by dense, thorny vegetation with a high degree of biological diversity (Parcher, 2010). Sugar Hackberry is the most common tree species found throughout the watershed except where mesquite is dominant near the coast and near Falcon Reservoir (Lonard and Judd, 2002). The riparian areas along the banks of the Lower Rio Grande/Río Bravo host tall, lush vegetation that provides important nesting and feeding habitats for local birds and animal life (Parcher, 2010; Lonard & Judd, 2002). The tidal portion of the Lower Rio Grande/Río Bravo is dominated by subtropical and tropical vegetation, such as Mexican Palmettos. At the mouth of the river, the vegetation is similar to the barrier islands along the Laguna Madre to the north and to the south, which have shrub-like plants and grasses with very few trees present.

According to Schmandt, et al. 2002, urban and agricultural development in the region has had an adverse effect on the natural environment and led to a considerable loss in biodiversity. The Lower Rio Grande/Río Bravo watershed has been identified as an area where wildlife habitat is rapidly vanishing and in immediate need of protection (Lonard & Judd, 2002). It is a critical habitat for many animal species, some of which are listed as threatened or endangered by the US Fish and Wildlife Service. Of the vertebrate species living in the watershed, more than 86 of them are listed as endangered, threatened, or are considered candidates for immediate action (Schmandt, et al., 2002). The diminished woody brushland habitat in this region is of specific concern to biologists because it is the hunting and breeding ground for the endangered ocelot, a small wild feline species. The ocelot's numbers in the United States have dwindled down to 50 individuals, largely due to habitat destruction, the single greatest threat they face. It is estimated that since the 1900's, 99% of native brush in the Lower Rio Grande/Río Bravo riparian zone has been destroyed (Jahrsdoerfer & Leslie, 1988).

Migrating waterfowl and songbird populations have also declined due to habitat loss. However, since the 1980's, the USFWS has been working to create a wildlife corridor by restoring patches of native riparian habitat and purchasing land to connect those land areas (USFWS, 2016). The USFWS Wildlife corridor program has helped preserve much of the existing native riparian environment in the Lower Rio Grande/Río Bravo watershed and the effort will continue to decrease habitat fragmentation and to increase the range of native habitat in the watershed, providing a refuge to species with declining populations. Improving the natural habitat in a river's watershed also benefits water quality in the river. Improvements in the quality of riparian vegetation have been shown to decrease erosion along river banks and improve the pollutant assimilative capacity of the water body. Rivers with healthy riparian areas often have higher levels of dissolved oxygen and less suspended sediment loads.

As riparian zones can be an indicator of river health, so too can the state of fish communities. In the Lower Rio Grande/Río Bravo, the number of native fish has declined by 70% in the last two decades (Lacewell, et al., 2010). Freshwater fish species have migrated further upstream and have been replaced in the mouth of the Rio Grande/Río Bravo by estuarine and marine species. This migration correlates with decreasing river flow, increases in nutrient concentrations, competition with non-native species for resources, and increasing salinity (Schmandt, et al., 2002). These changes have ultimately resulted in fewer and less diverse freshwater aquatic fauna.

Non-native and invasive species have also become a common problem in the region. Many invasive species were added to the ecosystem intentionally, such as saltcedar to reduce erosion and several fish species were introduced in the mid-20th century for game fishing (Lacewell, et al., 2010). These non-native species compete with the native ones for habitat and resources and, when left unchecked, can overtake and damage an ecosystem. Not only do invasive species jeopardize the functioning of natural ecosystems, they can also cause serious economic damage (Rauschuber, 2002). In the Lower Rio Grande/Río Bravo, the giant reed (Arundo donax) and saltcedar (Tamarix aphylla) aggravate water availability problems by consuming an amount of water equivalent to about 11% of all irrigation water diverted by US irrigation districts in the watershed (Lacewell et al., 2010). Invasive water plants, such as water hyacinth (Eichhornia crassipes) and hydrilla (Hydrilla verticillada), clog waterways and interfere with the movement of water for drainage and irrigation, ultimately affecting agricultural activities and urban water supply in the area.

1.0.6.5 Demographics

The following section is intended to provide a brief demographic profile of the Lower Rio Grande/Río Bravo watershed. Demographic information compiled for this report was obtained from the 2010 Decennial Census of the United States, conducted by the US Census Bureau (US Census, 2010), and the 2010 Censo de Población y Vivienda, conducted by INEGI (INEGI, 2010b).

Despite the fact that rural areas predominate in the Lower Rio Grande/Río Bravo watershed, the majority of the approximately 2.5 million people living in the region live within urban areas in the 4 Texas border counties and the 11 Tamaulipas municipios included in the watershed (Figure 1-12). The total population for the 4 counties on the US side of the watershed was 1,203,123 in 2010 and the total population for the 11 municipios included on the Mexican side of the watershed was 1,341,998, indicating an almost even split in the overall transboundary watershed population between the United States and Mexico. It should be noted that, although only a small fraction of Cameron and Hidalgo county residents live within the Lower Rio Grande/Río Bravo watershed, the service areas of public utilities that provide drinking water to county residents extend well north of the watershed boundary and the majority of the residents in these counties depend on the Lower Rio Grande/Río Bravo for drinking water. Comparisons between US and Mexican census data are difficult to make because the two countries collect different demographic data. The following sections provide separate descriptions of the demographic information collected in each country.

US DEMOGRAPHICS

The Lower Rio Grande/Río Bravo watershed on the US side includes portions of Starr and Jim Hogg Counties, which contain small, mainly rural populations. The small portion of Jim Hogg County included in the watershed is particularly sparsely populated, with less than 50 residents estimated to live in that portion of the Lower Rio Grande/Río Bravo watershed (US Census, 2010). A significant portion of western Hidalgo County, also composed mainly of rural areas but containing a number of urban and suburban residential areas near the river, is also included in the Lower Rio Grande/Río Bravo watershed. Narrow strips of land at the southern boundaries of Hidalgo and Cameron Counties complete the delineation of the Lower Rio Grande/Río Bravo watershed on the US side. Table 1-4 shows the percentage of each US county included in the Lower Rio Grande/Río Bravo watershed.

Cameron, Hidalgo, Starr and Jim Hogg counties share many common characteristics, but also exhibit some demographic differences. Between 2000 and 2010, the total population of Cameron, Hidalgo, Starr and Jim Hogg counties increased by 29.2 percent from 978,369 to 1,264,091 (US Census Bureau, 2010). Hidalgo County is the most populated county in the US portion of the Lower Rio Grande/Río Bravo watershed with 774,769 inhabitants (in 2010), which amounts to 61.3 percent of the four-county population. Starr County, the US County with the most land area in the watershed, contributes only 4.8 percent of the four-county population. Hidalgo County is the fastest growing county in the US portion of the Lower Rio Grande/Río Bravo watershed.

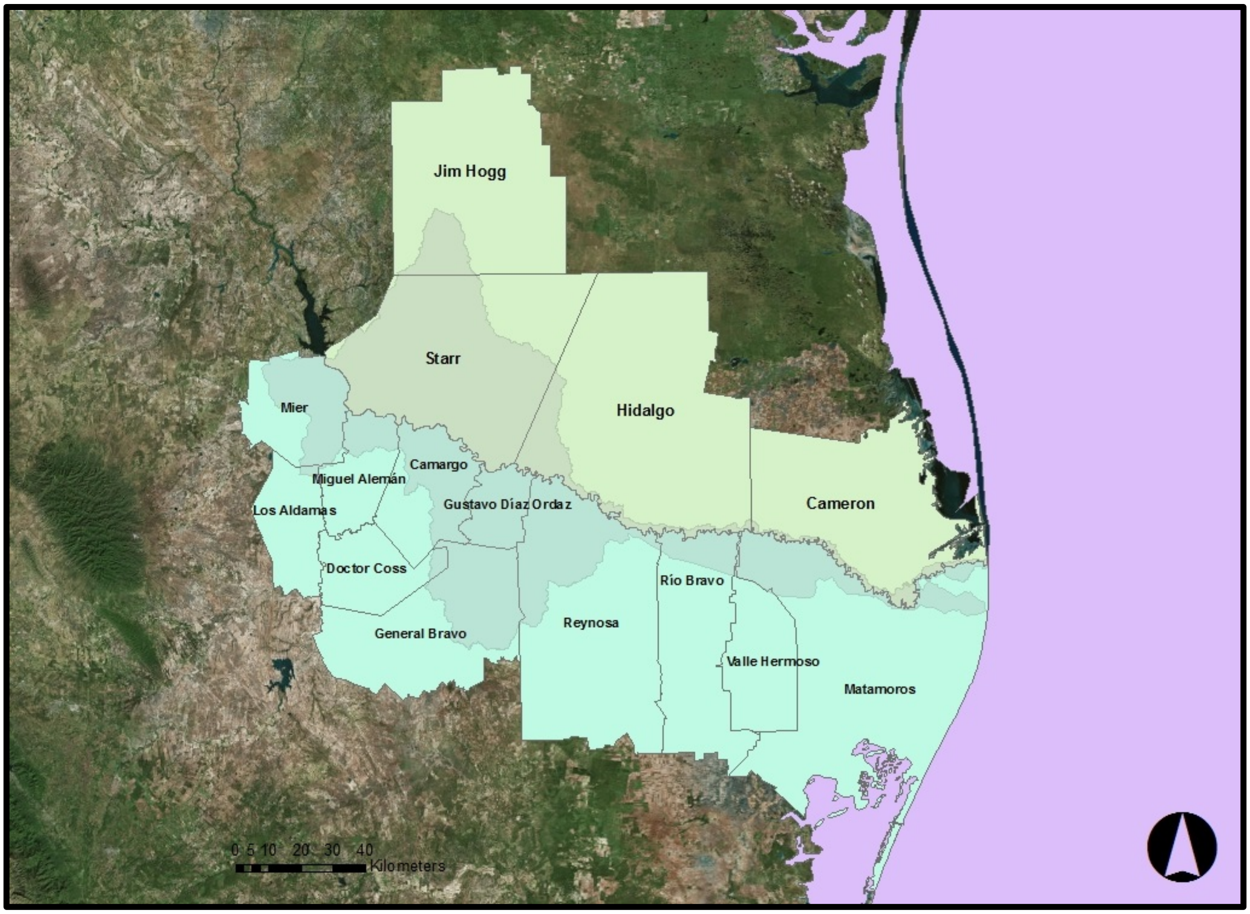

Figure 1-12. Portions of US Counties and Mexican Municipios Included within the Lower Rio Grande/Río Bravo Watershed.

Table 1-4. Areas of US Counties Included within the Lower Rio Grande/Río Bravo Watershed

US County Name	Total Area (km^2)	Area within the Watershed (km^2)	Percent of Area within the Watershed (%)
Jim Hogg	2,959.65	265.10	8.96
Starr	3,154.85	2,455.28	77.83
Hidalgo	4,128.74	431.55	10.45
Cameron	2,463.92	154.99	6.29

Between 2000 and 2010, Hidalgo County's population increased by 36.1 percent, whereas population growth in Jim Hogg County over the same period increased by only 1.78 percent (US Census Bureau, 2010). The population of all four US counties in the Lower Rio Grande/Río

Bravo watershed is predominantly Hispanic, ranging from 88.1 percent in Cameron County to 95.8 percent for Starr County (US Census Bureau, 2010). The population is young, with the median age for each county well below the national average of 37.2. Hidalgo County's median age is 28.3 and one third of the population of Cameron, Hidalgo, and Starr Counties are under the age of 18. The region is considered economically depressed, by US standards with half of all residents under 18 years of age living below the United States's annual income poverty level threshold of $22,050. The median annual income in the four counties ranges from $22,418 for Starr County to $30,760 for Cameron County (US Census Bureau, 2010).

In addition to total population and population growth, the demographic differences between the US counties in the Lower Rio Grande/Río Bravo watershed relate also to population density. Hidalgo County's population is not only 13 times greater than Starr County, 70 percent of people in Hidalgo County live in cities or towns, whereas in Starr County that figure is just over 40 percent. The population of Cameron County is also composed mainly of urban residents. In 2010 Cameron County had the greatest population density of the four watershed counties with 75% of the population living in urban areas. Residents living in the Brownsville and Harlingen areas make up the greatest portion of the urban population in Cameron County. In Hidalgo County, the largest population centers are clustered around the cities of McAllen, Edinburg, Mission, and Pharr. In Starr County, most of the urban population lives in the Roma and Rio Grande City urban areas.

Despite living in an economically depressed area of the United States, over two thirds of US Lower Rio Grande/Río Bravo watershed residents live in owner-occupied homes. However, an unusually high number of households in the four-county area lack basic water and sewer services. Many of these households are located in unincorporated suburban areas known as "colonias." In 2013, the Texas Attorney General's Office listed 942 colonias in Hidalgo County, 257 in Starr County and 195 in Cameron County, amounting to approximately 52 percent of all recognized borderland colonias in Texas (Texas Office of Attorney General, 2013).

MEXICAN DEMOGRAPHICS

Mexico's Municipios are political subdivisions roughly equivalent to US counties. These sub-state political subdivisions encompass urban and rural communities known as localides.

Portions of 11 municipios located along the US-Mexico Border Region are within the Lower Rio Grande/Río Bravo watershed and are subdivisions of the Mexican states of Tamaulipas and Nuevo León, including Mier, Los Aldamas, Miguel Alemán, Camargo, Doctor Coss, General Bravo, Gustavo Díaz Ordaz, Reynosa, Río Bravo, Valle Hermoso and Matamoros (Table 1-5).

Major population centers on the Mexican side of the Lower Rio Grande/Río Bravo watershed include Matamoros, Río Bravo, Reynosa, Gustavo Díaz Ordaz, Camargo, Miguel Alemán and Mier. The total population for these cities in 2010 was 1,341,998. Reynosa, with a population of 608,891, accounts for 45 percent of this total, while Matamoros, at 489,193, comprises 36 percent (INEGI, 2010b). The least populated municipios, Gustavo Díaz Ordaz, Camargo, Miguel Alemán, and Mier, together comprise only 4.7 percent of total population in the watershed. As with the watershed population living north of the Lower Rio Grande/Río Bravo, the population of all 11 watershed municipios is predominantly Hispanic.

The median age in the municipios of the watershed is 27, which is slightly higher than the 25.8 estimated for the rest of Mexico. This northern region of Mexico is considered economically prosperous by Mexican national standards, with an average annual per capita income of 62,400 Mex$, more than 1.5 times the national average of 37,752 Mex$. INEGI’s private dwelling data shows that the two most populated municipios in the watershed, Reynosa and Matamoros, have the lowest percentages of population with piped water, electricity, and sewage collection and treatment. For example, the number of people in Reynosa without access to a public sewer service is estimated to be 12.5 percent of inhabitants, or 81,478. In Reynosa, as many as 15 percent of private dwellings do not have a water utility connection, 12.5 percent do not have electricity and 12.6 percent do not flush to an indoor toilet connected to a sewer system (INEGI, 2010). In actual numbers, an estimated 21,440 homes of Reynosa’s 170,171 private dwellings do not have access to a sewer system.

Table 1-5. Areas of Mexican Municipios within the Lower Rio Grande/Río Bravo Watershed

Municipio Name	Total Area (km^2)	Area within the Watershed (km^2)	Percent of Area within the Watershed (%)
Mier	932.92	546.08	58.53
Los Aldamas	695.71	16.43	2.36
Miguel Alemán	634.63	190.98	30.09
Camargo	932.74	571.95	61.32
Doctor Coss	712.47	40.82	5.73
General Bravo	1,906.30	712.47	37.37
Gustavo Díaz Ordaz	429.20	429.20	100.00
Reynosa	3,139.97	891.00	28.38
Rio Bravo	1,571.70	236.97	15.08
Valle Hermoso	899.43	10.87	1.21
Matamoros	4,658.49	708.92	15.22

1.0.7 A History of Poor Water Quality

As mentioned in the introduction, a common perception among the general public, in the United States and in Mexico, is that water quality in the Lower Rio Grande/Río Bravo is very poor. One reason behind this collective view of poor water quality may be the negative coverage of this subject by the news media. Objective technical assessments of water quality conducted by environmental agencies from both countries *have* found persistent water quality problems in this portion of the river, albeit perhaps not to the level meriting the portrayal presented by some news media outlets.

A number of US and Mexican agencies and academic institutions have collected water quality in the Lower Rio Grande/Río Bravo over the last four decades, including the USIBWC, USGS, USFWS, USEPA, Texas Parks and Wildlife Department, TCEQ, CONAGUA, IMTA, University of Texas-Rio Grande Valley, Instituto Tecnológico de Monterrey and various local and regional public entities (e.g., Brownsville Public Utility Board, COMAPA-Reynosa, etc.), to name a few. Only the USIBWC, USGS, CILA, CONAGUA and the TCEQ have performed systematic assessments of water quality in this portion of the river.

1.0.7.1 US Assessments of Water Quality

As early as 1969, the Texas Water Commission (TWC), one of the precursor state agencies to the TCEQ, was compiling and analyzing water quality data the commission collected in Texas surface water bodies, including the Lower Rio Grande. Although the requirements of the 1972 federal Clean Water Act stipulate that states and territories must assess the quality of surface waters under their jurisdictions, it was not until 1992 that the first such assessment was published by the State of Texas. Official assessments of surface water quality in Texas, which include lists of impaired water bodies of the state, are now known as the Texas Integrated Report of Surface Water Quality (TCEQ 1992-2014). The reports are published by the TCEQ biennially and include a detailed analysis of the results of surface water quality monitoring conducted by the TCEQ in water bodies throughout the state of Texas. The portion of the report that identifies water quality "impairments," known as the 303(d) list (named after the section of the federal Clean Water Act that mandates its production), must be approved by the USEPA.

To facilitate the assessment of surface water quality, the State of Texas designates Surface Water Quality Segments for waters of the state. The segments, along with their uses and the standards and criteria assigned to each segment by the State of Texas, are codified in the state's Administrative Code (30 TAC Chapter 307), referred to as the Texas Surface Water Quality Standards. The river segments designated in the Texas Surface Water Quality Standards for the Lower Rio Grande are Segments 2302 (Rio Grande Below Falcon Reservoir) and 2301 (Rio Grande Tidal).

The Texas Integrated Report of Surface Water Quality classifies the results of the TCEQ's biennial assessment of water quality into several categories based on whether the results of the analysis show water bodies (i.e., segments) are meeting their designated uses. In segments for which there is sufficient data for analysis, the TCEQ determines if these "Fully Support" or do "Not Support" a particular designated use, based on the data collected and relevant standards and criteria. Segments that are deemed to not support one or more of their designated uses are considered "Impaired." Segments lacking sufficient data for analysis, but for which the existing data indicate a potential water quality problem, are deemed to have water quality "Concerns." The analysis of water quality parameters for which the state has not yet developed standards, for example nutrients such as phosphorus and nitrate, can also result in a segment being classified as having a Concern.

Table 1-6 shows a history of all Impairments and Concerns documented in the Lower Rio Grande by the State of Texas since 1992. As is evident from Table 1-6, the number and variety of water quality Concerns listed by the State of Texas has increased with time. There is some evidence that this is due partly to the increase in the frequency and sophistication of surface water quality monitoring over time in Texas. However, there is also evidence of an increase in the volume and type of pollutants entering the river, especially since the mid 1990's (Miranda & Harper, 2017). Also evident from Table 1-6 is the persistence of the Impairment of the Lower Rio Grande by fecal indicator bacteria (fecal coliform and *E. coli).* Fecal indicator bacteria have also been listed as a Concern in both segments of the river, including fecal coliform and Enterococci.

It should be noted that, at the time of this writing, the most recent Integrated Report of Water Quality published by the TCEQ was the 2014 report. The TCEQ completed its assessment of surface water quality for the state in 2016 and in 2018 but has published the results of these (2016 and 2018) assessments only in draft form because the USEPA has not granted approval the 2016 and 2018 State of Texas 303(d) lists. Although not as extensive as the State of Texas' surface water quality monitoring program, two US federal agencies, the USIBWC and the USGS, also maintain water quality monitoring programs in the Lower Rio Grande/ Río Bravo and have done so for several decades. The water quality monitoring programs of both the USIBWC and the USGS are composed of independent and collaborative routine monitoring efforts. That is, both agencies collect and internally archive data as part of their agency's programs. These agencies also collect and share water quality data with each other and with the TCEQ as part of collaborative monitoring efforts. As part of its commitments under the US-Mexico Water Treaty of 1944, the IBWC measures flow continuously at seven hydrometric stations located along the Lower Rio Grande/ Río Bravo. The IBWC also collects water quality data at those stations and at other locations along the Lower Rio Grande/ Río Bravo.

Table 1-6. Water Quality Impairments and Concerns Documented in Official Assessments of Surface Water Quality Conducted by the State of Texas. Source: TCEQ 1992-2014.

Year	Agency*	Segment	Impairment	Concern**
1992	TWC	2302	Fecal Coliform	Nutrients, Dissolved Oxygen
1994	TNRCC	2302	Ambient Toxicity, Chlorides, Fecal Coliform	Nutrients, Excessive Algal Growth, Dissolved Oxygen
1996	TNRCC	2301, 2302	Fecal Coliform	Fecal Coliform
1998	TNRCC	2302	Fecal Coliform	NA
1999	TNRCC	2302	Fecal Coliform	NA
2000	TNRCC	2302	Fecal Coliform	NA
2002	TCEQ	2301, 2302	Fecal Bacteria (Fecal Coliform)	Excessive Algal Growth, Total Phosphorus
2004	TCEQ	2301, 2302	Fecal Bacteria (Fecal Coliform and *E. coli*)	Excessive Algal Growth, Total Phosphorus, Chloride, Sulfate and Total Dissolved Solids
2006	TCEQ	2302	Fecal Bacteria (*E. coli*)	Dissolved Oxygen, Mercury in Fish
2008	TCEQ	2301, 2302	Fecal Bacteria (*E. coli*)	Chlorophyll a, Fecal Bacteria (Enterococci), Dissolved Oxygen, Mercury in Fish
2010	TCEQ	2301, 2302	Fecal Bacteria (*E. coli*)	Chlorophyll a, Fecal Bacteria (Enterococci), Dissolved Oxygen, Ammonia, Mercury in Fish
2012	TCEQ	2301, 2302	Fecal Bacteria (*E. coli*)	Chlorophyll a, Fecal Bacteria (Enterococci), Dissolved Oxygen, Ammonia, Mercury in Fish
2014	TCEQ	2301, 2302	Fecal Bacteria (*E. coli*)	Chlorophyll a, Fecal Bacteria (Enterococci), Dissolved Oxygen, Nitrate, Ammonia

*TNRCC is the acronym for the Texas Natural Resource Conservation Commission a predecessor agency of the Texas Commission on Environmental Quality

**NA is the acronym for Not Applicable

The water quality data collected under the IBWC's monitoring program consists mainly of dissolved solids. Although the agency does not provide an analysis of the data it collects under its independent monitoring program, the water quality data has been used to confirm the existence of several sources of high salinity to the Lower Rio Grande/ Río Bravo (IBWC, 1931-2006). Until 2006, these data were published annually in publications known as Water Bulletins. While the IBWC continues to collect flow and water quality data on a regular basis, the information must be now be requested in order to be obtained by the public.

In 1998, the USIBWC entered into a cooperative water quality monitoring agreement with the TCEQ under the TCEQ's Texas Clean Rivers Program. As a result of this agreement, the USIBWC began collecting and sharing a variety of water quality data in several locations along the Rio Grande/Río Bravo. The water quality data collected by the USIBWC under the Texas Clean Rivers Program is used by the TCEQ to assess water quality in the Lower Rio Grande. The USIBWC also publishes Basin Summary Reports annually, which contain a summary of all Clean Rivers data collected by the USIBWC during the previous year.

Like the USIBWC, the USGS also routinely collects water quality data in the Lower Rio Grande under its National Stream Quality Accounting Network (NASQAN). Once a network of over 500 water quality monitoring stations distributed over 42 US states, the USGS' NASQAN program has been significantly reduced. Of the remaining 118 NASQAN monitoring sites, two are located on the Rio Grande/Río Bravo, the most downstream station of which is located on the Lower Rio Grande/Río Bravo near Brownsville, Texas (Station ID 08475000). The main objective of the NASQAN program is to monitor long term trends in water quality, with specific emphasis on pollutants that are problematic nation-wide, such as nutrients and pesticides. Although the USGS monitors a wide set of water quality parameters at Station 08475000, its assessments of water quality are now focused on these parameters. The most recent results of the USGS' assessment of water quality trends in NASQAN Station 08475000 shows a significant upward trend in total nitrogen and total phosphorus (Figure 1-13 and Figure 1-14). High nutrients levels in surface waters can cause excessive algal growth, which in turn can cause dissolved oxygen depletion negatively impacting aquatic life habitats.

In contrast to public perceptions, however, USGS monitoring at this station shows no exceedances of human health benchmarks for the 224 pesticides monitored at Station 08475000 (Figure 1-15). The findings of the NASQAN program agree well with the results of water quality assessments conducted by the TCEQ and IBWC and documented in the Texas Integrated Report of Surface Water Quality. The lack of pesticide concerns also corroborates the results of a 1995 study conducted jointly by the TNRCC, IBWC and USEPA, which showed only low levels of pesticide contamination in water, sediment and fish tissue in most portions of the Rio Grande, but especially low in the Lower Rio Grande/Río Bravo (IBWC, 1998).

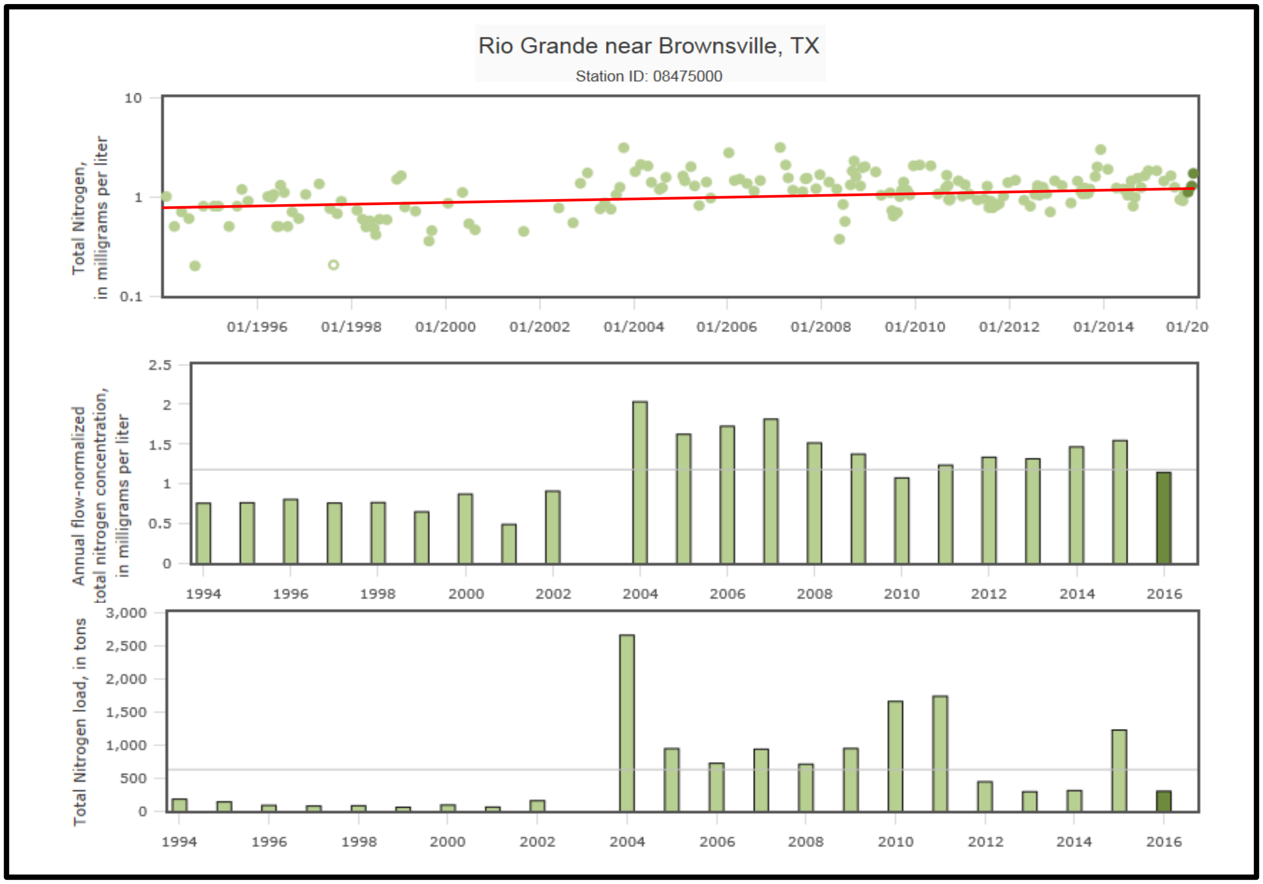

Figure 1-13. Total Nitrogen Trend in the Lower Rio Grande near Brownsville, Texas, as Reported by the NASQAN Program (USGS). Source: https://cida.usgs.gov/quality/rivers.

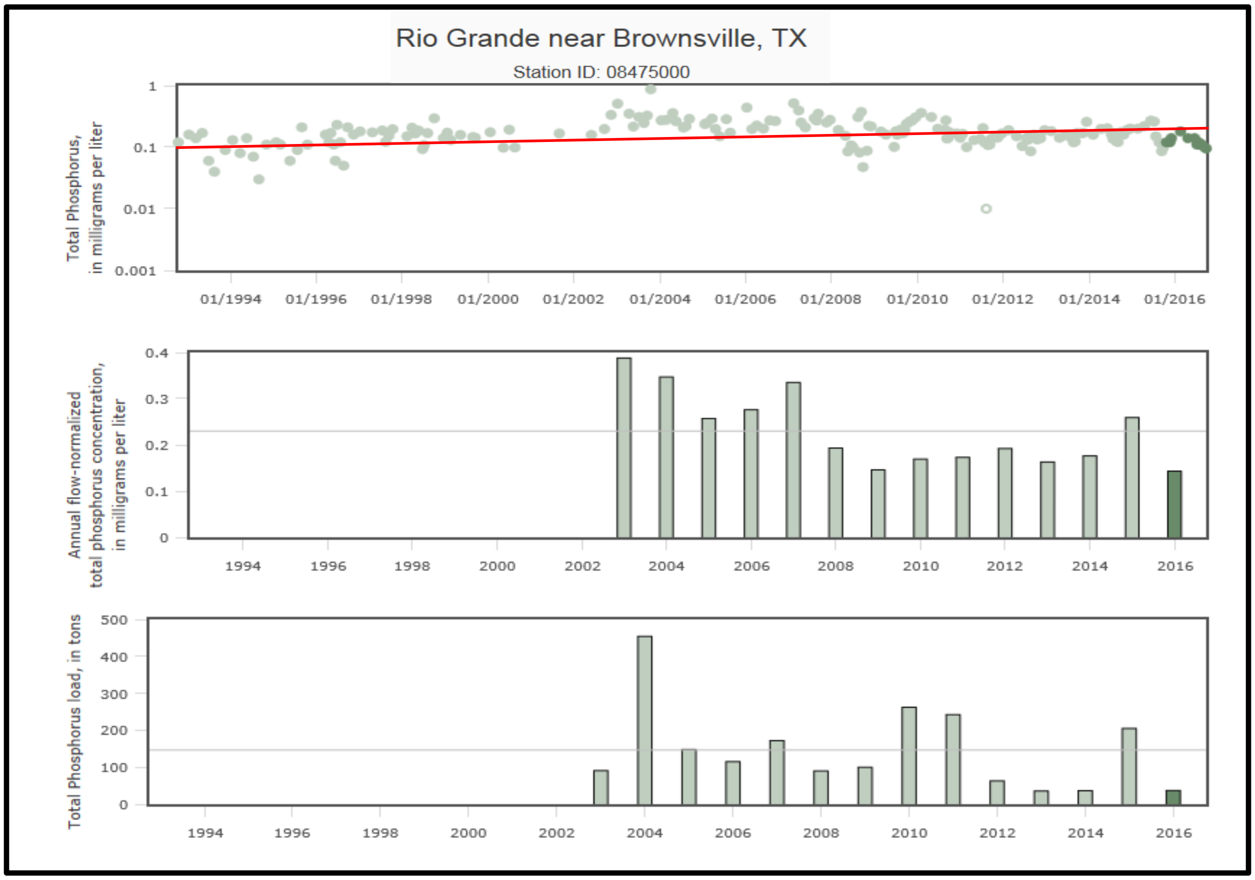

Figure 1-14. Total Phosphorus Trend in the Lower Rio Grande near Brownsville, Texas, as Reported by the NASQAN Program (USGS). Source: https://cida.usgs.gov/quality/rivers.

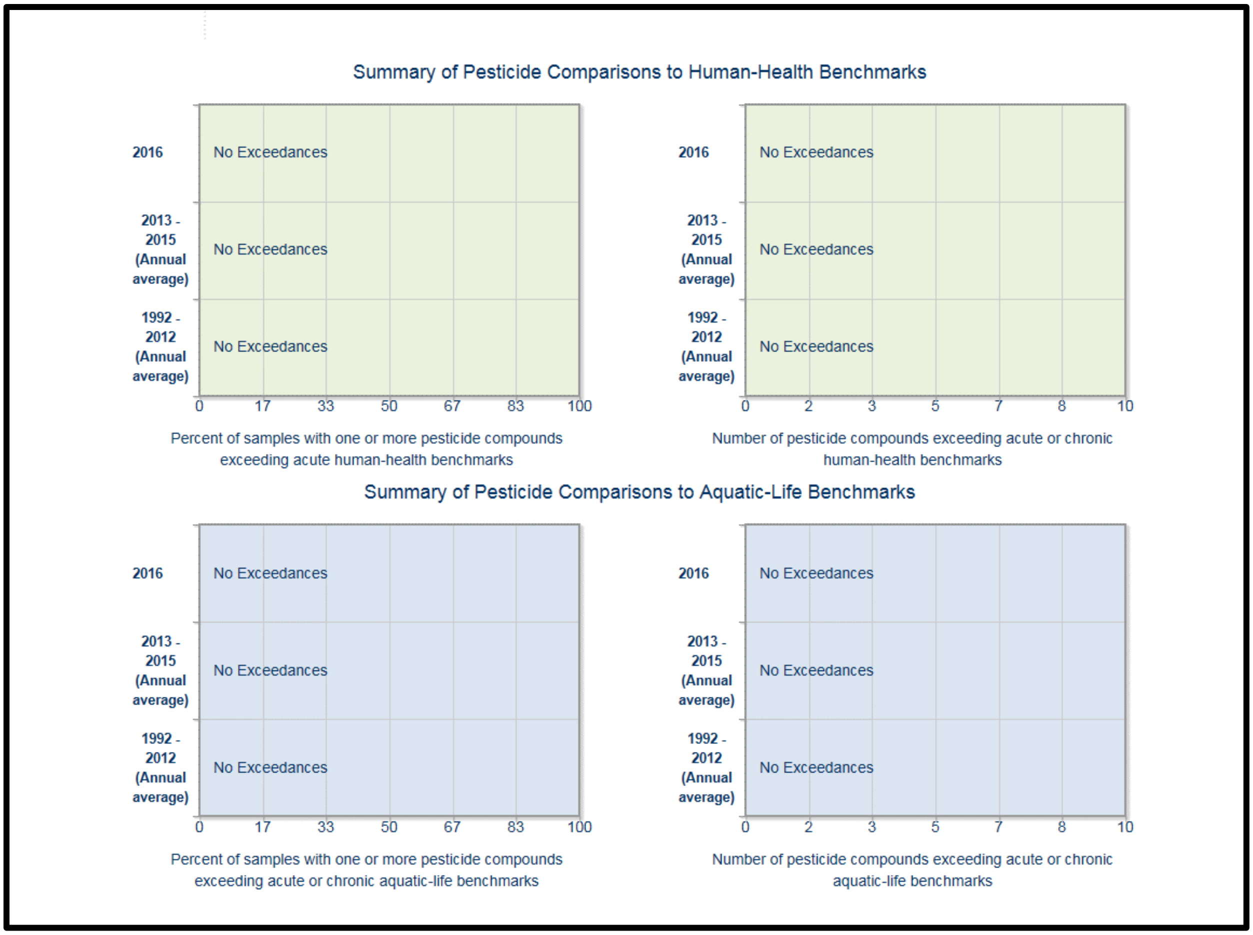

Figure 1-15. Pesticide Results in the Lower Rio Grande near Brownsville, Texas, as Reported by the USGS' NASQAN Program. Source: USGS, https://cida.usgs.gov/quality/rivers.

1.0.7.2 Mexican Assessments of Water Quality

Unlike in the United States, official monitoring and assessment of water quality in the Lower Rio Bravo is conducted almost exclusively by CONAGUA. Although some of the data collected by CILA in the Lower Río Bravo are included in these assessments, the analysis and interpretation of CILA data, within the context of official assessments of water quality, are conducted exclusively by CONAGUA. The water quality data collected under Mexico's Red Nacional de Monitoreo de la Calidad de las Aguas Nacionales, a nation-wide network of water quality monitoring stations located on Mexican water bodies, is the principal source of water quality data used by CONAGUA to assess the health of Mexican surface waters. The network consists of 4,926 monitoring stations, 16 of which are located along the Lower Río Bravo with another 7 situated on tributaries and ditches that contribute flow to the Lower Río Bravo.

CONAGUA reports the results of its official assessment of water quality every two years in a national publication titled "Estadísticas del Agua en México" (i.e., the EAM report). In addition to surface water quality, the biennial report includes a quantitative inventory of surface and ground water resources of the nation, meteorological data and climate projections, water usage and projected demand by sector, water infrastructure needs, and legal and institutional changes affecting water resources in Mexico (CONAGUA, 2016).

The Mexican government's approach to water quality assessment differs from that of the United States', in that water quality is assessed using an index of water quality indicators. The overall health of surface water bodies and the protection of their uses is determined using three water quality parameters, which are assumed to indicate overall levels of contamination by all other associated parameters. The indicator parameters are five-day biochemical oxygen demand (Spanish acronym: DBO_5), chemical oxygen demand (Spanish acronym: DQO) and total suspended solids (Spanish acronym: SST). CONAGUA reports the results of their assessment using these parameters, both by state and by hydrologic region, so, it is difficult to discern the status of water quality of individual water bodies from the biennial EAM report. Nevertheless, the information provided in the report provides a coarse look at overall water quality in Mexican states and in large river basins (i.e., hydrologic regions).

Figure 1-16 shows the results of CONAGUA's 2016 assessment of water quality for the hydrologic region of the Río Bravo in northern Mexico. Although, it is not possible to view the results for the Lower Río Bravo in isolation from the rest of the Rio Bravo Hydrologic Region, the EAM report shows that water quality in the Río Bravo Hydrologic Region is relatively good compared to that of many other Mexican hydrologic regions. For example, the percentage of monitoring sites sampled in the Río Bravo Hydrologic Region found to be contaminated or strongly contaminated with the DBO_5, DQO and SST indicators were 1.4, 16.2 and 4.7, respectively. In contrast, the percentage of monitoring sites found to be contaminated or strongly contaminated for these indicators nationwide in Mexico were 8.5, 32.4 and 6.6, respectively (CONAGUA, 2016).

Calidad del agua superficial, 2015	
Número de sitios de monitoreo según indicador de calidad del agua	
DBO_5	284
DQO	284
SST	294

Distribución de los sitios por indicador y clasificación (%)

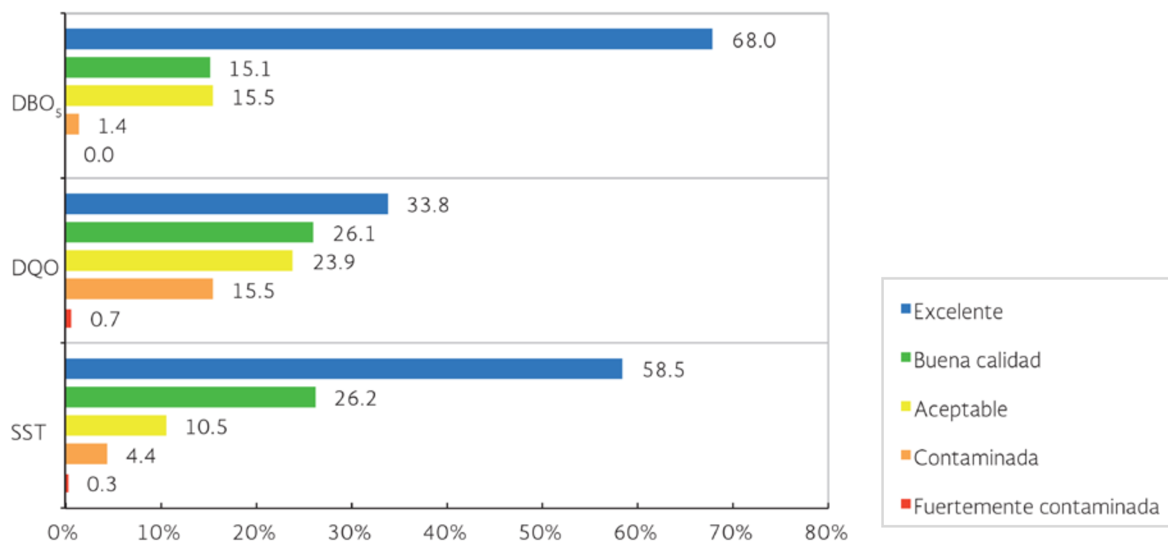

Figure 1-16. Results of CONAGUA's 2016 Assessment of Water Quality in the Río Bravo Hydrologic Region. Source: CONAGUA, 2016 (http://201.116.60.25/publicaciones/EAM_2016.pdf).

At a finer level of resolution, the results of CONAGUA's assessment of water quality shows only few individual Lower Rio Bravo monitoring sites Contaminated under the DQO and SST indicator parameters (Figures 1-17 and 1-18) and none for DBO_5.

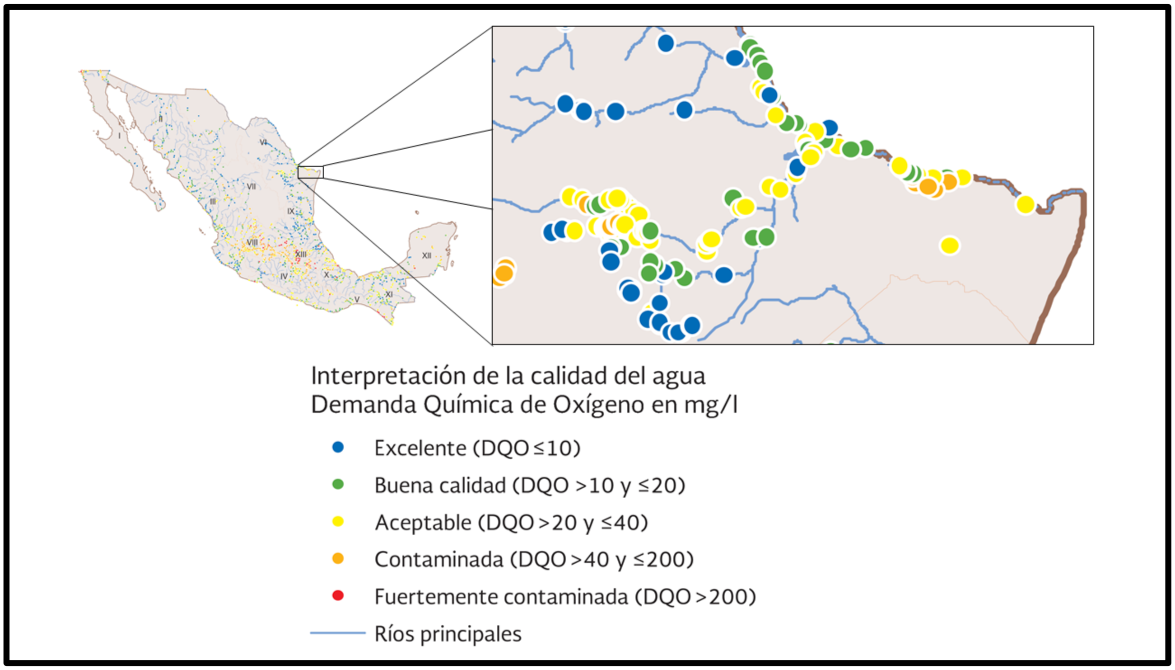

Figure 1-17. Assessment of the DQO Indicator in Monitoring Sites in the Lower Río Bravo and Associated Tributaries. Source: CONAGUA, 2016 (http://201.116.60.25/publicaciones/EAM_2016.pdf).

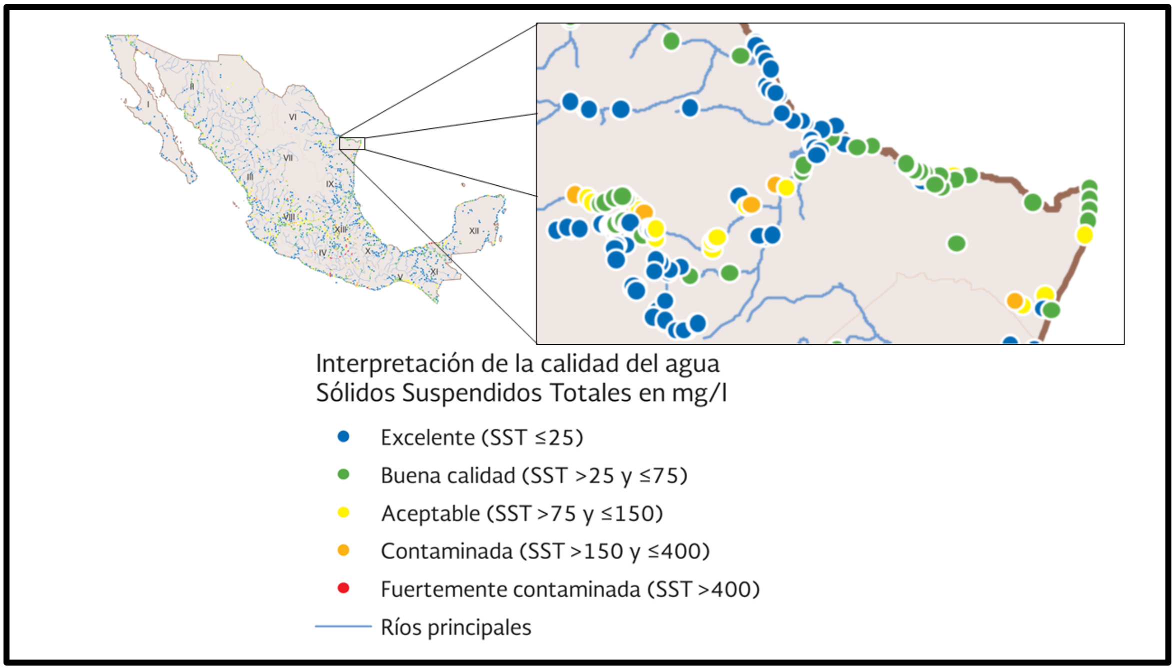

Figure 1-18. Assessment of the SST Indicator in Monitoring Sites in the Lower Río Bravo and Associated Tributaries. Source: CONAGUA, 2016 (http://201.116.60.25/publicaciones/EAM_2016.pdf).

In addition to the three indicator parameters used by CONAGUA to assess the overall health of surface water bodies, CONAGUA also assesses bacterial water quality at selected monitoring stations by analyzing water samples for fecal coliform concentrations. While the results of CONAGUA's bacterial assessments are not included in the EAM reports, the data are available for download from CONAGUA's web site. Figure 1-19 shows the results of assessments of bacterial water quality for the four water quality monitoring stations monitored by CONAGUA in the Lower Río Bravo.

Based on monitoring conducted since 2000, three of the four sections of the Lower Río Bravo represented by these stations have been classified as "Contaminated" or "Strongly contaminated" in at least one or more of the years CONAGUA has assessed bacterial water quality in the Lower Río Bravo. According to CONAGUA's assessment, the contamination appears to be persistent and of relatively high magnitude in the sections of the river that flow along the two highly urbanized areas along the Lower Rio Grande/Río Bravo, Reynosa and Matamoros.

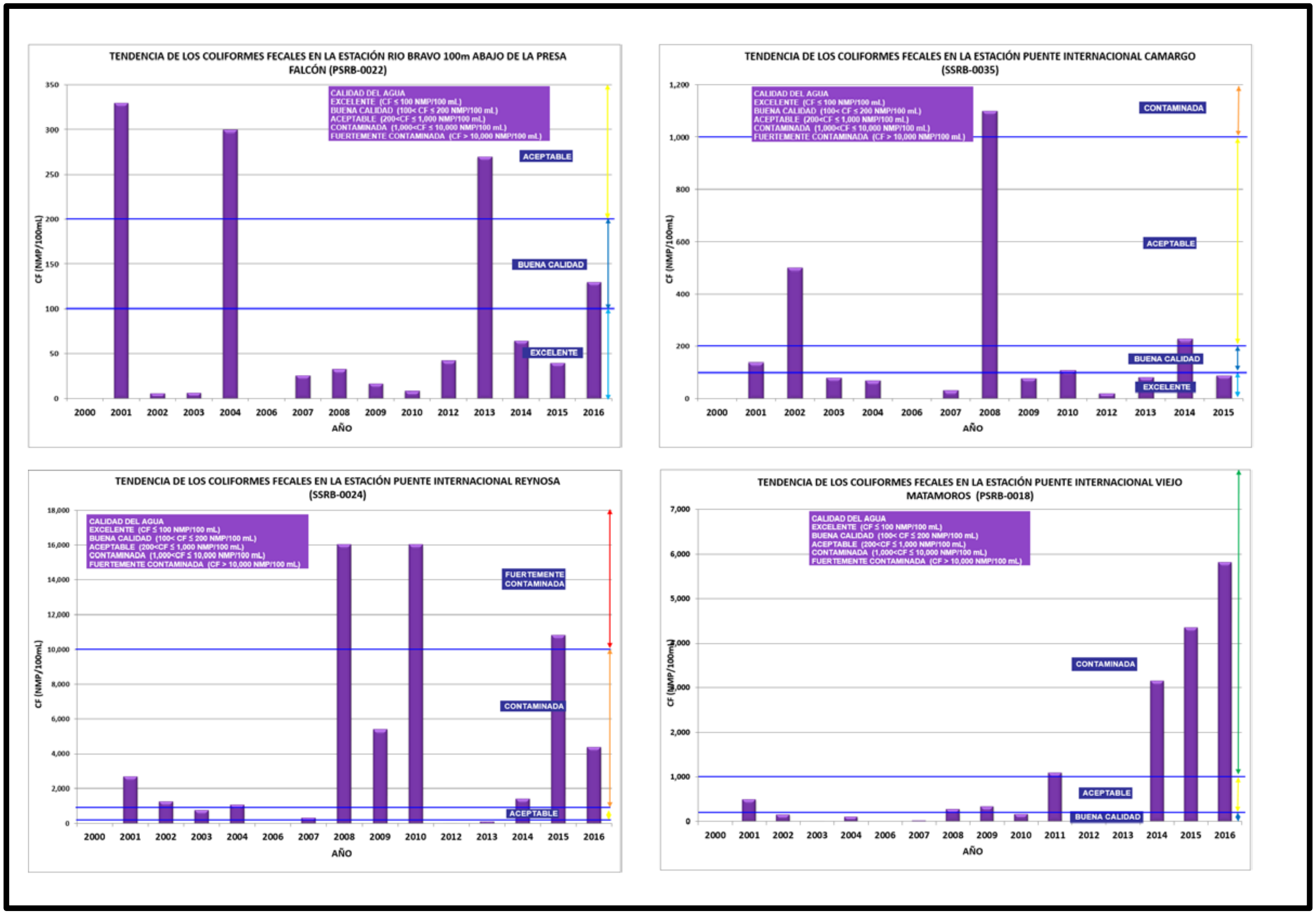

Figure 1-19. CONAGUA's Assessment of Bacterial Water Quality in the Lower Río Bravo. Source: CONAGUA, 2018

Both these urban areas show contamination levels several times the concentration threshold used by CONAGUA to designate a water body as contaminated and, in the case of Reynosa, the threshold is exceeded by an order of magnitude as recently as 2015. The only apparent trend is exhibited by the station near Matamoros, which shows increasing levels of bacterial contamination since 2014. It should be noted that CONAGUA's fecal coliform concentration threshold for the "Contaminated" designation is relatively high (1000 MPN/100ml) compared to the water quality standard used in US assessments (200 MPN/100ml)[2].

1.0.7.3 Local Water Quality Concerns

In addition to the findings of official assessments of water quality performed by US and Mexican environmental agencies several persistent specific local concerns regarding water quality have been documented in the Lower Rio Grande/Rio Bravo watershed. In many cases these concerns are the result of popular perceptions regarding the prevalence of pollution sources in the watershed, which are often bolstered by occasional occurrences of unexplained fish kills or disease clusters. In other cases, local concerns are supported by historical data.

TOXIC SUBSTANCES

Concern over toxic substances has been a long-standing matter in the Rio Grande Valley of south Texas. Anencephaly clusters (groups of infants born with neural tube defects [NTDs]) occurring in Brownsville in the early 1990s raised concern among local residents and prompted a series of studies funded by the US Centers for Disease Control and Prevention and the Texas Department of State Health Services. While data collection associated with these studies concluded in 2000, scientific research into the possible causes of NTDs continues to be published by the Texas Department of State Health Services ([TDSHS], 2018). These events coincided with the passage of NAFTA and the expansion of manufacturing facilities known as maquiladoras, which heightened local concerns over the release of toxic substances to the Lower Rio Grande/Río Bravo. Several National Priorities List Superfund sites are also located in the Rio Grande Valley, including the Helena Chemical Hayes Sammons Site in Mission and the Donna Canal and

[2] In 2000, to assess Contact Recreation Uses, the TCEQ began using *E. coli* in fresh water bodies and Enterococci in saltwater bodies as fecal indicator organisms. However, fecal coliform continues to be used by the State of Texas Surface Water Quality Standards as an indicator organism for assessment of beach advisories.

Reservoir PCB site, which are both within ten miles of the Lower Rio Grande/Río Bravo. Concerns over toxic substances in the river prompted the TCEQ and the IBWC to conduct a comprehensive binational toxic substances study of the entire Rio Grande/Río Bravo in the late 1990s. The study, found low, but measurable levels of toxic substances in the Lower Rio Grande/Río Bravo (IBWC, 1998).

As late as 2014, the TCEQ included several Rio Grande Valley water bodies in its list of impaired water bodies of the state for excessive levels of PCBs and mercury in edible fish tissue (TCEQ, 1992-2014). Two of these water bodies, the Arroyo Colorado and the Donna Canal are located within ten miles of the Rio Grande/Río Bravo. Although the Lower Rio Grande itself (Segments 2301 and 2302) is not currently listed for toxic substances, the prevailing local perception is that toxic substances routinely enter the river and are present at harmful levels in water, sediment and fish tissue (Texas AgriLife Research, 2016; The University of Texas - Lyndon B. Johnson School of Public Affairs [UT-LBJ], 2016).

SALINITY

As mentioned in the introduction, another water quality problem that is often cited by local US water users is high salinity (i.e., chloride, sulfate and total dissolved solids) in Segment 2302, the non-tidally influenced portion of the Lower Rio Grande. Dissolved solids have never been listed as an official Impairment by the TCEQ for this segment of Rio Grande and these parameters have been listed officially as water quality Concerns only once (in 2004) for Segment 2302. The lack of official recognition of a salinity problem in this portion of the Rio Grande is due, in part, to the nature of the method used by the TCEQ to assess dissolved solids in surface waters and also to the nature of this water quality problem in the Lower Rio Grande. Unlike the criteria used to assess other water quality parameters, the criteria used by the TCEQ to assess dissolved solids in Texas rivers is based on a long-term average of historical water quality data collected at surface water quality monitoring stations in the rivers being assessed. As such, the criteria are designed to identify changes in the concentration of dissolved solids occurring over relatively long periods of time (e.g., 5-10 years). However, salinity excursions in the Lower Rio Grande/Río Bravo tend to occur in sporadic pulses, which can last anywhere from 5 to 25 days (Miranda & Harper, 2017).

The routine surface water quality monitoring conducted by the TCEQ for official assessment purposes is typically performed on a quarterly basis. Consequently, pollutant loadings of short duration (i.e., in the order of days) are often not detected. In response to this problem, and as a result of requests from the local agricultural community, the TCEQ installed a network of continuous water quality monitoring (CWQMN) stations along the Lower Rio Grande/Río Bravo to record and document high salinity pulse events in the river. Every fifteen minutes, the CWQMN stations measure the electrical conductance of water in the river, which is a surrogate measurement of salinity. Since their installation in 2007, CWQMN stations have documented dozens of high salinity events at various locations along the Lower Rio Grande/Río Bravo. The events occur though out the year, but most are common during the late Winter, Spring and early Summer (April-July), during the local irrigation season. An example of a high salinity pulse event captured by a TCEQ CWQMN station is shown in Figure 1-20.

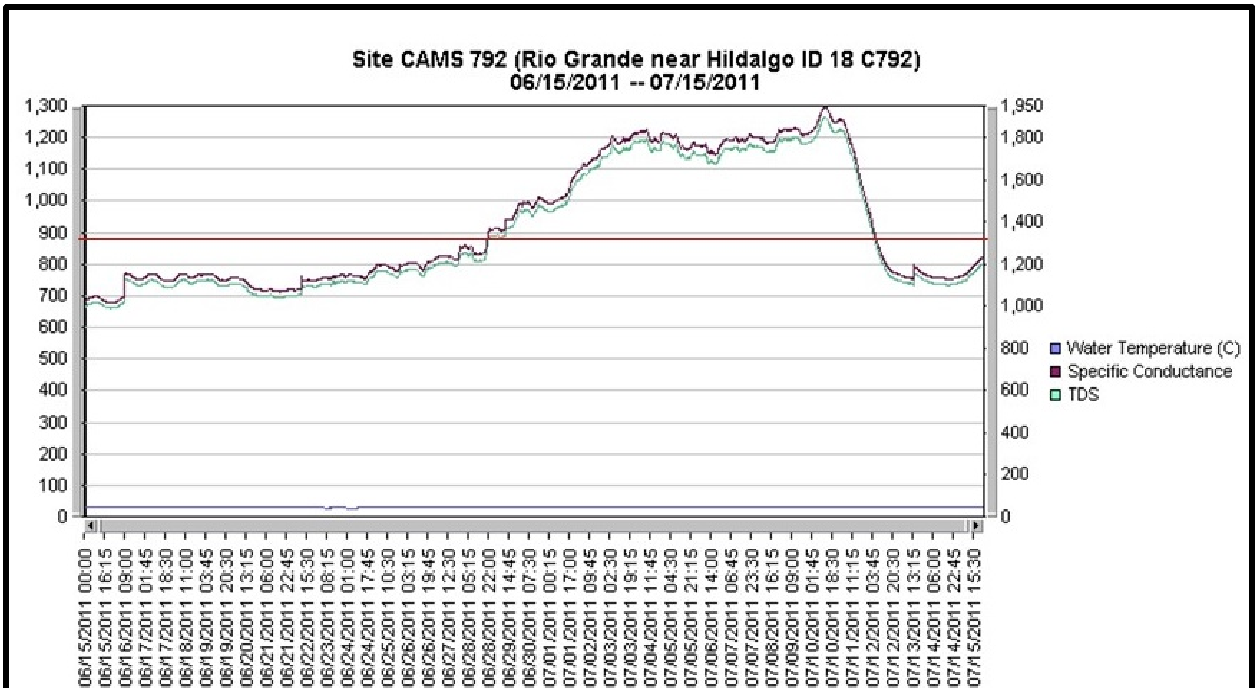

Figure 1-20. High Salinity Pulse Event Recorded by TCEQ CWQMN Station C792 in June and July of 2011. Source: TCEQ, 2016.

The problem of high salinity in the Lower Rio Grande/Río Bravo has been an issue of concern for US water users in the Lower Rio Grande Valley for decades (Lacewell et al., 2007). The principal causes of high salinity in the river have long been attributed to irrigation return flows entering the river mainly through Mexican agricultural drains. Evidence of these high salinity flows is documented in the Water Bulletins published by the IBWC. In 1969, at the urging of local irrigation districts and agricultural producers, the governments of the United States and Mexico entered into a binational agreement, under the auspices of the of the IBWC, to construct a diversion structure and canal designed to divert high salinity flows from the largest of the Mexican agricultural drains in the watershed, El Morillo, and away from the Lower Rio Grande/Río Bravo (Lacewell et al., 2007). However, poor maintenance of the diversion structure and associated canal have reduced the effectiveness of the El Morillo diversion works in the decades since its construction and an expansion in irrigated agriculture in the Mexican portion of the watershed has increase the volume of irrigation return flows entering the Lower Rio Grande/Rio Bravo in recent years, further exacerbating the problem.

1.0.7.4 Pollutants of Concern in the LRGWQI

As previously mentioned, the binational deliberations that culminated in the LRGWQI achieved consensus on the general goal of improving water quality in the Lower Rio Grande/Río Bravo. Based on US and Mexican assessments of water quality (including the binational Toxics Substances study and USGS’ NASQN data) and also based on information available from the IBWC, the TCEQ’s CWQMN stations, and the LRGWQI synoptic surveys, the pollutants of concern included in the Annex to the LRGWQI TOR are indicator bacteria (Fecal Coliform, *E. coli*, Enterococcus) and salinity (i.e., dissolved solids). However, TCEQ assessments of water quality have also identified concerns for dissolved oxygen (DO) and Nutrients (Ammonia nitrogen and nitrates). Similarly, CONAGUA’s effort to develop a Declaratoria for the Río Bravo broadens Mexican interest in examining water quality constituents beyond fecal bacteria and dissolved solids. The following section describes in more detail the causes and sources of water quality degradation in the Lower Rio Grande/Río Bravo, including a description of methods used to quantify point sources of pollution, such as wastewater discharges and steady state nonpoint sources of pollution, such as irrigation return flows.

1.0.8 CAUSES AND SOURCES OF WATER QUALITY DEGRADATION[3]

Sources of pollutants that affect surface water quality are classified in accordance with the mechanisms by which the pollutants are generated and transported in the environment. Environmental scientists and regulators generally classify surface water pollutant sources as either point sources or nonpoint sources. Point sources of surface water pollution emanate from distinct, well defined geographic locations or "points," such as pipes or other conduits that discharge directly into a receiving water body. These sources can include outfalls of untreated wastewater and outfalls of treated wastewater from municipal and industrial sources. Point source discharges are regulated or otherwise controlled by regulatory agencies using specific discharge criteria designed to minimize their impact to receiving water bodies. Other point source outfalls can emanate from unregulated or illicit activities or can be the result of faulty infrastructure at specific locations (e.g., malfunctioning sewer lift stations).

Nonpoint sources of pollution are the result of processes that accumulate and concentrate pollutants generated from large geographic areas. The resulting "diffuse" pollution can enter a receiving water body at multiple locations or through shallow groundwater base flow. The most common natural process associated with nonpoint source pollution is rainfall runoff. Some nonpoint sources, known as "steady state" nonpoint sources, can affect surface water bodies under dry weather conditions. Steady state nonpoint sources include pollutant sources such as broken or leaking sewer pipes, malfunctioning septic systems, irrigation return flows or the direct deposition of untreated wastes into receiving water bodies (e.g., human or animal defecation into or near surface waters). The mitigation of nonpoint source pollution is complicated by the paucity of regulation designed to control it. In the United States, the federal Clean Water Act specifically exempts non-urban nonpoint source pollution from federal regulation. While urban stormwater quality is currently regulated in the United States, the regulations were promulgated only after the USEPA classified stormwater runoff from urban areas as a point source of pollution. Nonpoint source pollution from agricultural activities is still largely unregulated in the United States. Mexico does not currently regulate nonpoint source pollution of any kind.

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[3] Some of the content of this section of Chapter 1 was excerpted from the 2017 report titled "Watershed Characterization Report: Lower Rio Grande/Río Bravo Water Quality Initiative," authored by Roger M. Miranda and Heidi E. Harper.

While negotiating the scope of the LRGWQI, US and Mexican agency representatives agreed to limit the scope of the initiative to the study of point sources and steady state nonpoint sources of pollution in the Lower Rio Grande/Río Bravo watershed. This is made clear in the LRGWQI's TOR, which also leaves open the possibility of addressing pollution from rainfall runoff in subsequent efforts between the two countries.

1.0.8.1 Point Sources of Pollutants

A total of 19 known wastewater outfalls discharge directly to the Lower Rio Grande/Río Bravo or to one of its tributaries (Figure 1-21). Ten of these outfalls are located on the US side of the river and the other 9 outfalls are located on the Mexican side. Fourteen of the 19 outfalls are associated with municipal wastewater treatment facilities. Three outfalls are discharges of untreated wastewater attributable to faulty sanitary sewer infrastructure on the Mexican side (i.e., one malfunctioning lift station and two broken sewer mains). One outfall is a discharge of filter backwash water from the City of Roma's drinking water treatment facility on the US side and 1 outfall is an intermittent discharge of a power plant cooling water from the Brownsville Public Utilities' (BPUB's) Silas Ray Power Plant on the US side (Table 1-7).

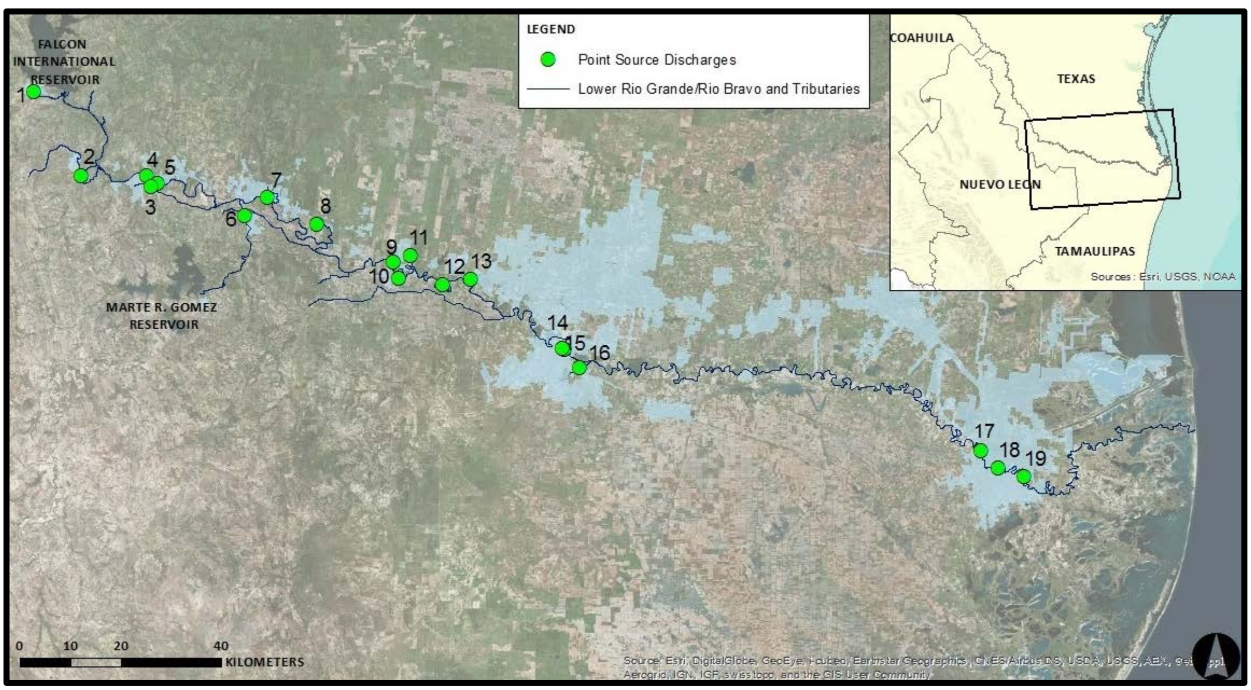

Figure 1-21. Locations of Point Source Discharges to the Lower Rio Grande/Río Bravo.

Table 1-7. Point Source Discharges to the Lower Rio Grande/Río Bravo

Map No.	Facility Name	Discharge Type	Design Flow (L/s)
1	Nueva Ciudad Guerrero (Imhoff Tank)	Treated Municipal Wastewater	12
2	Ciudad Mier	Treated Municipal Wastewater	20
3	Ciudad Miguel Alemán	Treated Municipal Wastewater	75
4	City of Roma 3	Drinking Water Treatment Facility Outfall (Treatment Filter Backwash)	20
5	City of Roma 2	Treated Municipal Wastewater	90
6	Ciudad Camargo	Treated Municipal Wastewater	30
7	City of Rio Grande City	Treated Municipal Wastewater	66
8	Union Water Supply Corporation	Treated Municipal Wastewater	34
9	AGUA Special Utility District	Treated Municipal Wastewater	61
10	Ciudad Gustavo Diaz Ordaz	Treated Municipal Wastewater	3
11	La Joya Independent School District	Treated Municipal Wastewater	0.5
12	City of La Joya	Drinking Water Treatment Facility Outfall (Filter Backwash)	64
13	City of Peñitas	Treated Municipal Wastewater	33
14	Descarga Municipal D2 Libramiento Luis Echeverría, Reynosa	Untreated Municipal Wastewater	NA*
15	Descarga Municipal D3 Libramiento Luis Echeverría (International Bridge), Reynosa	Untreated Municipal Wastewater	NA*
16	Ciudad Reynosa PTAR 1	Treated Municipal Wastewater	1000
17	Brownsville Public Utility Board	Power Plant Cooling Water	17
18	Descarga Municipal D4 Colonia El Jardín, Matamoros	Untreated Municipal Wastewater	NA*
19	Brownsville Public Utility Board	Treated Municipal Wastewater	561

* Not a wastewater treatment facility, therefore a design flow cannot be specified

Most of the point source discharges to the Lower Rio Grande/Río Bravo are relatively small (less than 100 L/s). However, 2 facilities in the watershed (Ciudad Reynosa PTAR 1 and BPUB's Southside Wastewater Treatment Facility) are designed to produce effluent flows exceeding 500 L/s each. The majority of point source discharges to the Lower Rio Grande/Río Bravo, or to one of its tributaries, occur in the middle and upper portions of the watershed (Figure 1-21). This is mainly due to the fact that wastewater from municipalities and several industrial facilities located in the lower third of the watershed is treated and discharged into drains that flow away from the river and thence to the US and Mexican portions of the Laguna Madre. These flows include several municipal wastewater treatment facilities on the US side of the river and a number of industrial discharges associated with manufacturing facilities, known as "maquiladoras," located mainly on the Mexican side. The detailed information provided in the following sections, along with additional information collected in the field during five surveys of water quality conducted by the BTWG as part of the LRGWQI, forms an integral part of the Point Sources module of the LRGWQIDSS.

US POINT SOURCES OF POLLUTION

Figure 1-22 shows the location of US point source discharges to the Lower Rio Grande/Río Bravo. Nine of the 10 US point source discharges are associated with municipal wastewater treatment facilities. The only industrial discharge to the Rio Grande/Río Bravo from the US is the cooling water outfall from BPUB's Silas Ray Power Plant. Eight of the 10 outfalls associated with these point source discharges are attributable to municipal wastewater treatment facilities located mainly in the upper portion of the watershed. One outfall discharges filter backwash water from the City of Roma's drinking water treatment facility. One outfall discharges cooling water from BPUB's Silas Ray Power Plant.

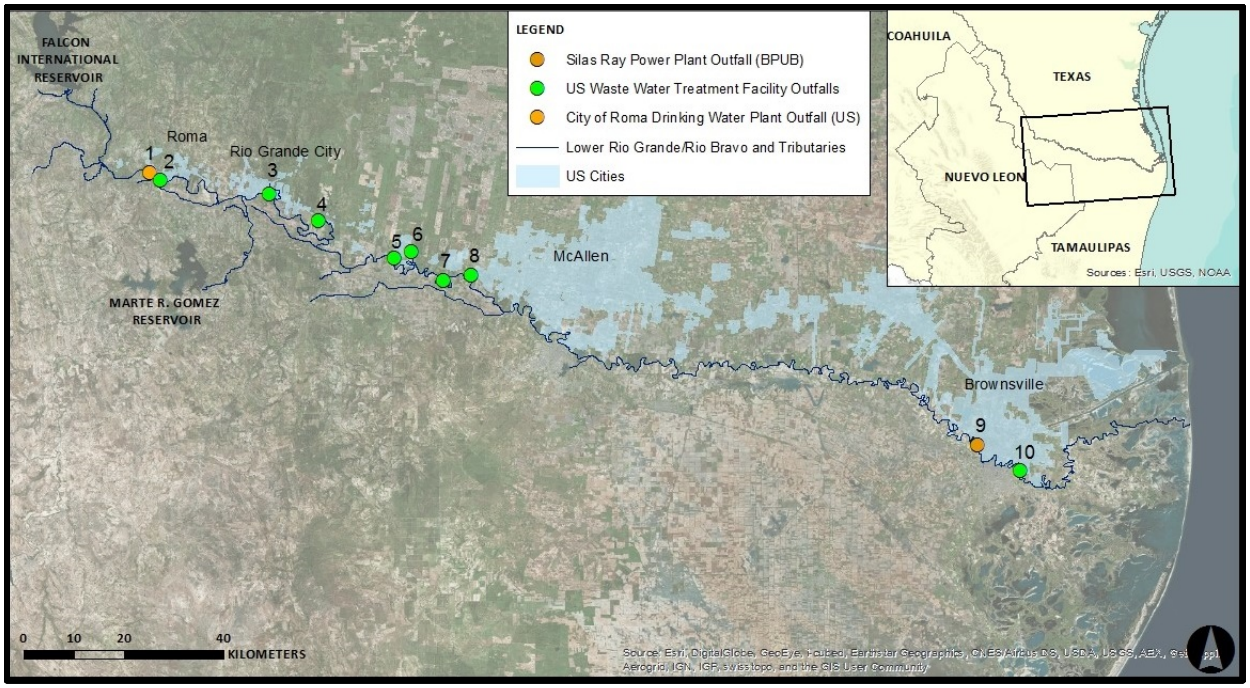

Figure 1-22. Locations of US Point Source Discharges to the Lower Rio Grande/Río Bravo

Table 1-8 shows the effluent limits permitted under the Texas Pollutant Discharge Elimination System (TPDES) and National Pollutant Discharge Elimination System (NPDES) for each of the US point source discharges in the Lower Rio Grande/Río Bravo watershed. The following sub-sections describe of each of the US point source discharges in the Lower Rio Grande/Río Bravo watershed. The author compiled the information presented in the following sections as part of a comprehensive watershed characterization effort. Sources of the information include BECC Environmental Information Documents, TPDES permit information and monitoring data collected during LRGWQI synoptic surveys conducted in 2014-2016.

Table 1-8. US Point Source Discharges to the Lower Rio Grande/Río Bravo and Permit Limits (daily averages)

Map Number	1	2	3	4	5	6	7	8	9	10
Facility Name	**City of Roma3**	**City of Roma2**	**City of Rio Grande City**	**Union WSC**	**AGUA SUD**	**La Joya ISD**	**City of La Joya**	**City of Peñitas**	**Brownsville PUB**	**Brownsville PUB**
Discharge Type	Municipal Wastewater	Municipal Wastewater	Municipal Wastewater	Municipal Wastewater	Municipal Wastewater	Municipal Wastewater	Municipal Wastewater	Municipal Wastewater	Industrial Wastewater	Municipal Wastewater
TPDES Permit Number	WQ11212003	WQ11212002	WQ10802001	WQ14313001	WQ14415001	WQ13523006	WQ12675001	WQ14884001	WQ03096000	WQ10397003
NPDES Permit Number	TX0119709	TX0117544	TX0068764	TX0124613	TX0125598	TX0124559	TX0127337	TX0131491	TX0105651	TX0055484
Flow (L/s)	19.7	87.6	65.7	33.9	61.3	0.6	64.4	32.9	17.1	560.8
Biochemical Oxygen Demand – 5 Day (mg/L)	-	20	20	10	10	20	20	20	-	10
Ammonia Nitrogen (mg/L)	-	-	-	3	3	-	3	-	-	3
Total Suspended Solids (mg/L)	-	20	20	15	15	20	20	20	-	3
Dissolved Oxygen (mg/L)	-	4	2	4	4	2	4	4	-	4
Temperature (ºC)	-	-	-	-	-	-	-	-	115	-
pH Minimum	-	6	6	6	6	6	6	6	6	6
pH Maximum	-	9	9	9	9	9	9	9	9	9
***E. Coli* (CFU/100ml or MPN)**	-	126	126	126	126	126	126	126	-	-
Enterococcus (CFU/100ml or MPN)	-	-	-	-	-	-	-	-	-	35
Sulfate (mg/L)	-	-	-	-	-	-	-	-	1893	-
Total Aluminum (mg/L)	-	-	-	-	-	-	-	-	0.78	-
Total Copper (mg/L)	-	-	-	-	-	-	-	-	0.11	-
Total Dissolved (mg/L)	-	-	-	-	-	-	-	-	4400	-
Free Available Chlorine (mg/L)	-	-	-	-	-	-	-	-	0.2	-

The City of Roma's Drinking Water Treatment Facility

Located less than 100 meters from the Lower Rio Grande/Río Bravo, the City of Roma's drinking water treatment facility provides potable water to approximately 30,945 residents living within Roma's city limits and surrounding area (Figure 1-23). The facility uses conventional treatment technology, which consists of coagulation, flocculation, sedimentation, and filtration. Discharge monitoring reports show this facility discharges a daily average of between 1.3 and 8.5 L/s of treatment filter backwash water to the river (minimum and maximum daily averages per month over the years 2000-2015) with an overall daily average discharge of 3.6 L/s.

Figure 1-23. The City of Roma's Drinking Water Treatment Facility.

The City of Roma's Wastewater Treatment Facility

Located approximately 2 kilometers southeast of the City of Roma's drinking water treatment facility and 568 meters from the Lower Rio Grande/Río Bravo, the City of Roma's wastewater treatment facility provides wastewater treatment services for approximately 10,088 residents living within Roma's city limits and an additional 4,582 living in the surrounding area

(Figure 1-24). The facility uses an extended aeration oxidation ditch system with activated sludge and chlorination. Discharge monitoring reports show this facility discharges a daily average of between 48.2 L/s and 363.6 L/s, with an overall daily average discharge of 157.4 L/s. The outfall for the City of Roma's wastewater treatment facility is located approximately 4 kilometers downstream from the city's drinking water treatment facility outfall.

Figure 1-24. The City of Roma's Wastewater Treatment Facility.

The City of Rio Grande City's Wastewater Treatment Facility

The City of Rio Grande City's wastewater treatment facility is located approximately 105 meters from the Lower Rio Grande/Río Bravo (Figure 1-25). The facility provides wastewater treatment services to approximately 13,834 residents living within the city limits of Rio Grande City. Like the City of Roma, the City of Rio Grande City's wastewater treatment facility is an oxidation ditch system with activated sludge and chlorination. Discharge monitoring reports show this facility discharges a daily average flow of between 18.3 and 59.5 L/s, with an overall daily average discharge of 36.6 L/s.

Figure 1-25. The City of Rio Grande City's Wastewater Treatment Facility.

Union Water Supply Corporation's Wastewater Treatment Facility

The Union Water Supply Corporation's wastewater treatment facility is located approximately 2.3 kilometers from the Lower Rio Grande/Río Bravo (Figure 1-26). The facility provides wastewater treatment services to approximately 5,913 residents living in the largely rural communities of Garciasville, La Casita, and El Refugio and surrounding areas. The wastewater treatment facility is an oxidation ditch system with activated sludge and chlorination. Discharge monitoring reports show this facility discharges a daily average flow of treated effluent of between 3.0 and 14.5 L/s, with an overall daily average discharge of 7.7 L/s.

Figure 1-26. Union Water Supply Corporation's Wastewater Treatment Facility.

AGUA Special Utility District's Wastewater Treatment Facility

The AGUA Special Utility District's (SUD's) wastewater treatment facility is located approximately 1.4 kilometers from the Lower Rio Grande/Río Bravo (Figure 1-27). The facility provides wastewater treatment services to approximately 3,250 residents living in the largely rural communities of Sullivan City, Los Ebanos and Cuevitas and surrounding areas. A sequencing batch reactor (SBR) plant, AGUA SUD's wastewater treatment facility discharges treated wastewater intermittently during the day. Discharge monitoring reports show this facility discharges a daily average effluent flow of between 5.5 and 8.3 L/s, with an overall daily average discharge of 7.7 L/s.

Figure 1-27. AGUA Special Utility District's Wastewater Treatment Facility.

La Joya Independent School District's Wastewater Treatment Facility.

The La Joya Independent School District's wastewater treatment facility is located approximately 2.0 kilometers from the Lower Rio Grande/Río Bravo (Figure 1-28). This small "package plant" facility provides wastewater treatment services to approximately 500 students of the Sam Fordyce Elementary School near Sullivan City. The facility uses an activated sludge process operated in the extended aeration mode with chlorination. Discharge monitoring reports show this facility discharges at highly irregular intervals during the year, with large intervals of little to no discharge, especially during the summer months and during other scholastic breaks in the school year. Discharge monitoring reports show that daily average effluent flows range between 0.02 and 0.3 L/s, with an overall daily average discharge of 0.1 L/s. Although considered a surface water discharge to the Lower Rio Grande/Río Bravo, the effluent flow from this outfall is unlikely to affect water quality in the Lower Rio Grande/Río Bravo, due to its small volume and distance from the river.

Figure 1-28. La Joya Independent School District's Wastewater Treatment Facility.

The City of La Joya's Wastewater Treatment Facility

The City of La Joya's wastewater treatment facility is located approximately 1.0 kilometer from the Lower Rio Grande/Río Bravo (Figure 1-29). Constructed in 1982, this facility is a facultative lagoon system that provides wastewater treatment services to approximately 3,985 city residents. Discharge monitoring reports show that daily average effluent flows range between 4.6 and 15.3 L/s, with an overall daily average discharge of 11.0 L/s. In recent years, the ability of this wastewater treatment facility to meet its permitted discharge limits for 5-day carbonaceous biochemical oxygen demand ($CBOD_5$), total suspended solids (TSS) and *E. coli* has diminished significantly due to a combination of several factors, including population growth and the facility's advanced age. During synoptic monitoring events conducted as part of the LRGWQI, participants in the monitoring event observed a significant accumulation of sludge in many of the facultative lagoons, which effectively diminishes the treatment capacity of the plant.

Figure 1-29. The City of La Joya's Wastewater Treatment Facility.

The City of Peñita's Wastewater Treatment Facility

The City of Peñitas' wastewater treatment facility is located approximately 500 meters from the Lower Rio Grande/Río Bravo (Figure 1-30). The facility provides wastewater services to approximately 4,632 residents of the city and surrounding areas. The wastewater treatment technology used by the facility is an oxidation ditch system with activated sludge and chlorination. Daily average effluent flows range between 1.3 and 12.8 L/s, with an overall daily average discharge of 7.7 L/s.

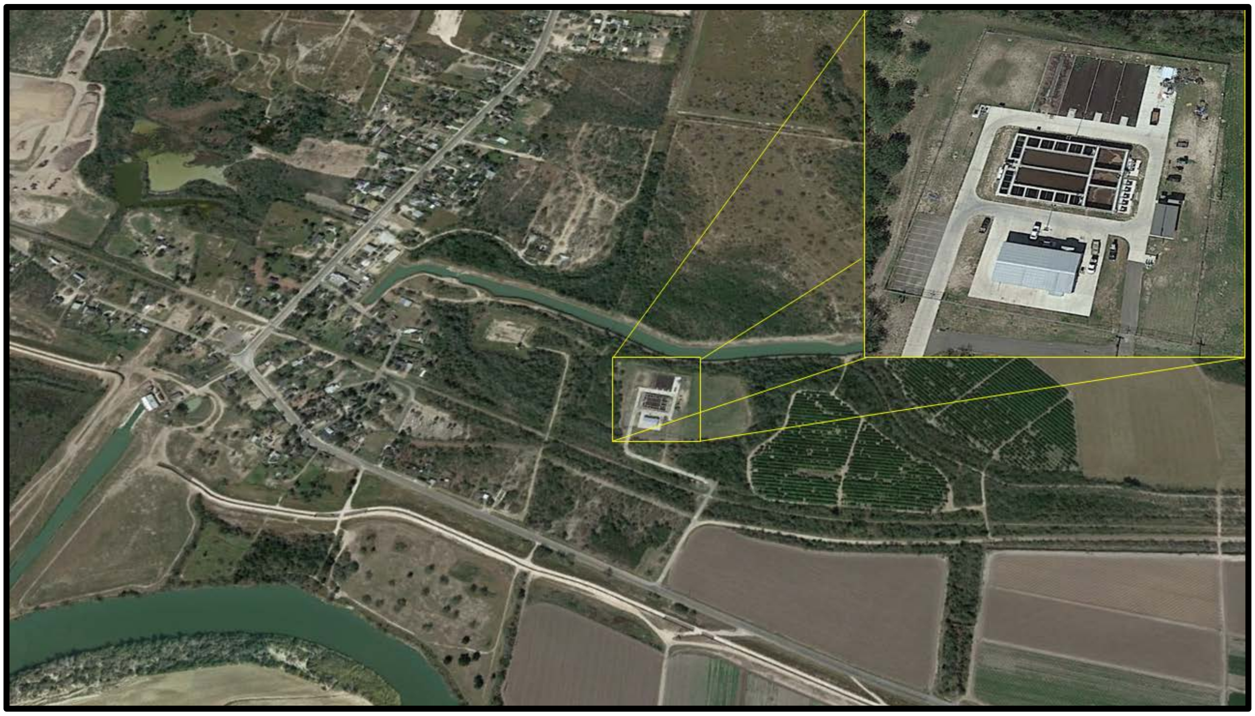

Figure 1-30. The City of Peñitas' Wastewater Treatment Facility.

The Brownsville Public Utilities Board's Silas Ray Power Plant Outfall

Brownsville Public Utility Board's (BPUB's) Silas Ray Power Plant is a 181.4 MW gas powered steam turbine electric generating facility (Figure 1-31). Originally built in 1947, this power plant serves as the primary source of electricity for the residents of the City of Brownville and also for residents living in portions of Harlingen and San Benito, Texas. The facility is located approximately 660 meters from the Lower Rio Grande/Río Bravo and occasionally discharges blowdown water from its cooling towers. Discharges from this facility flow into a dry oxbow lake prior to flowing into the Lower Rio Grande/Río Bravo. The oxbow lake has a capacity of approximately 150,000 m^3 and fills only on rare occasions. Discharge monitoring reports show this facility discharges at highly irregular intervals (flows are reported for only 69 of the 180 months between 2000 and 2015). Daily average flows during the months of discharge ranged between 0.003 and 16.3 L/s, with an overall daily average discharge of 0.9 L/s.

Figure 1-31. Brownsville Public Utility Board's (BPUB's) Silas Ray Power Plant.

Brownsville Public Utilities's (BPUB's) Southside Wastewater Treatment Facility

The Brownsville PUB's Southside Wastewater Treatment Facility is located approximately 880 meters from the Lower Rio Grande/Río Bravo (Figure 1-32). The largest of the US wastewater treatment facilities discharging to the Lower Rio Grande/Río Bravo, the facility provides wastewater services to approximately 27,500 residents of the city using a complete mix activated sludge treatment system. Daily average effluent flows range between 215.7 and 436.6 L/s, with an overall daily average discharge of 276.4 L/s. The facility discharges directly to the tidally-influenced portion of the Lower Rio Grande/Río Bravo.

Figure 1-32. BPUB's South Side Wastewater Treatment Facility.

MEXICAN POINT SOURCES OF POLLUTION

Nine point source outfalls currently discharge wastewater to the Lower Rio Grande/Río Bravo from the Mexican side of the river (Figure 1-33). Six of these outfalls are associated with municipal wastewater treatment facilities and 3 of the outfalls are discharges of untreated wastewater attributable to faulty sanitary sewer infrastructure at known locations. Table 1-9 provides further information on the point source outfalls currently discharging wastewater to the Lower Rio Grande/Río Bravo from the Mexican side of the river. Like US wastewater treatment facilities, Mexican wastewater treatment facilities must obtain a permit from CONAGUA to discharge their effluent to surface waters. While limits on flow rates and pollutant concentrations of effluent discharged from wastewater treatment facilities located on the Mexican side of the river are not water quality-based, all Mexican wastewater treatment facilities must be constructed and operated to meet Mexican federal criteria designed to protect surface water quality. The criteria are specified in the country's federal regulation NOM-001-SEMARNAT-1996, which establishes the permissible performance-based levels of contaminants in wastewater discharges to surface water.

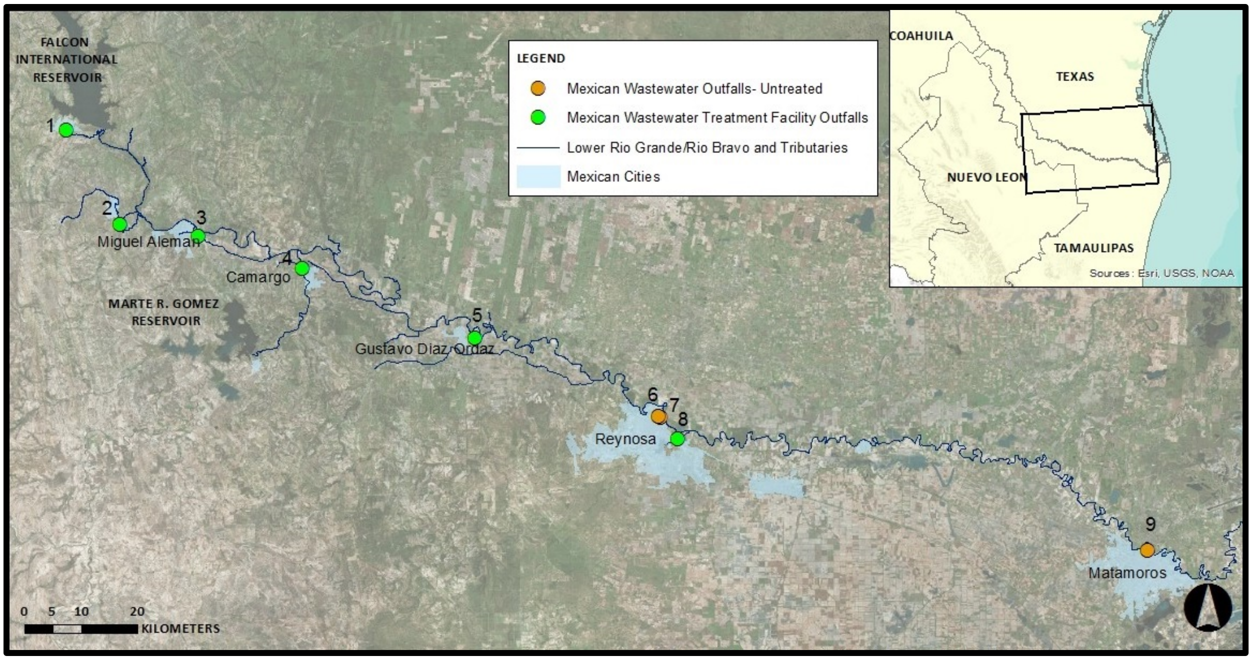

Figure 1-33. Locations of Mexican Point Source Discharges to the Lower Rio Grande/Río Bravo

Table 1-9. Mexican Point Source Discharges to the Lower Rio Grande/Río Bravo

Map No.	Facility Name	Discharge Type	Design Flow (l/s)
1	Nueva Ciudad Guerrero (Imhoff Tank)	Treated Municipal Wastewater	12
2	Ciudad Mier	Treated Municipal Wastewater	20
3	Ciudad Miguel Alemán	Treated Municipal Wastewater	75
4	Ciudad Camargo	Treated Municipal Wastewater	30
5	Ciudad Gustavo Díaz Ordaz	Treated Municipal Wastewater	3
6	Descarga Municipal D2 Libramiento Luis Echeverría, Reynosa	Untreated Municipal Wastewater	NA*
7	Descarga Municipal D3 Libramiento Luis Echeverría (International Bridge), Reynosa	Untreated Municipal Wastewater	NA*
8	Ciudad Reynosa PTAR 1	Treated Municipal Wastewater	1000
9	Descarga Municipal D4 Colonia El Jardín, Matamoros	Untreated Municipal Wastewater	NA*

* Not a wastewater treatment facility, therefore a design flow cannot be specified

Table 1-10 shows the discharge criteria currently used to design Mexican wastewater treatment facilities in the Lower Rio Grande/Río Bravo. Like the federal Clean Water Act in the United States, Mexican federal law provides for the establishment of water quality-based wastewater discharge permits with effluent concentrations and flow limits based on their simulated effect on ambient water quality. The establishment of water-quality-based wastewater permit limits is often preceded by the development of a "Declaratoria de Clasificación," which among other things, includes a study of the assimilative capacity of the receiving water body. CONAGUA has undertaken the task of developing a Declaratoria de Clasificación for the Lower Rio Grande/Río Bravo and anticipates completing it by the end of 2019. Depending on the results of the Declaratoria de Clasificación, CONAGUA could begin requiring water-quality-based permit limits for new wastewater treatment facilities or for future upgrades to existing wastewater treatment facilities in the Lower Rio Grande/Río Bravo, if deemed warranted. A brief description of each of the Mexican point source discharges to the Lower Rio Grande/Río Bravo is provided in the following sections.

Table 1-10. Discharge Criteria Applied to Mexican Wastewater Treatment Facilities

Parameter	Maximum Daily Average*	Maximum Monthly Average*
Flow (L/s)	-	-
Biochemical Oxygen Demand – 5 Day (mg/L)	150	75
Total Nitrogen (mg/L)	60	40
Phosphorus (mg/L)	30	20
Total Suspended Solids (mg/L)	125	75
Settable solids (mg/L)	2	1
Temperature	40	40
pH minimum (NTU)	6	6
pH maximum (NTU)	9	9
Fecal Coliform (MPN/100ml)	2000	1000
Oil and Grease	25	15

*NOM-001-SEMARNAT-1996

Nueva Ciudad Guerrero's Wastewater Treatment Facility

Located 5.1 Kilometers from the Lower Rio Grande/Río Bravo, the city of Nueva Ciudad Guerrero's wastewater treatment facility provides wastewater treatment services to approximately 4010 residents living within city limits and surrounding area (Figure 1-34). The facility consists of an Imhoff tank located in the southern portion of the city. The Imhoff tank is a relatively old facility and does not currently function in the way it was originally designed, providing only marginal primary treatment of influent wastewater. LRGWQI researchers estimate this facility produces daily effluent flows of between 2.5 and 4.3 L/s (highest and lowest average values estimated by LRGWQI researchers), with an overall average daily effluent flow of 3.1 L/s.

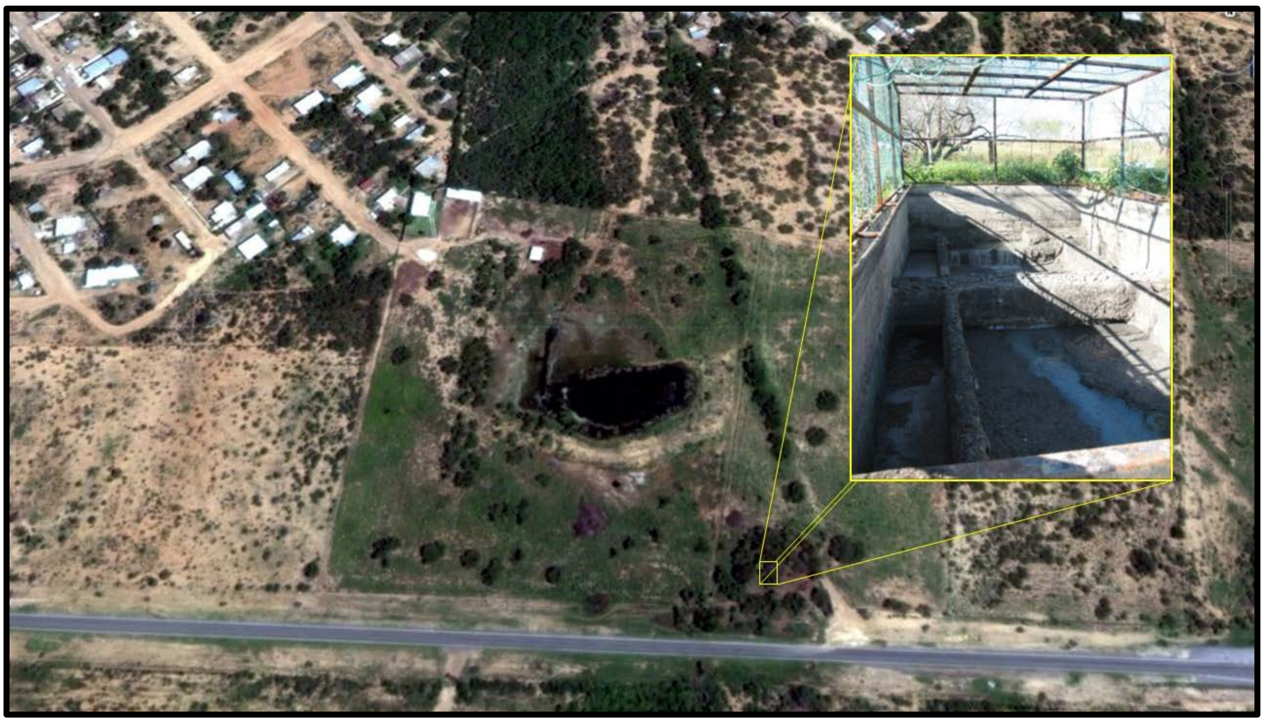

Figure 1-34. Ciudad Nueva Guerrero's (Imhoff Tank) Wastewater Treatment Facility.

Ciudad Mier's Wastewater Treatment Facility

Located 3.2 Kilometers from the Lower Rio Grande/Río Bravo, the city of Mier's wastewater treatment facility provides wastewater treatment services to approximately 5,435 residents living within its city limits (Figure 1-35). The facility utilizes a natural/lagoon processes for treatment and consists of an anaerobic pond, an integrated facultative pond, and polishing lagoons. The treatment plant also includes headworks with a coarse screen and sand settling chamber. Mier has experienced a negative population growth rate since 2008 and, although the city's wastewater treatment facility is designed to treat 20 L/s of raw sewage, the actual average daily effluent flow is estimated to be in the order of 2.8 L/s.

Figure 1-35. Ciudad Mier's Wastewater Treatment Facility.

Ciudad Miguel Alemán's Wastewater Treatment Facility

Located 630 meters from the Lower Rio Grande/Río Bravo, the city of Miguel Alemán's wastewater treatment facility provides wastewater treatment services to approximately 23,500 residents living within its city limits and in the nearby village of Los Guerra (Figure 1-36). The facility consists of a dual lagoon system composed of three treatment levels, first anaerobic, then facultative, and finally polishing. The treatment plant also includes headworks with coarse screens and sand settling chambers. Although the facility is designed to treat 75 L/s of raw sewage, the average daily effluent flow is estimated to be between 27 and 45 L/s, with an overall average daily effluent flow of 37.3 L/s.

Figure 1-36. Ciudad Miguel Alemán's Wastewater Treatment Facility.

Ciudad Camargo's Wastewater Treatment Facility

Located 2.4 Kilometers from the Lower Rio Grande/Río Bravo, the city of Camargo's wastewater treatment facility provides wastewater services to approximately 15,075 residents living within its city limits (Figure 1-37). The facility consists of a four-celled oxidation and facultative lagoon system situated 0.88 kilometers north of the city. Originally designed to treat 20 L/s of raw sewage, the facility does not have a visible discharge of effluent. However, due to its advanced age, poor working condition and proximity to the Río San Juan, LRGWQI researchers estimate that two thirds of the current influent flow to the plant reaches the Río San Juan through infiltration from its oxidation lagoon. This volume amounts to an average daily effluent flow of between 2.3 and 4.3 L/s, with an overall average daily effluent flow of 3.3 L/s.

Figure 1-37. Ciudad Camargo's Wastewater Treatment Facility

Ciudad Gustavo Díaz Ordaz's Wastewater Treatment Facility

The wastewater treatment facility for the city of Gustavo Díaz Ordaz is located 680 meters from the Lower Rio Grande/Río Bravo (Figure 1-38). The facility is a small (3.4 Ha) two-lagoon system which is currently non-functioning and essentially operates as an infiltration/evaporation basin. The wastewater collection system for the city of Gustavo Díaz Ordaz services approximately 1,728 residents living within its city limits. It is estimated that the city's collection system generates an average daily flow of raw sewage of 27.6 L/s to the plant. LRGWQI researchers estimate that, on average, at least 10% of the total volume of sewage conveyed to the wastewater facility reaches the Lower Rio Grande/Río Bravo (2.8 L/s).

Figure 1-38. Ciudad Gustavo Díaz Ordaz's Wastewater Treatment Facility.

Municipal Discharge D2 Libramiento Luis Echeverría, Reynosa

Located on the south bank of the Lower Rio Grande/Río Bravo within the city limits of the City of Reynosa, this discharge of untreated wastewater is associated with faulty or inadequate wastewater conveyance (Figure 1-39). The flow of untreated wastewater reaches the Lower Rio Grande/Río Bravo directly through a stormwater pipe. It is estimated this highly variable discharge contributes a daily flow of untreated wastewater to the Lower Rio Grande/Río Bravo of between 0.01 and 0.58 L/s, with an overall daily average flow of 0.33 L/s.

Municipal Discharge D3 Libramiento Luis Echeverría, Reynosa

Also located on the south bank of the Lower Rio Grande/Río Bravo in the City of Reynosa just upstream of the Reynosa-Hidalgo International Bride and only 575 meters from Municipal Discharge D2, this discharge of untreated wastewater (D3) is also associated with faulty or inadequate wastewater conveyance (Figure 1-39). Like Municipal Discharge D2, the flow of untreated wastewater from discharge D3 reaches the Lower Rio Grande/Río Bravo directly through a stormwater pipe. It is estimated this highly variable discharge (D3) contributes a daily flow of untreated wastewater to the Lower Rio Grande/Río Bravo of between 0.01 and 8.11 L/s, with an overall daily average flow of 4.1 L/s.

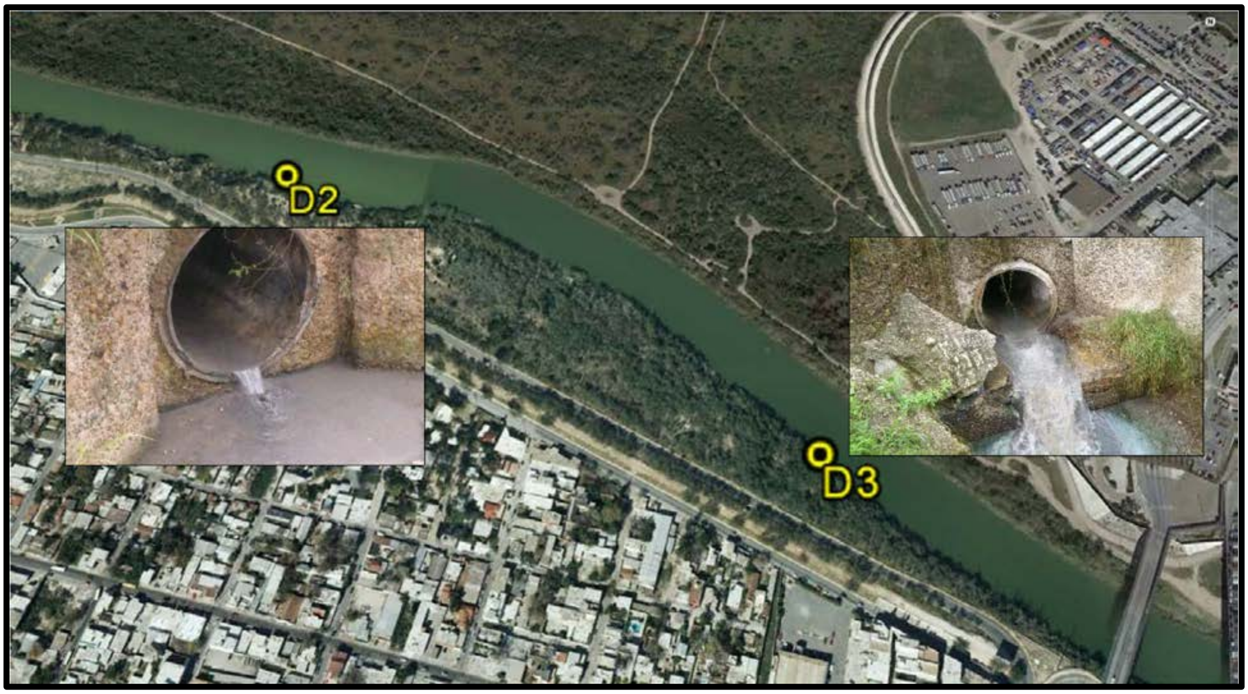

Figure 1-39. Municipal Discharges D2 and D3 Libramiento Luis Echeverría, Reynosa.

The City of Reynosa Wastewater Treatment Facility No. 1 (PTAR No. 1)

Located less than 50 meters from the Lower Rio Grande/Río Bravo, the city of Reynosa's Wastewater Treatment Facility No.1 (referred to by its Spanish acronym PTAR1) provides wastewater treatment services to approximately 247,000 residents living within its city limits (Figure 1-40). Originally built in 1970, Reynosa's PTAR No. 1 has undergone a number of expansions and rehabilitations over the last 46 years, the last of which occurred in 2001. Originally constructed as a large, multi-celled lagoon system, the facility now consists of an activated sludge unit with anaerobic ponds followed by aeration and facultative lagoon units arranged in sequence. The new mechanical treatment system was constructed adjacent to the original lagoon system. The average daily effluent flow from Reynosa's PTAR No. 1 is estimated to be between 550 and 750 L/s, with an overall daily average flow of 616.7 L/s. Although the Reynosa PTAR No. 1 facility is currently designed to treat 1000 L/s of influent raw sewage, a portion of the raw wastewater conveyed to the facility is occasionally diverted directly to the aged lagoon system adjacent to the activated sludge unit in PTAR No. 1, bypassing the activated sludge treatment system. The lack of capacity to accommodate existing influent flows conveyed to Reynosa's PTAR No.1 results in the discharge of untreated wastewater into the Lower Rio Grande/Río Bravo via a drainage canal known as Dren El Anhelo.

Figure 1-40. Ciudad Reynosa's Wastewater Treatment Facility No. 1 (PTAR No. 1).

Municipal Discharge D4 Calle Ignacio Ramirez y Tamaulipas, Matamoros

Located on the bank of the Lower Rio Grande/Río Bravo in the City of Matamoros, this discharge of untreated wastewater is associated with faulty wastewater conveyance (Figure 1-41). The flow of untreated wastewater reaches the Lower Rio Grande/Río Bravo directly through a stormwater culvert. LRGWQI researchers visually estimated that this discharge contributes a daily flow of untreated wastewater to the Lower Rio Grande/Río Bravo of 0.75 L/s.

Figure 1-41. Municipal Discharges D4, Calle Ignacio Ramirez y Tamaulipas, Matamoros (the inset is a vertical, bird's eye, view of the outfall).

POINT SOURCE POLLUTANT LOADING ESTIMATES

To estimate the average daily loadings, to the Lower Rio Grande/Rio Bravo, of LRGWQI pollutants of concern emanating from point source discharges in the watershed, the author used the daily average effluent flow information associated with the individual point sources of pollution described in the previous sections of this chapter, in combination with reported and estimated concentrations of pollutants of concern in the LRGWQI. For US point sources, average daily loading data of pollutants of concern such as $CBOD_5$ TSS are available from the USEPA's Integrated Compliance Information System (ICIS) database, along with average daily effluent flow and bacteria concentrations (USEPA, 2016b). The author downloaded data from ICIS for LRGWQI period of record (2000-2015). To estimate loadings of pollutants not reported to the USEPA under the NPDES, such as total nitrogen (TN) and total phosphorus (TP), the author used pollutant concentrations derived from stoichiometric ratios of these constituents to the daily average CBOD5 concentrations in their wastewater effluent, as reported in ICIS. These stoichiometric ratios were conservatively established based on their relative concentrations in wastewater of "weak" strength as reported in Metcalf and Eddy (1991). The author also obtained the concentration of TDS in effluent from US wastewater treatment facilities that do not report this constituent to the USEPA from Metcalf and Eddy (1991). Although the preferred indicator bacteria used by USEPA and the State of Texas to assess fecal contamination in surface waters are *E. coli* and *Enterococcus*, the fecal indicator bacteria common to both the United States and Mexico is fecal coliform. Under some circumstances, the State of Texas continues to use fecal coliform to assess water quality. Two of the US wastewater facilities in the Lower Rio Grande/Río Bravo watershed, the City of Roma and the City of Rio Grande City, reported more fecal coliform effluent data than any other indicator bacteria to the USEPA during the LRGWQI period of record (2000-2015). Partly for these reasons, but mainly out of a preference to derive comparative pollutant loadings for the project, the LRGWQI's BTWG agreed to use fecal coliform as the indicator bacteria for the LRGWQI. For US facilities that exclusively report *E. coli* or *Enterococcus* in their discharge monitoring reports to USEPA, the author transformed the daily average concentrations of these parameters to fecal coliform using the ratio of their geometric mean criteria as specified in past State of Texas' Surface Water Quality standards (126 MPN *E. coli*:200 MPN fecal coliform and 35 NPM *Enterococcus*:200 MPN fecal coliform).

For Mexican point sources, the author used the estimated average daily effluent flow values for each Mexican wastewater outfall, as described in the previous section of this chapter, in combination with the maximum monthly average effluent criteria specified in the Mexican federal standard NOM-001-SEMARNAT-1996 (Table 1-10) to calculate average daily loadings of LRGWQI pollutants of concern. The author calculated ammonia nitrogen loadings using effluent concentrations derived from the stoichiometric ratio of ammonia nitrogen to BOD from Metcalf and Eddy (1991) (weak strength). The author also calculated total dissolved solids loadings using the concentration of TDS in wastewater from Metcalf and Eddy (1991). Table 1-11 shows the results of the analysis of average daily point source loadings of constituents of concern to the Lower Rio Grande/Río Bravo.

Table 1-11. Estimated Daily Loading of LRGWQI Pollutants of Concern from Point Source Discharges

Facility Name	Flow (L/day)	CBOD5 (kg/day)	TSS (kg/day)	TDS (kg/day)	TP (kg/day)	TN (kg/day)	NH_3-N (kg/day)	Fecal Coliform (CFU/day)
Nueva Ciudad Guerrero (Imhoff Tank)	268,704	20	20	134	5	11	2	2.69E+11
Ciudad Mier	241,920	18	18	121	5	10	1	2.42E+11
Ciudad Miguel Alemán	3,222,720	242	242	1,611	64	129	26	3.22E+12
City of Roma 3 (Filter Backwash)	310,933	-	3	155	-	-	-	-
City of Roma 2	13,595,760	9	12	6,798	<1	2	1	2.46E+10
Ciudad Camargo	285,984	21	21	143	6	11	2	2.86E+11
City of Rio Grande City	3,163,449	21	25	1,582	1	4	2	4.53E+12
Union Water Supply Corporation	667,305	3	3	334	<1	4	2	5.51E+09
AGUA Special Utility District	631,551	2	4	316	<1	2	1	5.21E+09
Ciudad Gustavo Díaz Ordaz	238,464	18	18	119	5	10	2	2.38E+11
La Joya Independent School District	9,694	<1	<1	5	<1	<1	<1	1.93E+07
City of La Joya	952,067	39	116	476	1	7	4	7.85E+11
City of Peñitas	666,280	4	3	333	<1	1	<1	2.59E+09
Descarga Municipal D2, Reynosa	28,080	2	2	14	1	1	<1	2.81E+10
Descarga Municipal D3, Reynosa	354,326	27	27	177	7	14	2	3.54E+11
Ciudad Reynosa PTAR 1	53,280,029	3,996	3,996	26,640	1,066	2,131	436	5.33E+13
Brownsville Public Utility Board (Silas Ray Power Plant)	76,455	-	-	38	-	-	-	-
Descarga Municipal D4, Matamoros	64,800	5	5	32	1	3	1	6.48E+10
Brownsville Public Utility Board (Southside Wastewater Treatment Plant)	23,882,877	67	203	11,941	2	12	11	1.90E+11
Total	**101,941,398**	**4,494**	**4,719**	**50,971**	**1,165**	**2,350**	**494**	**6.35E+13**

1.0.8.2 Steady State Nonpoint Sources of Pollutants

The diffuse nature of nonpoint sources of pollution complicates their characterization and quantification. Unlike point sources, which can be monitored at their point of discharge, nonpoint sources can affect a receiving water body over wide geographic areas making them hard to measure directly. As previously discussed, the TOR for the LRGWQI limited the investigation of nonpoint sources in the Lower Rio Grande/Río Bravo watershed to steady state nonpoint sources, which excludes sources of pollutants entering the river under rainfall runoff conditions. Steady state nonpoint sources in the Lower Rio Grande/Río Bravo can be classified into three broad categories based on their origin; they include (1) residential nonpoint sources, (2) agricultural nonpoint sources, and (3) wildlife nonpoint sources.

The most widely used method for characterizing nonpoint sources of pollutants is through geospatial analysis using GIS. A description of the methods used to characterize the steady state nonpoint sources pollutants of concern to the LRGWQI, and to quantify their magnitude, is included in Sub-section 1.0.11.2 of this chapter. The following sections provide the results of the geospatial and loading analyses.

RESIDENTIAL NONPOINT SOURCES

Due to wide disparities in sewage collection and treatment services provided in border communities on both sides of the Lower Rio Grande/Río Bravo, estimates of pollutant loadings produced by riparian populations must take into account levels of sanitation prevailing in each of these communities. For this reason, the author and his Mexican collaborators focused the analysis of steady state residential nonpoint sources quantifying residents living in riparian communities (i.e., living within 500 m of the Lower Rio Grande/Río Bravo of a contributing tributary, drain or ditch) falling into one of three sanitation categories, (1) residents receiving centralized sewage disposal services (2) residents using septic systems, and (3) residents lacking any means of sanitation. Table 1-12 summarizes the results of the geospatial analysis conducted by the author and his Mexican collaborators to estimate riparian residential populations with varying sanitation types on the US and Mexican sides of the Lower Rio Grande/Río Bravo. Table 1-13 shows the result of the estimates of potential daily loadings of LRWQI pollutants of concern to the Lower Rio Grande/Río Bravo from steady state residential nonpoint sources in the watershed.

Table 1-12. Estimated Number of Lower Rio Grande/Río Bravo Watershed Residents Living within 500 Meters of the Lower Rio Grande/Río Bravo or One of Its Tributaries, Distributed by Sanitation Type

Country	Total Number of LRG/RB* Watershed Residents Living within 500 m of the LRG/RB or a Tributary	Number of LRG/RB Watershed Residents Living within 500 m of the LRG/RB or a Tributary Receiving Centralized Sewage Disposal Services	Number of LRG/RB Watershed Residents Living within 500 m of the LRG/RB or a Tributary Using Septic Systems	Number of LRG/RB Watershed Residents Living within 500 m of the LRG/RB or a Tributary Lacking Sewage Disposal Services
US	10,641	7,290	3,065	286
Mexico	44,449	31,732	8,580	4,137

*LRG/RB is an acronym for Lower Rio Grande/Rio Bravo

Table 1-13. Estimated Potential Daily Loading of Constituents of Concern to the LRG/RB from Steady State Residential Nonpoint Sources in the Watershed

Pollutant Load	US Subwatershed	Mexican Subwatershed	Total LRG/RB* Watershed
BOD (kg/day)	32	202	234
TSS (kg/day)	32	202	234
TDS (kg/day)	73	460	533
TP (kg/day)	1	7	8
TN (kg/day)	6	37	43
NH3-N (kg/day)	4	23	27
Fecal Coliform (MPN/day)	9.29E+14	5.88E+15	6.81E+15

*LRG/RB is an acronym for Lower Rio Grande/Rio Bravo

AGRICULTURAL NONPOINT SOURCES

Based on the pollutants of concern identified by the LRGWQI's BTWG, steady state agricultural nonpoint sources in the LRG/RB watershed can be subdivided into two main categories, (1) pollutant contributions from irrigation return flows and (2) pollutant contributions from livestock and domestic animals. These two types of nonpoint sources of pollution result from distinctly different agricultural activities and their characterization and quantification requires different data sources and data analysis methods.

Irrigation Return Flows

During dry weather conditions (i.e., steady state conditions), agricultural activities associated with irrigated crop production can contribute to surface water pollution in the Lower Rio Grande/Río Bravo watershed through the production of irrigation return flows. The most common irrigation method used on both sides of the watershed is flood irrigation, which commonly saturates soils producing excess irrigation water. Excess irrigation water can flow directly from agricultural fields into drainage ditches as irrigation return flows. Excess irrigation water also pools in the shallow subsurface below the root zone where it can travel laterally as phreatic groundwater, which also flows into agricultural drainage ditches or directly into the Lower Rio Grande/Río Bravo as base flow. Excess irrigation water can leach dissolved salts from agricultural soils loading irrigation return flows and raising their salinity. These flows can mobilize salts from the subsurface and concentrate them in the upper layers of the soil horizon, along with other constituents commonly produced during agricultural production, including dissolved organic matter, fertilizers, and pesticides. As a result, irrigation return flows can be a substantial and persistent source of these pollutants in the Lower Rio Grande/Río Bravo watershed.

A high percentage of agricultural land in the Lower Rio Grande/Río Bravo watershed is irrigated using water from the Lower Rio Grande/Río Bravo or from one of its two major tributaries, the Río Álamo or the Río San Juan. Approximately 1770 km^2 of the Lower Rio Grande/Río Bravo watershed (24.3%) is used for crop production (Miranda & Harper, 2017). However, not all this agricultural land is irrigated. To estimate the area of irrigated agricultural land in the Lower Rio Grande/Río Bravo watershed, the author conducted a geospatial analysis using a binational land use/land cover GIS layer developed by the BEHI. The analysis is described in detail in Sub-section 1.0.11.2. of this chapter.

Figure 1-42 shows the estimated areas of irrigated agricultural land in the Lower Rio Grande/Río Bravo watershed. Evident from this figure is the relatively uneven distribution of irrigated land between the two national sub-watersheds of the Lower Rio Grande/Río Bravo.

Irrigated agricultural land in the US portion of the Lower Rio Grande/Río Bravo watershed is estimated to total 227.24 km^2. The total amount of irrigated agricultural land on the Mexican side of the watershed is estimated to be 887.59 km^2, nearly four times the area on the US portion of the Lower Rio Grande/Río Bravo watershed.

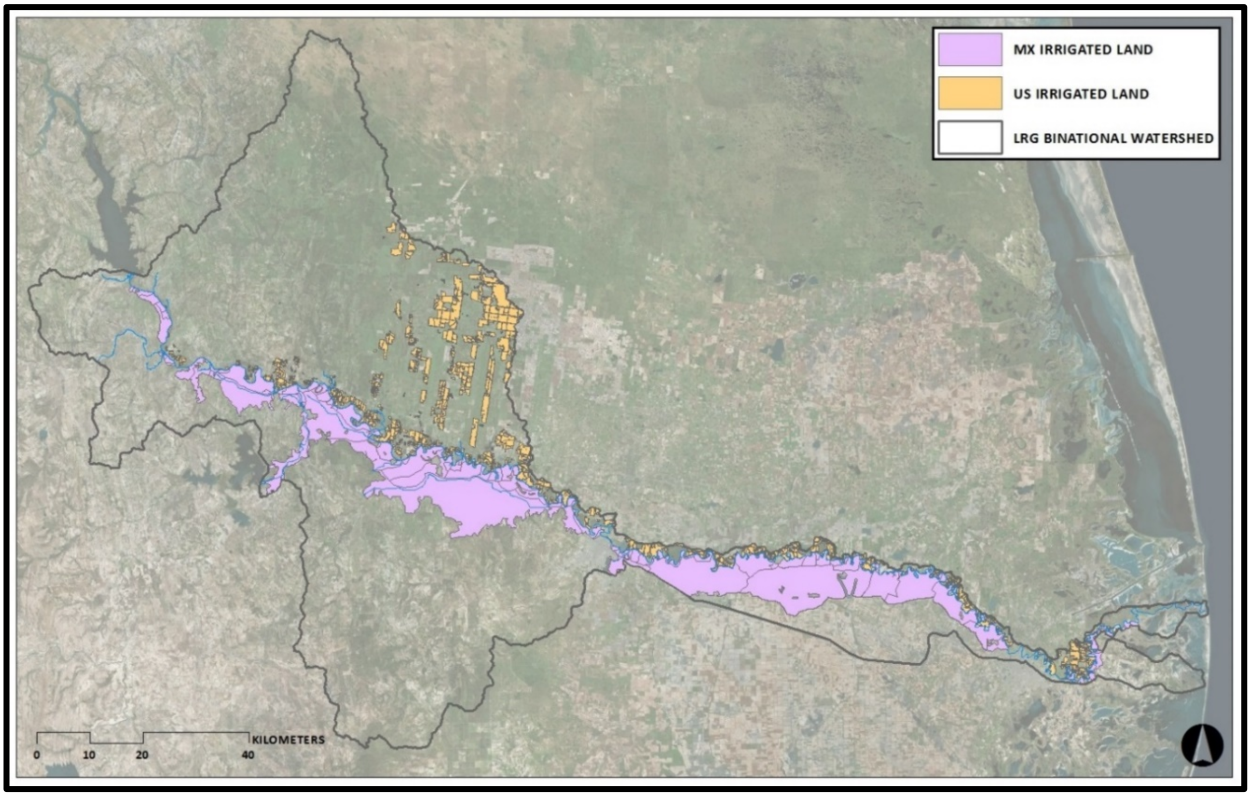

Figure 1-42. Irrigated Agricultural Land in the Lower Rio Grande/Río Bravo Watershed.

The disparity in the amount of irrigated agricultural land on either side of the Lower Rio Grande/Río Bravo watershed is due mainly to the difference in hydrology between the two national sub-watersheds. Out of the approximately 2,392 km^2 of irrigated land in the three Texas counties included as part of the US portion of the Lower Rio Grande Valley, less than ten percent (9.5%) are inside of the Lower Rio Grande/Río Bravo watershed (Miranda & Harper, 2017). The remainder of the US agricultural land in the Lower Rio Grande Valley is in the Arroyo Colorado watershed, which is the adjacent watershed located to the north of the Lower Rio Grande/Río Bravo watershed. Correspondingly, the majority of the irrigation return flows produced by US agricultural land in the Lower Rio Grande Valley flow into the Arroyo Colorado and three other large drainage ditches that flow away from the Lower Rio Grande/Río Bravo watershed and into the Laguna Madre on the US side.

Conversely, 98% of the irrigated land in the eight Mexican municipios that border the Lower Rio Grande/Río Bravo are within the Lower Rio Grande/Río Bravo watershed. Over forty percent (44.2%) of the Mexican agricultural land in the Lower Rio Grande/Río Bravo watershed (392.49 km^2) is in the Río San Juan Irrigation District (CONAGUA's Distrito de Riego 026), which diverts water from the Marté Gómez Reservoir, an impoundment on the main tributary to the Lower Rio Grande/Río Bravo downstream of Falcon Reservoir, the Río San Juan (Rymshaw, 2011). Water from the Marté Gómez Reservoir and the Río San Juan is diverted for irrigation to agricultural land in the San Irrigation District through large irrigation canals. The irrigation return flows produced from irrigating this land is collected by a network of drainage ditches and is transported directly to the Lower Rio Grande/Río Bravo through five large ditches that flow into the river upstream of the city of Reynosa.

Irrigated Agriculture on the US side of the Lower Rio Grande/Río Bravo Watershed

The bulk of the water diverted from the Lower Rio Grande/Río Bravo on the US side is pumped by irrigation districts that supply water from the river mainly for agricultural irrigation, but also for industrial and domestic use. Twenty-nine independent irrigation districts supply over 360,000 acre-ft of water for these uses annually (Huang et al. 2010) (Figure 1-43). Originally established in the early part of the twentieth century, the irrigation districts in the Rio Grande Valley are largely governed by local boards of directors and operate much like public county or municipal utilities.

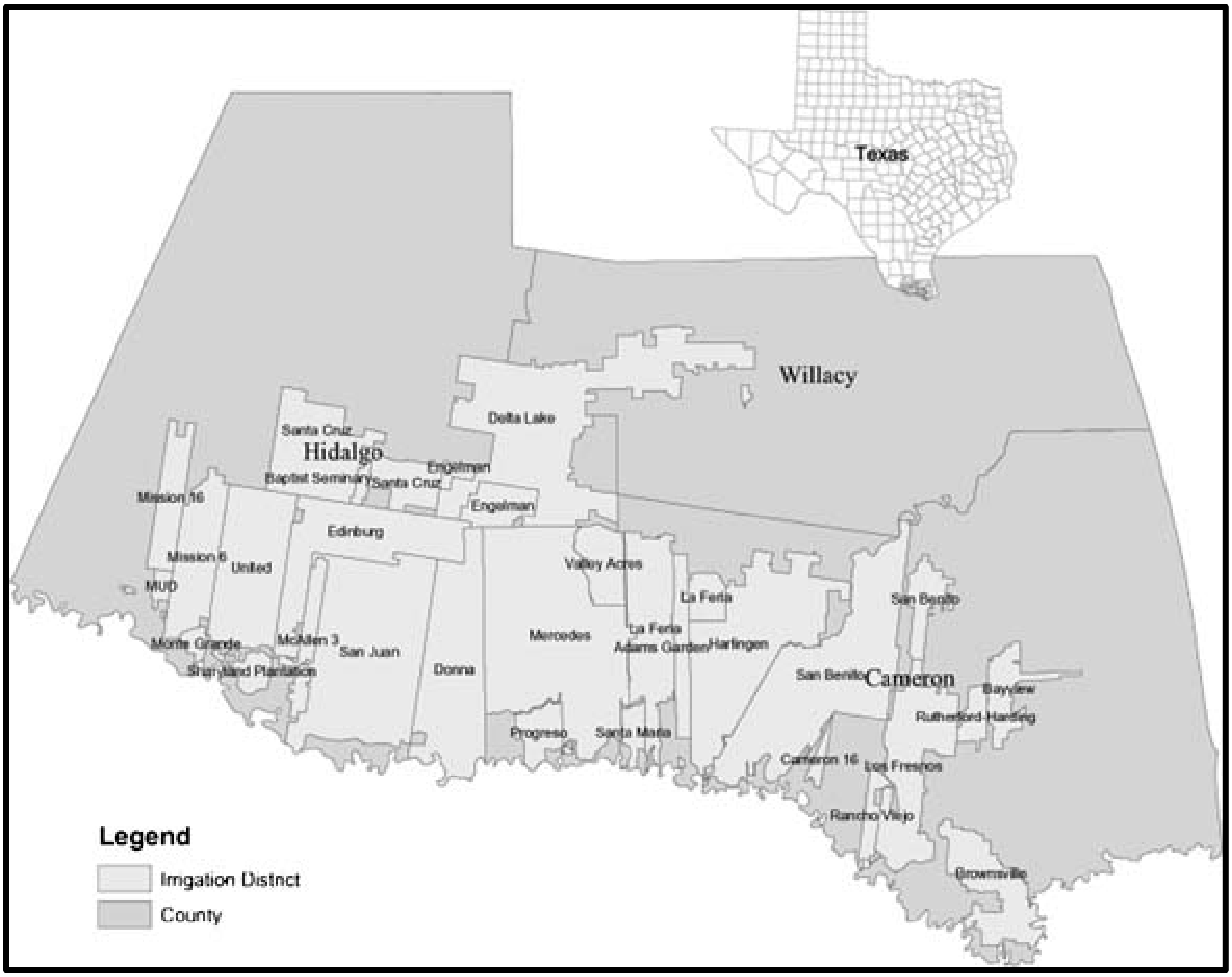

Figure 1-43. US Irrigation Districts in the Lower Rio Grande Valley. Source: Huang et al. 2010.

The districts own large senior water rights which allow them, under Texas law, to pump water from the river at several pumping locations into elaborate irrigation canal systems that distribute the water to large areas of agricultural land within their districts. The districts sell water to local agricultural producers, municipalities and industrial customers. As previously mentioned, the bulk of the irrigated land on the US side drains away from the Lower Rio Grande/Río Bravo. Smaller individual water rights owners, commonly referred to by the TCEQ as "minor" diverters, also pump water from the river for individual use. The portion of the US irrigated land located in Starr County is irrigated by "minor" diverters. The irrigation return flows from these agricultural areas are collected by non-perennial tributaries and drainage ditches that flow into the Lower Rio Grande/Río Bravo along the southern edge of Starr County on the US side. Although very little flow data are available for these ditches, their contributions to the Lower Rio Grande/Río Bravo are thought to be small compared to those of Mexican agricultural ditches (W. Halbert, Personal Communication, May 26, 2016).

Irrigated Agriculture on the Mexican side of the Lower Rio Grande/Río Bravo Watershed

In Mexico, CONAGUA authorizes and administers federal water rights. Figure 1-44 shows the two federal irrigation districts that are within the boundaries of the Mexican portion of the Lower Rio Grande/Río Bravo Watershed, the Distrito de Riego Bajo Río San Juan (CONAGUA's Distrito No. 026) and the Distrito de Riego Bajo Río Bravo (CONAGUA's Distrito No. 025).

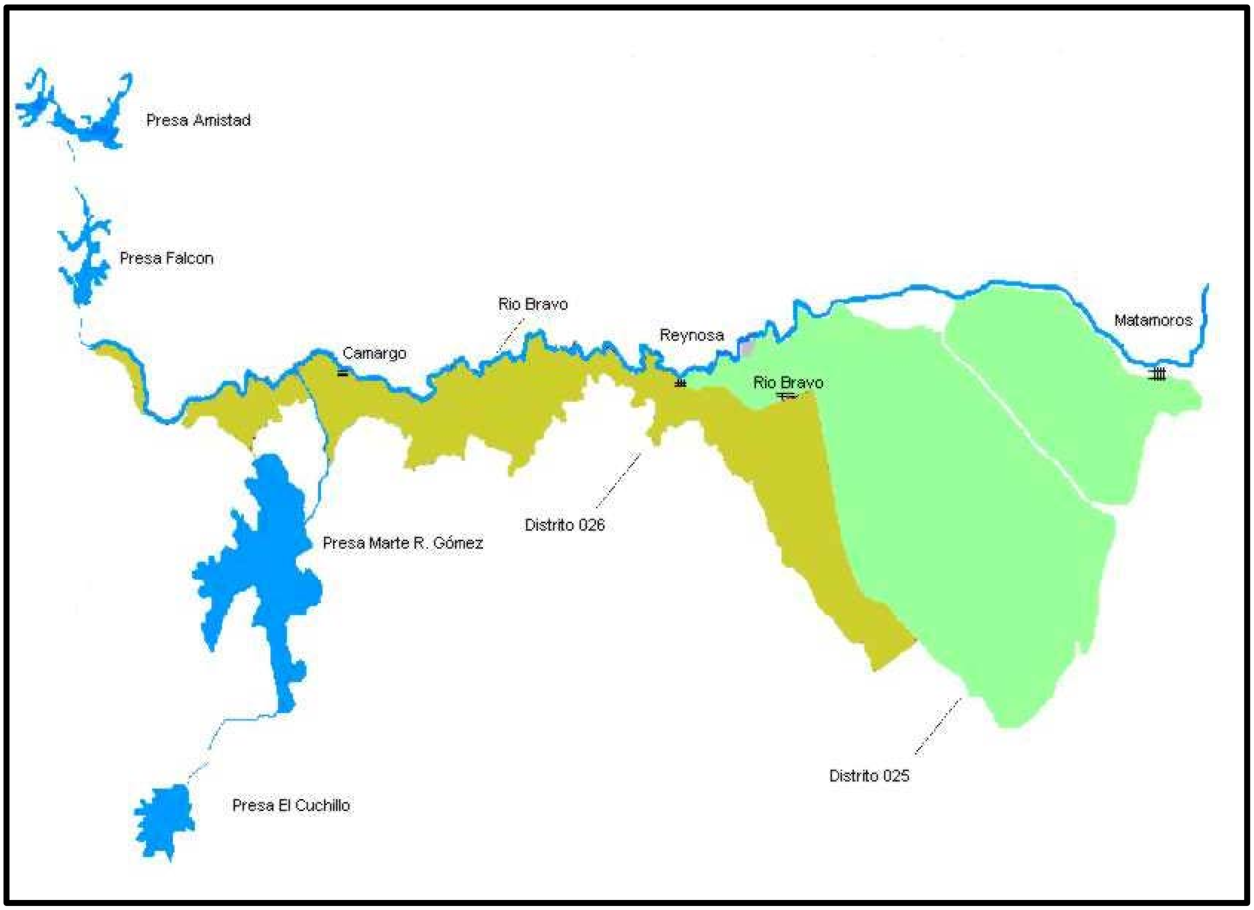

Figure 1-44. Mexican Irrigation Districts along the Lower Río Bravo. Source: Rymshaw, 2011

In Distrito No. 026, most of the water is diverted from the Marté R. Gómez reservoir, the second in a series of impoundments of the Río San Juan, in northern Tamaulipas. The smaller El Cuchillo reservoir is the first impoundment. Some irrigation water is drawn directly from the Río San Juan, downstream of Marté R. Gómez Reservoir (Figure 1-44). Diversions from the Marté R. Gómez reservoir are conveyed mainly through open irrigation canals in Distrito No. 026 and the water is used almost exclusively for agriculture. In contrast, water in Distrito No. 025 is diverted from the Lower Rio Grande/Río Bravo at one of two in-stream dams on the river, Anzalduas Dam and Retamal Dam. Irrigation water is diverted into large distribution canals that provide water for agricultural, municipal and industrial uses in the eastern portion of the watershed and in a large area of the coastal plain south of it. Upstream of Anzalduas Dam, which is located near the Mexican city of Reynosa, five large agricultural drains collect irrigation return flows from these large agricultural areas in the Mexican portion of the Lower Rio Grande/Río Bravo watershed; they are the Rancherías, Los Fresnos, Puertecitos, Huizache and El Morillo drains. Four of these five drains flow directly into the Lower Rio Grande/Río Bravo upstream of Anzalduas Dam. The fifth drain, Los Fresnos, flows into the Río San Juan, a tributary of the Rio Grande/Río Bravo, approximately 4 km from the confluence with the Lower Rio Grande/Río Bravo (Figure 1-45).

CILA monitors water quality in these drains and, until 2006, the IBWC published these data in yearly Water Bulletins. The data showed levels of total dissolved solids, often exceeding 10,000 mg/L during the growing seasons. There is general binational agreement that these agricultural drains are a major source of high salinity in the river (W. Belzer, personal communication, March 11, 2015). Downstream of Anzalduas Dam, Mexican irrigation return flows are diverted away from the Lower Rio Grande/Río Bravo through a series of drains that flow in a southeast direction and ultimately empty into the marshlands that border the Mexican Laguna Madre, which effectively mitigates the contribution of pollutants from Mexican agriculture in this portion of the watershed. Table 1-14 summarizes the results of the geospatial analysis conducted by the author to estimate the square kilometers of irrigated agricultural land on US and Mexican side of the Lower Rio Grande/Río Bravo watershed.

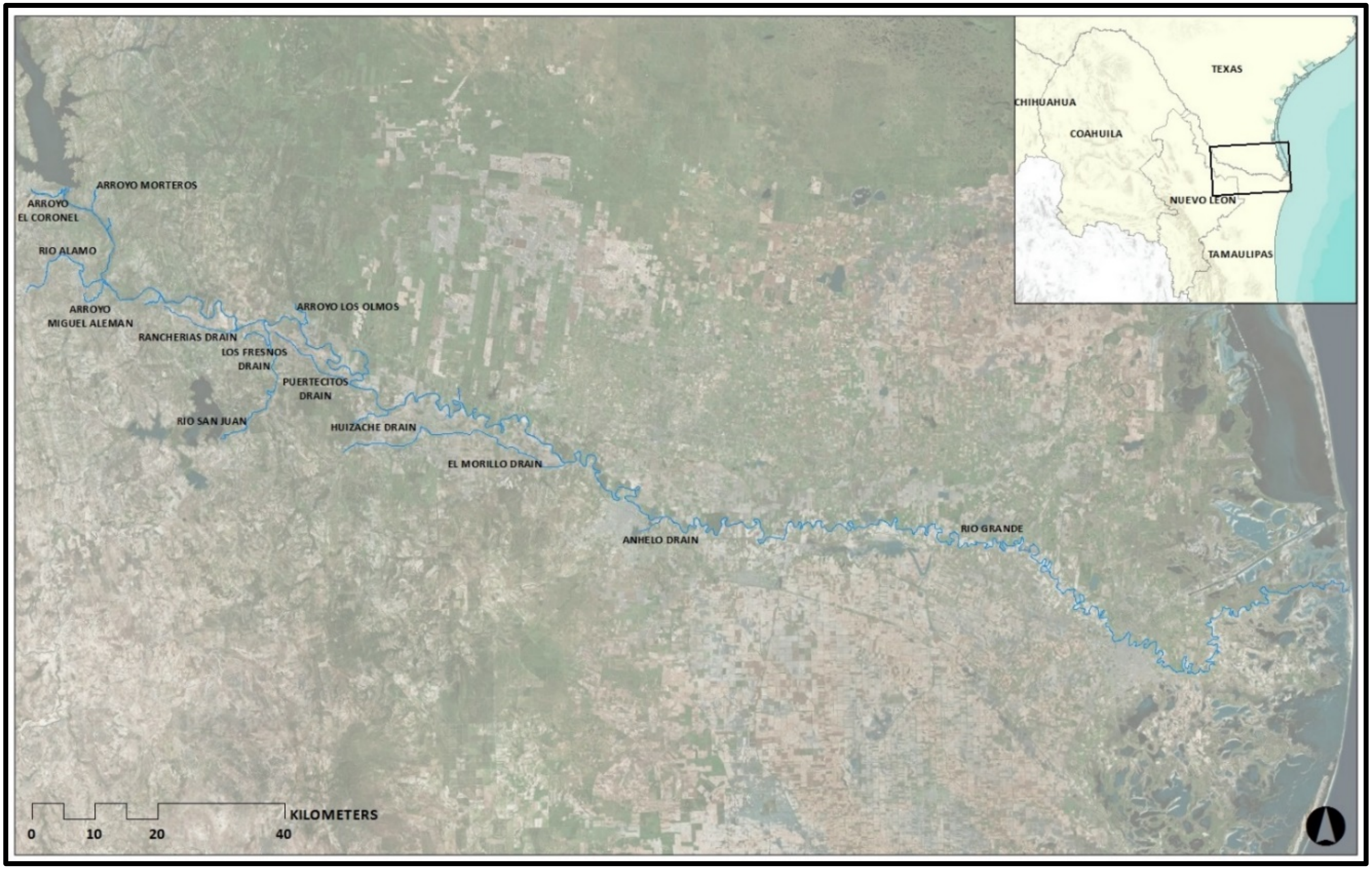

Figure 1-45. Tributaries and Drains of the Lower Rio Grande/Río Bravo

Table 1-14. Irrigated Agricultural Land in US and Mexican Portions of the Lower Rio Grande/Río Bravo Watershed

Country	Irrigated Agricultural Land in the LRG/RB* Watershed (km^2)
US	227.24
Mexico	887.59

*LRG/RB is an acronym for Lower Rio Grande/Rio Bravo

Table 1-15 shows the result of the estimates of daily loadings of pollutants of concern to the Lower Rio Grande/Río Bravo from irrigation return flows in the Lower Rio Grande/Río Bravo watershed. The estimates were derived from the LRGWQI models of water quality.

Table 1-15. Estimated Average Daily Loading Rates of Constituents of Concern to the Lower Rio Grande/Río Bravo from Agricultural Irrigation Return Flows*

Pollutant Load	US Subwatershed	Mexican Subwatershed	Total LRG/RB Watershed**
BOD (kg/day)	284.36	826.33	1,110.69
TSS (kg/day)	33,177.41	96,412.18	129,589.59
TDS (kg/day)	589,652.93	1,713,506.93	2,303,159.86
TP (kg/day)	12.09	35.13	47.22
TN (kg/day)	386.90	1,124.31	1,511.20
NH3-N (kg/day)	7.66	22.25	29.91
Fecal Coliform (MPN/day)	2.25E+11	6.54E+11	8.79E+11

* Irrigation return flows are seasonal. The daily loads represented in this table were derived from the LRGWQI models of water quality, which modeled water quality in the Rio Grande/Río Bravo during two irrigation season months and three non-irrigation season months, the average loads presented in this table include model output only for the months modeled.

** LRG/RB is an acronym for Lower Rio Grande/Rio Bravo

Livestock and Domestic Animals

Another steady state nonpoint source of pollutants of concern related to agricultural activity is livestock and domestic animals. The contribution of pollutants from livestock and domestic animals to surface water, under steady state conditions, is limited to direct deposition of feces into, or directly adjacent to, the Lower Rio Grande/Río Bravo or a contributing tributary or ditch. The population of animals of interest under this category include grazing animals such as cattle, horses, sheep and goats. Domestic pigs, chickens, ducks and geese are excluded from this analysis, because, unlike grazing livestock animals that can defecate in or adjacent to surface water bodies, these species are generally confined to areas where direct deposition of feces into surface water does not occur (e.g., pens and coops). Table 1-16 shows the estimated number of livestock and domestic animals in the US and Mexican Portions of the Lower Rio Grande/Río Bravo Watershed.

Table 1-16. Estimated Number of Livestock and Domestic Animals in the US and Mexican Portions of the Lower Rio Grande/Río Bravo Watershed

Country	Cattle	Horses	Sheep	Goats
US	24,410	420	417	714
Mexico	1,879	16	113	19

Table 1-17 shows the result of the estimates of potential daily loadings of constituents of concern to the Lower Rio Grande/Río Bravo from livestock and domestic animals in the Lower Rio Grande/Río Bravo watershed.

Table 1-17. Estimated Potential Daily Loading of Pollutants of Concern to the Lower Rio Grande/Río Bravo from Livestock and Domestic Animals under Steady State Conditions

Pollutant Load	US Subwatershed	Mexican Subwatershed	Total LRG/RB Watershed
BOD (kg/day)	254	20	274
TSS (kg/day)	206	16	222
TDS (kg/day)	69	5	74
TP (kg/day)	15	1	16
TN (kg/day)	23	2	25
NH3-N (kg/day)	14	1	15
Fecal Coliform (MPN/day)	4.37E+13	3.42E+12	4.71E+13

WILDLIFE NONPOINT SOURCES

Like agricultural livestock and domestic animals, grazing wildlife species are considered sources of pollutants in surface water because of the feces they produce which can be directly deposited into surface waters. As is the case with livestock and domestic animals, the contribution of pollutants from wildlife to surface water under steady state conditions is limited to direct deposition of feces into the Lower Rio Grande/Río Bravo or a contributing tributary or ditch. Based on their relative abundance, and following the work of Lynch (2012), the author chose to concentrate his analysis of pollutant contributions from wildlife on three representative species; deer, feral hogs and waterfowl. Table 1-18 shows the estimated populations, based on geospatial analysis, of representative wildlife species within the riparian corridors (91m buffer) on both sides of the Lower Rio Grande/Río Bravo watershed.

Table 1-18. Estimated Wildlife Populations within the Riparian Corridors (91m) on Both Sides of the LRG/RB Watershed

Wildlife Species	US	Mexico
Deer	72	174
Feral Hogs	12	39
Waterfowl	528	258

Table 1-19 shows the result of the estimates of potential daily loadings of constituents of concern to the Lower Rio Grande/Río Bravo from these representative populations in the Lower Rio Grande/Río Bravo watershed.

Table 1-19. Estimated Potential Daily Loading Rates of Constituents of Concern to the Lower Rio Grande/Río Bravo watershed, under Steady State Conditions, from Deer, Feral Hogs and Migratory Waterfowl

Pollutant Load	US Subwatershed	Mexican Subwatershed	Total LRG/RB Watershed
BOD (kg/day)	<0.5	<0.5	<0.5
TSS (kg/day)	<0.5	<0.5	0.5
TDS (kg/day)	<0.5	<0.5	<0.5
TP (kg/day)	<0.5	<0.5	<0.5
TN (kg/day)	<0.5	<0.5	<0.5
NH3-N (kg/day)	<0.5	<0.5	<0.5
Fecal Coliform (MPN/day)	5.20E+10	9.05E+10	1.00E+11

COMPARISON OF POINT SOURCE AND NONPOINT SOURCE POLLUTANT LOADINGS

While estimates of nonpoint source pollutant loadings are typically not as reliable as those of point sources, due primarily to the higher uncertainty associated with the geospatial and constituent analysis of the former, it is sometimes informative to compare the results of these estimates to gain some insight into the relative magnitude of each broad category of pollutant sources in a watershed. Table 1-20 shows a comparison of estimated daily loading rates of constituents of concern form point and nonpoint sources in the Lower Rio Grande/Río Bravo watershed. The table shows that, while point source loadings of BOD, TP, TN and NH_3-N exceed those of steady state nonpoint sources, loadings of TSS, TDS and fecal coliforms from nonpoint sources exceed those of point sources by several orders of magnitude.

Table 1-20. Estimated Daily Loading of Pollutants of Concern from Point Sources and Steady State Nonpoint Sources in the Lower Rio Grande/Río Bravo Watershed

General Category of Pollutant Source	BOD* (kg/day)	TSS (kg/day)	TDS (kg/day)	TP (kg/day)	TN (kg/day)	NH_3-N (kg/day)	Fecal Coliform (CFU/day)
Point Sources	4,494	4,719	50,971	1,165	2,350	494	6.35E+13
Nonpoint Sources‡	1,619	130,046	2,303,767	71	1,579	72	6.86E+15
Total	6,113	134,765	2,354,738	1,236	3,929	566	6.92E+15

*$CBOD_5$ loading values were used to represent BOD for point sources
‡ Refers only to steady state nonpoint sources

It is important to note that the portion of the total nonpoint source loading of pollutants of concern estimated from irrigation return flows shown in Table 1-20 were derived from the average loads of these pollutants resulting from water quality simulations conducted using the LRGWQI models of water quality in the Lower Rio Grande/Río Bravo using the LA-QUAL software.

1.0.9 Overview of Water Quality Management in the Lower Rio Grande/ Río Bravo

The management of wastewater generated in the Lower Rio Grande/Río Bravo watershed is conducted by each nation through a combination of regulatory efforts, local and regional planning assisted through, national and binational financing. In the United States, the federal Clean Water Act, administered by the USEPA, specifies the general regulatory requirements for wastewater management and treatment. The USEPA delegates its authority to issue wastewater discharge permits to the State of Texas (TCEQ), which also sets surface water quality standards. In Texas, all entities wishing to build wastewater treatment facilities or systems (i.e., cities, counties, river authorities, private companies, nonprofit utility corporations, etc.) must first obtain a discharge permit from the TCEQ.

The TCEQ bases its wastewater permitting decisions for the Lower Rio Grande on a waste load evaluation conducted using a deterministic computer model of water quality of the river (QUAL-TX). The model estimates the maximum amount of pollutants the river can assimilate and still meet state surface water quality standards at steady state conditions. The TCEQ evaluates each request for a new discharge permit by simulating the effects the discharges on water quality using the QUAL-TX model. The TCEQ's QUAL-TX model was calibrated, and is currently used, without including steady state nonpoint source pollutant contributions (e.g., untreated wastewater, irrigation return flows, etc.). The TCEQ incorporates in its models only limited knowledge of pollutant contributions from Mexican discharges, which can result in a less than realistic simulation of water quality in the river.

Under Mexico's national water law (Ley Nacional de Aguas), local entities in Mexico, such as municipal potable water and drainage commissions (COMAPAs) or water and drainage boards (JADs), must obtain a permit from the Mexican federal water commission (CONAGUA) to discharge treated wastewater into surface water bodies. As previously mentioned, CONAGUA currently relies on performance-based technological controls to issue wastewater discharge permits in the Lower Río Bravo watershed. CONAGUA has declared its intention to base wastewater permits on a water quality-based criteria in a fashion similar to that used by the State of Texas (E. Gutierrez, Personal Communication, May 25, 2015).

Planning for potable water and sanitation services is conducted by local entities on both sides of the border. Municipal governments, utility corporations, JADs, COMAPAS, etc., make infrastructure expenditure decisions, balancing the perceived needs of their communities with the budgetary constraints of their organizations. In Texas, regional and state governments (i.e., county and state health departments and state environmental agencies) may put external pressure on municipal utility boards and utility districts to improve environmental infrastructure when sanitary conditions are thought to contribute to regulatory violations.

Regional planning (i.e., coordinated infrastructure planning on a regional basis), occurs separately in both countries, primarily as a function of the financial mechanisms available to local entities for the funding of water and wastewater infrastructure projects. On the US side, low interest loans are made available through state and federal programs, such as the Texas Water Development Board's (TWDB's) State Revolving Fund Program or directly from federal agencies, such as the USDA's Rural Development Program (USDA-RD). Financing is also available through the North American Development Bank (NADB), although interest rates are typically higher for NADB loans than for those offered through the State Revolving Fund or from USDA-RD. Private sector loans for water and wastewater infrastructure projects in the Lower Rio Grande Valley are rare, probably due to the option, available to most municipal governments, of low interest loans from the TWDB and other public programs and the NADB. However, even with the existence of these infrastructure financing programs, many communities in the Rio Grande Valley find it difficult to fund needed water and wastewater infrastructure projects due to depressed economic conditions that plague most of the Texas-Mexico border region, including the Lower Rio Grande Valley.

As a condition for approval of infrastructure grants or low interest loans from the TWDB, NADB or USDA-RD, applicants must develop facility plans that demonstrate the technical and financial feasibility of the projects proposed for funding. This planning includes the compilation of information used by state agencies to assess the impact the projects may have on human health and the environment. In Texas, this assessment is conducted by the TCEQ's Water Quality Division. Loan and grant applicants are often directed to modify their facility plans based on the results of these assessments.

Interestingly, Mexican wastewater projects certified by the BECC for funding under the NADB are also evaluated by the TCEQ for their impact on stretches of the river immediately downstream of the proposed discharge (M.A. Rudolph, personal communication, 2010). However, as alluded to earlier in this chapter, only discharges requiring permits from the TCEQ (i.e., TPDES permit applications) are evaluated. Other regional entities such as local councils of government are contracted by the State of Texas to compile information about current and projected future water and wastewater needs for different regions of the state. The state uses this information to plan its own state-wide infrastructure financing efforts.

In a similar fashion to that described for the US side of the Lower Rio Grande/Río Bravo watershed, Mexican COMAPAS and JADs assess the water and wastewater infrastructure needs of the communities they serve. However, unlike the US, regional water and wastewater infrastructure planning and financing is more centralized on the Mexican side of the border. Under federal programs administered by CONAGUA, such as the federal Urban Zone Potable Water and Drainage Program (APAZU) and the Sustainable Water and Sanitation for Rural Communities Program (PRODDER), low interest loans and some small grants are made available to local entities and also to Mexican state governments. The NADB also can and does support Mexican wastewater collection and treatment systems. Although significant regional planning is conducted by state agencies, such as CEAT, which assesses infrastructure needs in the Mexican state of Tamaulipas, the bulk of the funding made available for infrastructure projects in Mexico is provided by CONAGUA, which also prioritizes and approves disbursements of financial resources on a national level to all 31 of the Mexican states. Some financial resources are available to local entities through some of the wealthier Mexican state governments. However, the amount of state funding available for Mexican state agencies like CEAT for infrastructure financing is typically small compared to Mexican federal funding. In recent years, the bulk of the financing of water and wastewater infrastructure projects on the Mexican side of the Lower Río Bravo has involved a combination of funding sources, including Mexican federal programs (APAZU and PRODDER), NADB, Mexican state and local funding and even US federal grants awarded through the EPA’s BEIF program, with much of the financing coming from NADB. Although the BECC certification process required assessment of the impact of each proposed project on the water bodies receiving treated wastewater, both CONAGUA and CEAT assess regional infrastructure status and needs simply by estimating the percentage of the population in a specific region served by water and wastewater systems.

Evident from these descriptions of wastewater infrastructure planning in the Lower Rio Grande/Río Bravo watershed is the fragmented nature of general sanitation and water quality planning efforts in this portion of the border region. Planning efforts on the US side of the river, although coordinated regionally and evaluated using water quality information and regional water quality modeling, do not fully take into account the pollutant contributions emanating from the Mexican side of the watershed. Mexican planning efforts for this region do not currently involve the use of regional water quality models at all.

Under the current framework, it is conceivable that pollutant loads permitted to enter the Lower Rio Grande/Río Bravo could exceed the river's capacity to assimilate them, despite individual efforts on the part of both countries to avoid this undesirable water quality condition. Ideally, infrastructure and water quality planning efforts should be integrated on a watershed scale to protect water quality and human health more effectively and efficiently. Any watershed planning should involve key stakeholders and decision makers on a local, state and federal level. Such a task would be complex in watersheds located within the boundaries of a single nation, but is much more difficult in a transboundary situation, where sovereign regulatory controls over pollutant sources stop at the international border and local planning priorities are influenced by national interests.

1.0.10 RESEARCH GOAL

The research goal of this dissertation is to find answers to the following research questions:

1. How does the insight gained form institutional analysis inform the development of decision support tools designed to facilitate and enhance transboundary water quality planning and management efforts such as the Lower Rio Grande/Río Bravo Water Quality Initiative?

2. What aspects of a decision support system (DSS) developed using the insight gained form an analysis of existing institutional arrangements to protect water quality in the Lower Rio Grande/Río can be identified as transferable to other transboundary settings?

1.0.11 Research Approach

The research conducted in support of this dissertation employed a combination of qualitative and quantitative methods. Efforts to characterize and analyze unilateral and bilateral institutional arrangements (formal and informal) currently in place to manage and protect water quality in the Lower Rio Grande/Río Bravo employed standard qualitative methods, including review of printed and web-based materials, structured, semi-structured and unstructured key informant interviews, focus groups and surveys. The author also used qualitative methods to conduct a comparative analysis of institutional arrangements to manage and protect surface water quality in other transboundary settings. Efforts to construct a binational water quality model of the Lower Rio Grande/Río Bravo involved field collection methods of physical, chemical and biological parameters and quantitative laboratory analysis of surface water samples which generated empirical water quality data used to parameterize and calibrate a model of water quality in the river. Parameterization of the model of water quality also involved the compilation and processing of data acquired from state and federal agencies involved in the regulation of water use from Lower Rio Grande/Río Bravo and from a series of binational synoptic surveys of water quality conducted in the Rio Grande/Rio Bravo watershed in 2014, 2015 and 2016. The author used geospatial analysis methods to quantify the steady state loadings of pollutants and constituents of concern produced by human and non-human nonpoint sources in the Lower Rio Grande/Rio Bravo watershed, which the author and his collaborators also used to parameterize the binational water quality model of the Lower Rio Grande/Río Bravo.

1.0.11.1 Qualitative Research Methods and Design

A central hypothesis underlying the research presented in this dissertation is that, an analysis of the existing unilateral and bilateral institutional arrangements in place to manage and protect water quality in the Lower Rio Grande/Río Bravo would enhance the development of a decision support tool designed to facilitate bilateral decision making associated with water quality management in the river. To this end, the author worked with David Eaton Ph.D., of the Lyndon B. Johnson (LBJ) School of Public Affairs at The University of Texas at Austin, and participated in a Policy Research Project (PRP) designed to investigate and analyze the existing formal and informal institutional arrangements in place to manage and protect water quality in the transboundary watershed of the Lower Rio Grande/Río Bravo (Falcon Dam to the Gulf of Mexico).

Titled "The Lower Rio Grande/Río Bravo Water Quality Initiative Policy Research Project" (LRGWQIPRP), the effort employed qualitative methods to acquire, compile and analyze information from various sources including published and unpublished written materials, community representatives (elected and appointed), representatives of the institutions and organizations currently involved in water quality protection of Lower Rio Grande/Río Bravo, and the water user community at large. Additionally, the author collaborated with Dr. Eaton and the participants in the LRGWQIPRP to conduct research into existing governance of transboundary water bodies with an emphasis on investigating existing bilateral and multilateral institutional arrangements to manage and protect water quality in transboundary water bodies. The LRGWQIPRP effort was funded by the Texas General Land Office through a grant from the National Oceanographic and Atmospheric Administration (NOAA) and involved the participation of 32 graduate students.

The LRGWQIPRP was designed to address four major research goals, to:

- characterize the existing institutional frameworks governing water quality management and protection in the Lower Rio Grande/Río Bravo,
- characterize the informal institutional arrangements and networks associated with water quality management and protection in the Lower Rio Grande/Río Bravo,
- examine and compare existing institutional arrangements to manage and protect water quality in transboundary surface water bodies, and
- investigate attitudes and perceptions of the water user communities on both sides of the river, identifying preferences for mechanisms to protect water quality.

Compilation and Review of Descriptive Printed and Web-based Materials

To address the first research goal (i.e., characterize the existing institutional frameworks governing water quality management and protection in the Lower Rio Grande/Río Bravo), the author and his collaborators first conducted an extensive search of printed documents and materials available on the world wide web. The search targeted five general types of organizational sectors: governmental agencies, offices of elected and appointed officials, private companies, non-governmental organizations, academic institutions, and water user associations/organizations (i.e., trade organizations, irrigation districts, water supply corporations, etc.). The search targeted information about agencies, organizations and individuals (1) associated with the management and/or protection of natural resources, (2) associated with the funding or construction of water and wastewater of infrastructure projects, (3) associated with the funding or implementation of agricultural best management practices, (4) associated with the regulation of drinking water or wastewater, (5) providing water and/or sewer services, (6) providing assistance (financial or other) to low income residents. The search effort included entities operating on either side (or both sides) of the international boundary, at all levels of government, and in the nonprofit and private sectors. Following the information gathering phase of this effort, the author reviewed the information gathered and used it to construct a generalized conceptual model of the formal unilateral and bilateral institutional framework(s) currently in place to manage and protect water quality in the Lower Rio Grande/Río Bravo.

Semi-structured and Unstructured Informant Interviews

While the review of information gathered from print and web sources provides the means to construct a generalized view of existing formal institutional frameworks, operational details are often lacking in the documents and other materials available in the public domain, as are the interrelationships that often exist between formal institutional actors, between institutional and non-institutional actors, and within networks of interested individuals. To fill in these knowledge gaps the LRGWQIPRP employed additional qualitative methods, including semi-structured and unstructured informant interviews, focus group discussions with selected individuals, and random and targeted surveys. The information gathered from the interviews and focus groups was mainly recorded using hand-written notes. However, some interviews were recorded using digital audio recording equipment and video cameras. All interview and focus group participants provided the researchers informed consent prior to participating in the study and all standard anonymity and confidentiality protocols specified in the approved University of Texas Institutional Review Board (IRB) project were strictly followed, including those applicable to survey participants (UT IRB, 2011).

The author, in collaboration with Dr. David Eaton and the participants of the LRGWQIPRP project, initially selected interview subjects based on the subjects' likely knowledge of local water issues. However, the standard interview practice of "snowballing" was employed by the interviewers. Thus, many of the interview subjects were subsequently selected based on referral from other subjects previously interviewed. The interview subjects included professionals as well as everyday residents with knowledge deemed by the author, in consultation with Dr. David Eaton, to have the potential to fill the gaps in knowledge identified by the author and his collaborators in the LRGWQIPRP during the first phase of information collection (i.e., review of printed and web-based material). The research design included semi-structured interviews and open-ended unstructured interviews and was modeled after the interview procedures established by Dr. David Eaton (Eaton, 2007a, Eaton 2007b), additional details regarding the interview protocols can be found in UT IRB (2011).

LRGWQIPRP interview team conducted fifty-eight interviews over a five-month period (November 16, 2011 through April 23, 2012). The team produced detailed transcripts of all interviews. The information gathered through the interviews helped to answer many of the questions that arose during the first phase of information collection (i.e., the review of printed and web-based material) and played a crucial role in the filling of the knowledge gaps remaining after the first information collection phase of the project.

Focus Group Sessions

While, informant interviews proved a valuable tool for obtaining nuanced information about formal and informal institutional arrangements in the Lower Rio Grande/Río Bravo watershed, researchers must always keep in mind that the information conveyed during an interview is done so through the subjective filter of the interview subject. One of the options available to qualitative researchers to reduce the subjectivity and potential inaccuracy of information gathered from verbal statements made by human subjects is the use of focus groups discussions. Knowing that other participants knowledgeable in the discussion subject may have differing interpretations of facts, focus group participants tend to be more measured in their statements. Participants in focus groups are often careful to be more accurate about facts and often signal when their statements are opinions and when they are stating facts. Focus groups, though typically small and nonrandom samples, also offer the researcher a cursory means to assess consensus regarding certain facts or opinions among the participants. The author conducted two focus groups in association with the research conducted to support this dissertation.

Agricultural Stakeholders Focus Group Session

The participants in the first focus group discussion, conducted on August 9, 2016 at the Texas A&M AgriLife Research and Extension Center in Weslaco, Texas, were invited to participate based on previous interviews conducted between May and July of 2016. For this focus group, the author purposely targeted participants considered to be agricultural stakeholders. The selection/invitation process resulted in the participation of a group of ten stakeholders. The participant group was composed of agricultural producers, irrigation district managers and a representative of an agricultural trade organization; all were US citizens operating on the US side of the Lower Rio Grande/Río Bravo watershed. The author contracted with A&M AgriLife Research to facilitate the focus group session. Initially, the author considered including Mexican stakeholders as participants, but ultimately decided to limited participation in the focus group discussion to US stakeholders from fear that inviting Mexican stakeholders would breach protocols established under the LRGWQI TOR.

The agricultural stakeholder focus group session followed four steps. The author gave a short presentation about the project, including information about standard IRB informed consent and confidentiality protocols. Participants were asked to fill out a short survey of water quality preferences and perceptions. The facilitator initiated a discussion lasting approximately 1 hour and 45 minutes in which ten separate topics were discussed in an open-ended format, while the author took notes. To close the focus group discussion, the facilitator thanked the participants.

Public "Water and Wastewater" Stakeholder Focus Group

The participants in the second focus group discussion, conducted on November 2, 2016 at the Offices of Lower Rio Grande Valley Development Council, in Weslaco, Texas, were invited to participate based on previous interviews conducted between May and July of 2016. Unlike the first focus group session, no specific sector or stakeholder group was targeted for the second focus group session. However, the majority of the participants of the focus group were individuals involved in providing or facilitating water and/or wastewater services in the Lower Rio Grande/Río Bravo watershed. In all ten individuals participated in the focus group, including representatives of three local water/sewage utilities (four participants), the local council of governments (three participants), a federal natural resource agency (one participant), a public university (one participant), and a state agricultural services provider (one participant). All participants were US citizens operating on the US side of the Lower Rio Grande/Río Bravo watershed. For this focus group, the author was offered and accepted the facilitation services of the Border Affairs Section of the Texas Commission on Environmental Quality, which also helped arrange the focus group session. Dr. David Eaton of the LBJ School of Public affairs provided funding for the 2 hour and 30-minute session.

The structure of the Public "Water and Wastewater" Focus Group session was similar to that of the previous Agricultural Stakeholder Focus Group session. However, the order of the events was altered slightly. First, the facilitator gave a brief introductory statement about the project and followed standard IRB informed consent and confidentiality protocols. Participants were asked to fill out a short survey of water quality preferences and perceptions. The author gave a short presentation about the project. The facilitator initiated a discussion lasting approximately 1 hour and 45 minutes in which ten separate topics were discussed in an open-ended format, while the author took notes. The facilitator then thanked the participants and closed the discussion.

SURVEYS OF WATER QUALITY PREFERENCES

In addition to the qualitative methods discussed in the previous sections, the LRGWQIPRP used written surveys to investigate the preferences and perceptions of water quality of residents living along the Lower Rio Grande/Río Bravo (Appendix C). For example, the surveys asked questions such as: Do you believe the river is clean enough for swimming, fishing, or boating? How polluted is the Rio Grande/Río Bravo? How important is it that the river be clean? However, the survey also solicited information on what residents thought was being done and should be done to decrease pollution and who, in their opinions, was or should be responsible for leading that process. The premise behind the questions soliciting this information is that residents understand the political and social environment in which their community operates and can not only provide insight into current efforts to protect water quality but can also inform future efforts to develop water quality improvement programs.

While the primary aim of the LRGWQIPRP survey effort was to produce information that could be used by decision-makers to determine water quality management priorities and develop effective transboundary water quality protection strategies, the information gleaned from the survey effort also afforded the potential to investigate and characterize informal institutional arrangements currently in place to manage and protect water quality in the river by identifying commonalities in the answers to open-ended questions such as: Who do you think should be responsible for making sure the Rio Grande is clean? And, how do you get information about water quality in the Rio Grande? The surveys served to augment the previously-described efforts associated with informant interviews and focus group discussions by providing a means by which to focus discussions on existing efforts to protect water quality in the river.

Initial drafts of the survey were tested and refined by the participants of the LRGWQIPRP over a period of four months. The survey was translated into Spanish to accommodate the language preferences of the respondents on both sides of the river and the final twenty-question bilingual survey was printed on a double-sided page, with the English language survey printed on one side and the Spanish version of the survey printed on the opposite side of the page. The water quality survey was administered to three population samples; (1) a pseudo-random sample of residents, (2) a targeted sample of residents, and (3) leaders of organizations involved with water quality management and protection. The geographic areas of survey distribution included Cameron, Hidalgo, Starr, and Willacy counties on the US side of the Lower Rio Grande/Río Bravo watershed and, with the help of CEAT personnel, the Mexican municipios of Guerrero, Mier, Miguel Alemán, Camargo, Gustavo Díaz Ordaz, Reynosa, Río Bravo, Valle Hermoso, and Matamoros on the Mexican side of the watershed, as the residents of these political subdivisions withdraw water from the river for municipal, industrial or agricultural uses, have easy access to the river, or discharge wastewater to the river.

Survey Data Collected from the US Portion of the Rio Grande/Río Bravo Watershed

The LRGWQIPRP Survey Team distributed the survey to the three groups of US stakeholders via mail and in person. These efforts included: (1) site-administered field surveys; (2) surveys mailed to a pseudo-random sample of residents; and (3) surveys mailed to representatives of organizations associated with water quality management or protection of natural resources. Survey respondents were informed, verbally or in writing, that the goal of the survey was to gather information about perceptions of water quality in their area and to understand local attitudes about water quality in the Rio Grande.

In March of 2011, LRGWQIPRP Survey Team members conducted the site-administered survey effort over a 2.5-day period in the Rio Grande Valley of South Texas. A team of four graduate students participating in the LRGWQIPRP traveled to various locations in Cameron and Hidalgo counties to administer the survey to local residents using structured interviews. The team visited five locations in these two counties: (1) Nuestra Clinica del Valle in Pharr Texas; (2) a low-income community (*colonia)* meeting in San Juan, Texas; (3) a farmers' market in Brownsville, Texas, (4) a street market in Harlingen, Texas; and (5) a Red Cross health services event in Harlingen, Texas. At the clinic in Pharr, the research team surveyed patients who were waiting in the main lobby, almost all of whom responded to the Spanish-language survey. Many of the Pharr respondents had lower incomes than participants surveyed later that week. In San Juan, Texas, the team attended a *colonia* self-help meeting at La Union del Pueblo Entero (LUPE). Many of the respondents surveyed were *colonia* residents. In Brownsville, the team surveyed vendors and shoppers at a farmers' market. The farmers' market respondents had attained overall higher levels of education and reported higher incomes than the respondents surveyed in Pharr and San Juan. In Harlingen, Texas, the graduate students surveyed individuals at a street market and a health event organized by the Southern Texas Chapter of the Red Cross. The individuals surveyed in the Harlingen events reported a wide range of education and income levels.

In addition to administering the LRGWQIPRP surveys using structured interviews, the LRGWQIPRP Survey Team conducted a random-sample survey distribution and collection effort. The bilingual survey was mailed to a sample of 1,000 residents of Starr, Willacy, Cameron, and Hidalgo counties, based on a pseudo-random sample generated from the US Postal Service's Delivery Sequence File. The file, which was purchased from a private company (Survey Sampling International [SSI]), covered 95 percent of households in the four-county area. The survey was mailed on March 6, 2012. The response rate of was 8 percent.

On November 6, 2012, 185 surveys were mailed to representatives of US organizations involved in water quality management and/or natural resource protection of which 30 were returned (6.2%). The organizations to which the surveys were mailed included state, county and municipal governments, local utilities, irrigation districts, local academic institutions, and local nonprofit organizations. The LRGWQIPRP Survey Team coded the returned surveys and imported the coded data into the Statistical Packaging for the Social Sciences (SPSS) software for analysis. The results of the LRGWQIPRP US Survey efforts are included in The University of Texas - Lyndon B. Johnson School of Public Affairs PRP Report 117, (UT-LBJ, 2013a).

Survey Data Collected from the Mexican Portion of the Rio Grande/Río Bravo Watershed

In 2013, the LRGWQIPRP continued its survey efforts, collaborating with the Mexican State of Tamaulipas (CEAT), the City of Reynosa's COMAPA, and the Centro de Bachillerato Tecnologico Industrial y de Servicios (part of the public-school system in the Mexican municipio of Reynosa). It should be noted that the author was not involved in the data collection associated with the 2013 LRGWQIPRP survey efforts but was given access to the raw and processed data for use in this dissertation.

In contrast to the surveys administered to US stakeholders in 2011 and 2012, the survey efforts associated with Mexican stakeholders did not include a pseudo-randomized mailing effort. All surveys distributed on the Mexican side of the Lower Rio Grande/Rio Bravo watershed were administered in person at nine separate sites. The surveys were not distributed to representatives of Mexican organizations associated with water quality management or protection of natural resources.

In 2013, during end-of-term parent-teacher conferences (June-July), representatives of the Centro de Bachillerato Tecnologico Industrial y de Servicios (Centro) hand-distributed 1,000 surveys to the parents of high school students attending the Centro's high schools. The surveys were distributed at eight of the Centro's high schools and, of the 1000 surveys distributed, 841 were completed and returned (84.1%).

In January of 2014, representatives of CEAT, agreed to distribute the surveys to Reynosa's COMAPA. The COMAPA made the surveys available to customers at five COMAPA payment centers located in portions of the city adjacent to the river. In all, 275 surveys were completed by Reynosa COMAPA customers. The Mexican survey responses were coded in a similar fashion as the US surveys and then imported into the Software for Statistics and Data Science - STATA for analysis. The results of the LRGWQIPRP Mexican Survey efforts are included in UT-LBJ (2015).

1.0.11.2 Empirical Research Methods and Design

An important part of developing a decision support tool effective in facilitating bilateral decision making associated with water quality management in the Lower Rio Grande/Río Bravo is the development of a binational model of water quality in the river. Binational discussions regarding the software that would be used in LRGWQI water quality modeling effort began in July of 2013, prior to the official Exchange of Letters that initiated the LRGWQI. The water quality model developed for the initiative was parameterized and calibrated using a combination of field and surface water quality data collected during a series of binational synoptic surveys of water quality conducted between July of 2014 and April of 2016 by the LRGWQI's BTWG and with data received from, or downloaded from databases supported by, TWDB, USIBWC, TCEQ, USEPA, CILA and CONAGUA**.** The LRGWQI model of water quality in the Lower Rio Grande/Río Bravo is described in more detail in Sub-section 3.1.1.2 of this dissertation**.**

SYNOPTIC SURVEYS OF WATER QUALITY

The LRGWQI's synoptic surveys were a collaborative binational effort undertaken by the LRGWQI's BTWG primarily to parameterized and calibrate the LRGWQI's LA-QUAL model of water quality. However, the surveys also provided the physical and biochemical data used by IMTA to characterize the Lower Rio Grande/Río Bravo watershed as part of their efforts to develop a draft Declaratoria de Clasificación, which was IMTA's main deliverable to CONAGUA under the two agency's agreement with CONACYT. For their part, the US LRGWQI Partner agencies agreed to collaborate with Mexican LRGWQI Partners to conduct the binational synoptic surveys, primarily to advance efforts to develop a model of water quality for use in the initiative. The TCEQ used CIAP grant funds received from USFWS through the TGLO for this purpose and the USIBWC contributed funding for their collaboration in the binational synoptic surveys from its Texas Clean River's Program.

Planning efforts for the binational synoptic surveys began in March 2014 with binational reconnaissance excursions, conducted by members of the LRGWQI's BTWG to identify potential sampling sites. The BTWG also held binational meetings to agree on the measurement and analysis parameters, compare US and Mexican sampling techniques and analysis methods, and agree on the location of sampling sites that would be included in the final binational synoptic sampling and analysis plan. The BTWG finalized the plan in May 2014. Details of the plan are included in separate quality assurance documents prepared by each country. In addition to the reconnaissance efforts, representatives of each country provided training to survey personnel on field methods and sampling techniques necessary to meet the quality assurance protocols required by CONAGUA and USEPA, respectively. The US LRGWQI Partners also enlisted the help of local US universities (Texas A&M University at Kingsville, The University of Texas Pan American and The University of Texas at Brownsville) to assist with monitoring activities on the US side of the watershed.

The first synoptic survey, conducted July 21-30 of 2014, included only US personnel. A delay in finalizing the financial and working arrangements between IMTA, CONACYT, and CONAGUA prevented IMTA personnel from participating in the 2014 synoptic sampling event. Despite advanced binational planning efforts for the survey, which began in March 2014, the Mexican LRGWQI partners did not notify the US LRGWQI Partners of the internal funding problem until the first week in July. At that point, postponing the synoptic survey presented a serious problem to US participants. Vehicles and equipment had already been leased, laboratories had been placed on standby for receipt of samples, and sampling personnel had been scheduled and assigned. During the second week in July the US LRGWQI US Partners decided to proceed with the synoptic survey, without the participation of Mexican sampling teams. Consequently, the first LRGWQI synoptic survey, conducted in July 2014, did not include sampling sites located on the Mexican side of the Lower Rio Grande/Río Bravo watershed.

Figure 1-46 shows the location of sampling sites included in the July 2014 LRGWQI synoptic survey, which included 16 sites located on the main stem of the Lower Rio Grande/Río Bravo, 1 US tributary (Arroyo Los Olmos) and the outfalls of 10 wastewater treatment facilities located on the US side. Although there are only 10 US outfalls to the Rio Grande/Río Bravo, an additional monitoring site was added to the July 2014 synoptic survey downstream of the Union WSC wastewater treatment facility to gage attenuation of pollutants in the outfall ditch.

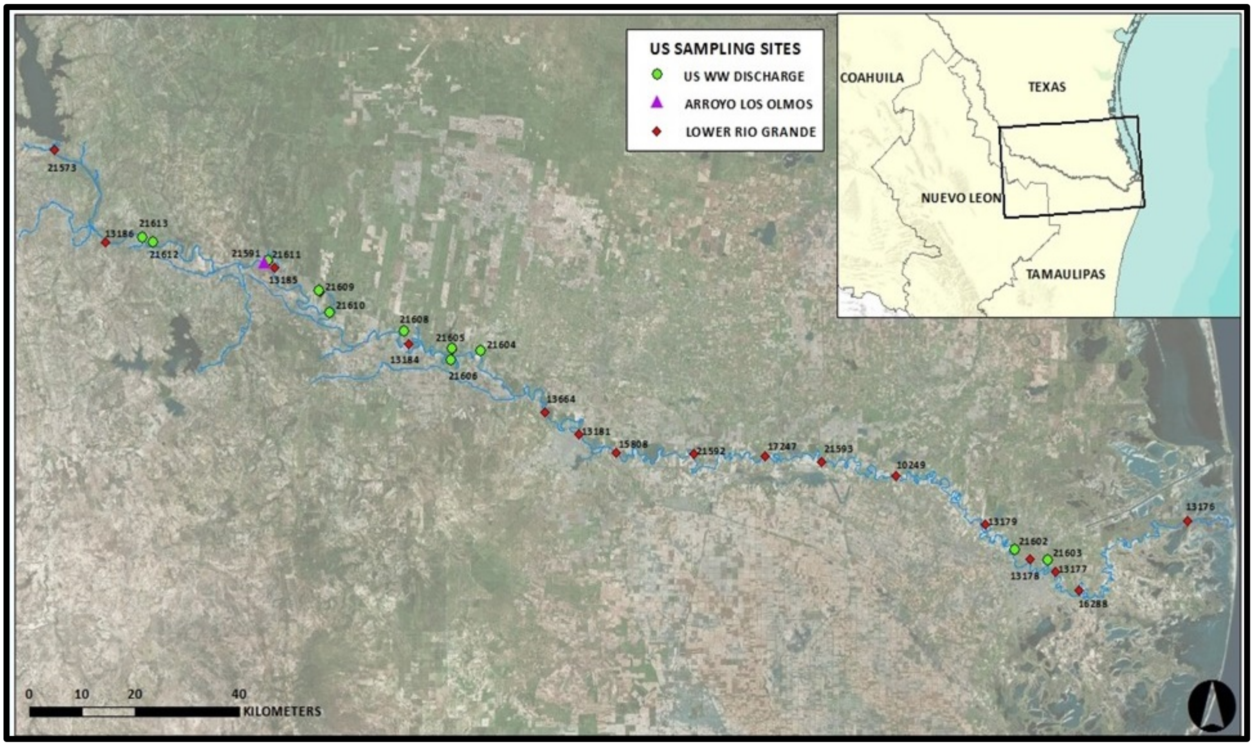

Figure 1-46. Type and Location of Sampling Sites; July 2014 Synoptic Survey.

Table 1-21 shows the 9 field parameters measured by US monitoring personnel and Table 1-22 shows the 16 laboratory analyses conducted on the water samples collected by US monitoring personnel during the July 2014 synoptic survey; 2 parameters, Total Nitrogen and Total Organic Nitrogen are calculated from other analyses included in Table 1-22. The US LRGWQI Partners, TCEQ and USIBWC, contracted with A&B Laboratories, Inc., a private NELAP-accredited laboratory, to conduct the laboratory analyses shown in Table 1-22. In addition to instantaneous field measurements, US monitoring personnel conducted measurements of water temperature, specific conductivity, dissolved oxygen, and pH every 15 minutes over a 24-hour period at all 16 main stem sites in the Lower Rio Grande/Río Bravo to investigate levels of eutrophication in the river. US sampling personnel conducted vertical profiles of these 4 parameters at 18 additional sampling sites located in the tidally-influenced portion of the Lower Rio Grande/Río Bravo to characterize the behavior of the tidal wedge in the river.

Table 1-21. Field Parameters Measured during the July 2014 Synoptic Survey

Parameter	Units	Matrix	Method
Air Temperature	°C	Air	TCEQ SOP, V1
Water Temperature	°C	water	SM 2550 B and TCEQ SOP, V1
Specific Conductance, Field	µS/cm	water	EPA 120.1 and TCEQ SOP, V1
DO[1]	mg/L	water	SM 4500-O G and TCEQ SOP, V1
pH	Standard Units	water	EPA 150.1 and TCEQ SOP, V1
Salinity	ppt, marine only	water	SM 2520 and TCEQ SOP V1
Transparency, Secchi depth	meters	water	TCEQ SOP, V1
Flow Stream, Instantaneous[2]	cfs	water	TCEQ SOP, V1
Floating Debris/Scum Percent Cover	%	NA	NA

[1]Dissolved Oxygen

[2]Stream velocity and flow measurements only collected on tributaries, drains, and wastewater outfalls. IBWC flow gage measurements used for (6) main stem sites

Table 1-22. Laboratory Analyses Conducted on Water Samples Collected by US Sampling Personnel During the July 2014 LRGWQI Synoptic Survey

Parameter	Units	Matrix	Method	Lab
Total Ammonia as Nitrogen	mg/L	water	SM4500-NH_3D low level	A&B
Total Chloride	mg/L	water	EPA 300.0	A&B
Chlorophyll *a* - Spectrophotometric Acid Method	µg/L	water	SM 10200-H	A&B
E. coli	MPN/100 mL	water	SM 9223-B	A&B
Enterococcus	MPN/100 mL	water	ASTM D-6503	A&B
Fecal Coliform	cfu/100 mL	water	SM 9222-D	A&B
Total Kjeldahl Nitrogen	mg/L	water	EPA 351.4	A&B
Total Nitrite Plus Nitrate as Nitrogen	mg/L	water	EPA 353.3	A&B
Total Organic Nitrogen (Calculated)	mg/L	water	EPA 351.4 - SM4500-NH_3D low level	A&B
Total Nitrogen (Calculated)	mg/L	water	EPA 351.4 + EPA 353.3 - SM4500-NH_3D low level	A&B
Total Sulfate	mg/L	water	EPA 300.0	A&B
Total Phosphorous, Wet Method	mg/L	water	EPA 365.2	A&B
Total Suspended Solids (Total Residue - nonfilterable)	mg/L	water	SM 2540 D	A&B
Volatile Suspended Solids (Total Residue-volatile - nonfilterable)	mg/L	water	EPA 160.4	A&B
Carbonaceous Biochemical Oxygen Demand 5-day, Nitrogen Suppressed ($CBOD_5$)	mg/L	water	SM 5210-B	A&B
Carbonaceous Biochemical Oxygen Demand 5- day, Nitrogen Suppressed, Dissolved	mg/L	water	SM 5210-B	A&B
Orthophosphate Phosphorus (field filtered <15 microns)	mg/L	water	EPA 300.0	A&B
Total Dissolved Solids (Total Residue - filterable)	mg/L	water	SM 2540 C	A&B

Following the signing of the final financial and working agreements between IMTA CONACYT and CONAGUA, in October 2014, the Mexican LRGWQI Partners requested to revise the sampling plan for the binational LRGWQI synoptic surveys developed jointly by the LRGWQI's BTWG in June 2014. Specifically, the Mexican LRGWQI Partners requested changes to the location of 8 of the 16 main stem monitoring sites specified in the plan and sampled by US personnel in July 2014. The Mexican LRGWQI Partners also requested the elimination of one sampling site included in the July synoptic survey, reducing the total number of main stem monitoring sites to 15. The Mexican LRGWQI Partners offered Mexican monitoring teams to conduct all water quality monitoring on the main stem of the river (15 sites) in addition to monitoring all Mexican tributary and wastewater outfall sites (8 sites and 11 sites, respectively). The US LRGWQI Partners accepted the Mexican LRGWQI Partners' proposed changes to the sampling plan, as well as the offer to conduct the monitoring of all main stem sites, as long as US monitoring personnel were allowed to participate in, or at least observe, the monitoring activities on the main stem of the river. The Mexican Partners agreed to this stipulation and also invited US monitoring personnel to participate in the monitoring conducted at all Mexican monitoring sites, including tributary and wastewater outfall sampling sites located in Mexico. The US LRGWQI Partners accepted these terms and reciprocated, extended an offer to have Mexican personnel participate in monitoring activities conducted on the US side of the watershed, which included one US tributary site and 9 US wastewater outfall sites (by consensus, the BTWG agreed to drop the BPUB Silas Ray power plant outfall site due to its infrequent discharge and the high quality of its effluent).

In February 2015, IMTA developed a final quality assurance document detailing the Mexican monitoring activities agreed to by all members of the BTWG. With the agreement of the US LRGWQI Partners, the author revised the Quality Assurance Project Plan developed written for the July 2014 LRGWQI synoptic survey to incorporate the changes to the sampling plan agreed to by the BTWG. Following revision of the sampling plan, the LRGWQI's BTWG conducted binational synoptic surveys in March, August, and November of 2015, and in April of 2016. Figure 1-47 shows the location of sampling sites included in the binational surveys, which included 15 sites on the main stem of the Lower Rio Grande/Río Bravo, 8 Mexican tributary sites, 6 Mexican wastewater treatment facility outfall sites, and 3 untreated wastewater outfall sites, 2 additional suspected untreated wastewater outfalls and 2 drinking water intakes on the Mexican side of the river.

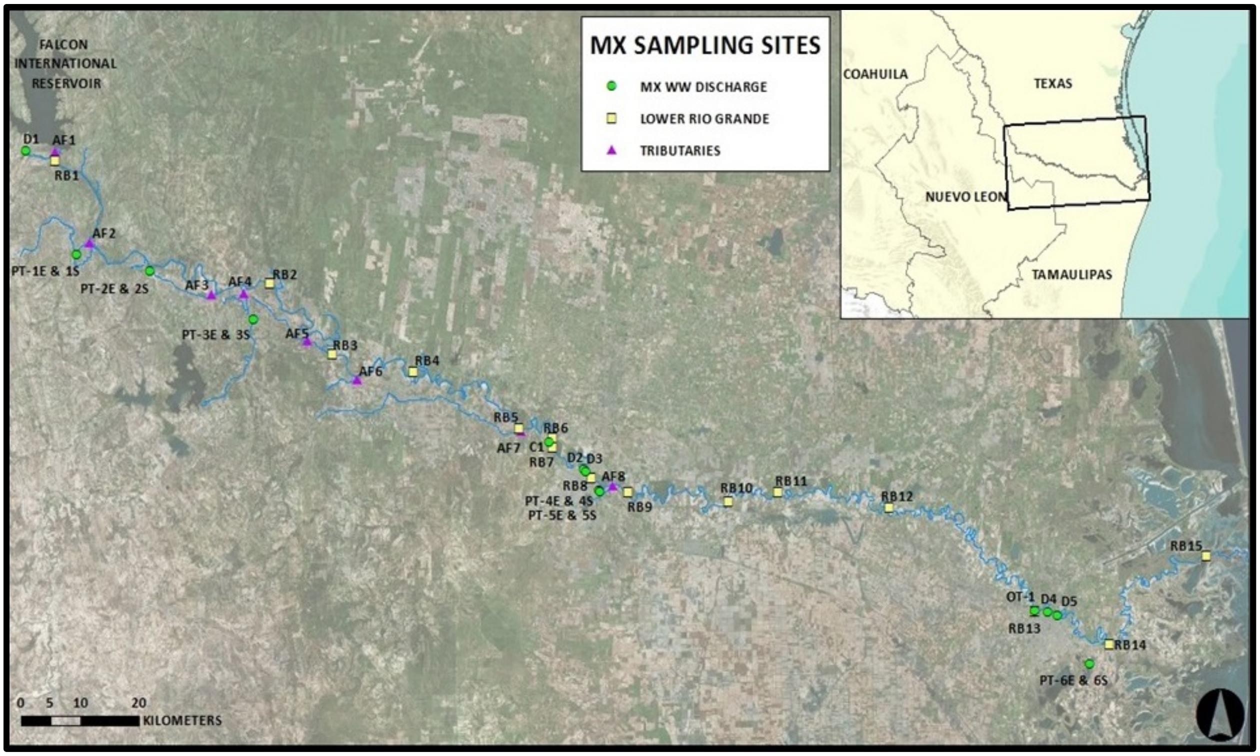

Figure 1-47. Type and Location of Mexican Sampling Sites; Synoptic Surveys Conducted March 2015 – April 2016.

Table 1-23 shows the 10 field parameters measured by Mexican monitoring personnel at main stem, Mexican tributary and Mexican outfall sites (dissolved oxygen saturation was calculated from measurements of temperature and dissolved oxygen). Table 1-24 shows the laboratory analyses conducted on water samples collected by Mexican monitoring personnel.

Table 1-23. Field Parameters Measured by Mexican Monitoring Personnel during LRGWQI Synoptic Surveys Conducted in 2015 and 2016

Parameter	Units	Matrix	Method
Air Temperature	°C	NA[1]	NMX AA-007-SCFI-2013
Water Temperature	°C	water	NMX AA-007-SCFI-2013
Specific Conductance, Field	µS/cm	water	NMX AA-093-SCFI-2000
DO[2]	mg/L	water	NMX AA-012-SCFI-2001
DO (Calculated)	% Sat.	water	NMX AA-012-SCFI-2001
pH	Standard Units	water	NMX AA-008-SCFI-2011
Flow Stream, Instantaneous[3]	cfs	water	Molinete (Sección - Velocidad)[4]
Chlorine Residual	mg/L	water	NMX-AA-108-SCFI-2001
Floating Material	NA	NA	NMX AA-006-SCFI-2010
Redox Potential	Eh (mV)	water	SM 2580B

[1]Not Applicable
[2]Dissolved Oxygen
[3]Stream velocity and flow measurements only collected on tributaries, drains, and wastewater outfalls. IBWC gage measurements were used for (6) main stem sites
[4]Equivalent to TCEQ SOP, V1

Table 1-24. Laboratory Analyses Conducted on Water Samples Collected by Mexican Monitoring Personnel During LRGWQI Synoptic Surveys Conducted in 2015 and 2016

Parameter	Units	Matrix	Method	Lab
Total Ammonia as Nitrogen	mg/L	water	NMX AA-026-SCFI-2010	IMTA/A&B
Total Chloride	mg/L	water	NMX AA-073-SCFI-2001	IMTA
E. coli	MPN/100 mL	water	SM 9223-B	UANL
Fecal Coliform	MPN/100 mL	water	NMX AA-042-1987	UANL
Total Coliforms	MPN/100 mL	water	NMX AA-042-1987	UANL/A&B
Total Kjeldahl Nitrogen	mg/L	water	NMX AA-026-SCFI-2010	IMTA
Total Nitrite Plus Nitrate as Nitrogen (Calculated)	mg/L	water	NMX-AA-099-SCFI-2006+ NMX-AA-079-SCFI-2001	IMTA
Total Nitrite as Nitrogen	mg/L	water	NMX-AA-079-SCFI-2001	IMTA/A&B
Total Nitrate as Nitrogen	mg/L	water	NMX-AA-099-SCFI-2006	IMTA/A&B
Organic Nitrogen	mg/L	water	NMX AA-026-SCFI-2010	IMTA
Soluble Organic Nitrogen	mg/L	water	NMX AA-026-SCFI-2010	IMTA
Total Nitrogen	mg/L	water	NMX AA-026-SCFI-2010	IMTA
Total Sulfate	mg/L	water	NMX AA-074-1981	IMTA
Total Phosphorous	mg/L	water	NMX-AA-029-SCFI-2001	IMTA
Total Inorganic Phosphorus	mg/L	water	NMX-AA-029-SCFI-2001	IMTA
Dissolved Inorganic Phosphorus	mg/L	water	NMX-AA-029-SCFI-2001	IMTA
Total Phosphate as Phosphorus (Calculated)	mg/L	water	Calculated from NMX-AA-029-SCFI-2001	IMTA
Total Reactive Phosphorus (Orthophosphate)	mg/L	water	NMX-AA-029-SCFI-2001	IMTA
Dissolved Orthophosphate Phosphorus	mg/L	water	NMX-AA-029-SCFI-2001/ EPA 365.1-1984	IMTA
Total Organic Phosphorus	mg/L	water	NMX-AA-029-SCFI-2001	IMTA
Total Suspended Solids (Total Residue – nonfilterable)	mg/L	water	NMX AA-034-SCFI-2001	IMTA
Carbonaceous Biochemical Oxygen Demand 5-day, Nitrogen Suppressed ($CBOD_5$)	mg/L	water	NMX-AA-028-SCFI-2001	IMTA
Carbonaceous Biochemical Oxygen Demand 5-day, Nitrogen Suppressed ($CBOD_5$) Dissolved	mg/L	water	NMX-AA-028-SCFI-2001	IMTA
Total Dissolved Solids (Calculated from Specific Conductance values)	mg/L	water	NMX AA-034-SCFI-2001 (Calculated from NMX AA-093-SCFI-2000)	IMTA
True Color	U (Pt/Co scale)	water	NMX AA-045-SCFI-2001	IMTA/A&B

Table 1-24. Laboratory Analyses Conducted on Water Samples Collected by Mexican Monitoring Personnel During LRGWQI Synoptic Surveys Conducted in 2015 and 2016 (Continued)

Parameter	Units	Matrix	Method	Lab
Turbidity	NTU	water	NMX AA-038-SCFI-2001	IMTA
Total Sediments	ml/L	water	NMX AA-004-SCFI-2000	IMTA/A&B
Total Solids	mg/L	water	NMX AA-034-SCFI-2001	IMTA/A&B
Phenothalein Alkalinity	mg/L as $CaCO_3$	water	NMX AA-036-SCFI-2001	IMTA
Total Alkalinity	mg/L as $CaCO_3$	water	NMX AA-036-SCFI-2001	IMTA/A&B
Total Bicarbonates	mg/L as $CaCO_3$	water	NMX AA-036-SCFI-2001	IMTA/A&B
Total Carbonate	mg/L	water	NMX AA-036-SCFI-2001	IMTA/A&B
Total Cyanide	mg/L	water	NMX AA-058-SCFI-2001	IMTA/A&B
Total Hardness	mg/L as $CaCO_3$	water	NMX AA-072-SCFI-2001	IMTA/A&B
Total Fluoride	mg/L	water	NMX AA-077-SCFI-2001	IMTA/A&B
Total Sulfides	mg/L	water	NMX AA-084-1982	IMTA/A&B
Chemical Oxygen Demand	mg/L	water	NMX-AA-030-SCFI-2001	IMTA/A&B
Total Organic Carbon	mg/L	water	IMTA-CAQAO6-14	IMTA/A&B
Methylene Blue Active Substances (Surfactants)	mg/L	water	NMX-AA-039-SCFI-2001	IMTA
Total Phenols	mg/L	water	NMX-AA-050-SCFI-2001	IMTA
Toxicity - Daphnia magna	EC50	water	NMX AA-087-SCFI-2010	IMTA
Toxicity Daphnia magna	UT	water	NMX AA-087-SCFI-2010	IMTA
Toxicity Vibrio fischeri	EC50	water	NMX-AA-112-1995-SCFI	IMTA
Toxicity Vibrio fischeri	UT	water	NMX-AA-112-1995-SCFI	IMTA
Total Arsenic	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Total Boron	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Total Cadmium	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Total Calcium	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B

Table 1-24. Laboratory Analyses Conducted on Water Samples Collected by Mexican Monitoring Personnel During LRGWQI Synoptic Surveys Conducted in 2015 and 2016 (Continued)

Parameter	Units	Matrix	Method	Lab
Total Copper	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Total Chromium	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Total Hexavalent Chromium	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Total Magnesium	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Total Mecury	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Total Nickel	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Total Lead	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Total Sodium	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Total Zinc	mg/L	water	NMX AA-051-SCFI-2001	IMTA/A&B
Atrazine	µg/L	water	EPA 8270	IMTA
Alachlor	µg/L	water	EPA 8081A	IMTA
Cyanazine	µg/L	water	EPA 8081A	IMTA
Deltramethrin	µg/L	water	EPA 8081A	IMTA
Endrin Aldahyde	µg/L	water	EPA8081A	IMTA/A&B
Metolachlor	µg/L	water	EPA 8081A	IMTA
Methoxychlor	µg/L	water	EPA 8081A	IMTA/A&B
Mirex	µg/L	water	EPA 8081A	IMTA/A&B
Pendimethalin, dissolved	µg/L	water	EPA 8081A	IMTA
Simazine	µg/L	water	EPA 8081A	IMTA
Toxaphene	µg/L	water	EPA 8081A	IMTA/A&B
Terbuthylazine	µg/L	water	EPA 8081A	IMTA
Trifluralin (Treflan), filtered	µg/L	water	EPA 8081A	IMTA
Ϭ-Hexachlorocyclohexane (BHC)	µg/L	water	EPA 8081A	IMTA/A&B
Bolstar	µg/L	water	EPA 8141B	IMTA

Table 1-24. Laboratory Analyses Conducted on Water Samples Collected by Mexican Monitoring Personnel During LRGWQI Synoptic Surveys Conducted in 2015 and 2016 (Continued)

Parameter	Units	Matrix	Method	Lab
Bromacil	µg/L	water	EPA 8141B	IMTA
Coumaphos	µg/L	water	EPA 8141B	IMTA
Chlorpyriphos	µg/L	water	EPA 8141B	IMTA/A&B
Diclorvos	µg/L	water	EPA 8141B	IMTA
EPN	µg/L	water	EPA 8141B	IMTA/A&B
Endosulfan Sulfate	µg/L	water	EPA 8141B	IMTA/A&B
Ethoprop	µg/L	water	EPA 8141B	IMTA/A&B
Fenitrothion	µg/L	water	EPA 8141B	IMTA
Fensulfothion	µg/L	water	EPA 8141B	IMTA
Fenthion	µg/L	water	EPA 8141B	IMTA
Forato	µg/L	water	EPA 8141B	IMTA
Imetoato	µg/L	water	EPA 8141B	IMTA
Merphos	µg/L	water	EPA 8141B	IMTA
Metilazinfos	µg/L	water	EPA 8141B	IMTA
Metribuzin	µg/L	water	EPA 8141B	IMTA
Mevinphos	µg/L	water	EPA 8141B	IMTA
Molinate, dissolved	µg/L	water	EPA 8141B	IMTA
Parathion	µg/L	water	EPA 8141B	IMTA/A&B
Phorate	µg/L	water	EPA 8141B	IMTA/A&B
Pyriproxyfen	µg/L	water	EPA 8141B	IMTA
Ronnel	µg/L	water	EPA 8141B	IMTA
Sulfotepp	µg/L	water	EPA 8141B	IMTA
Terbufos	µg/L	water	EPA 8141B	IMTA/A&B
Tokuthion	µg/L	water	EPA 8141B	IMTA

Table 1-24. Laboratory Analyses Conducted on Water Samples Collected by Mexican Monitoring Personnel During LRGWQI Synoptic Surveys Conducted in 2015 and 2016 (Continued)

Parameter	Units	Matrix	Method	Lab
Triallate, dissolved	μg/L	water	EPA 8141B	IMTA
Trichloronate	μg/L	water	EPA 8141B	IMTA
Triclorfon	μg/L	water	EPA 8141B	IMTA
Trialato	**μg/L**	water	EPA 8141B	IMTA

Figure 1-48 shows the LRGWQI synoptic survey sites monitored by US monitoring personnel in 2015 and 2016; they include one tributary site (Arroyo Los Olmos) and 10 wastewater treatment plant outfall sites. During the 2015-2016 binational LRGWQI synoptic surveys, two sampling sites were used to characterize the outfalls of the wastewater treatment facilities outfalls of the La Joya ISD and Union WSC facilities because of their distance from the river.

Figure 1-48. Type and Location of US Sampling Sites; LRGWQI Synoptic Surveys Conducted March 2015 – April 2016.

Except for the measurement of Chlorine Residual, which US monitoring personnel agreed to measure at the request of the Mexican LRGWQI Partners, the field parameters measured, and sampling techniques used, by US monitoring personnel during the 2015 and 2016 binational LRGWQI synoptic surveys were the same as those measured during the July 2014 LRGWQI US synoptic survey (Table 1-23). Mexican monitoring personnel accompanying the US monitoring teams measured Redox Potential in the field at US sites. In addition to the parameters analyzed during the 2014 synoptic surveys (Table 1-22), US monitoring teams collected water samples for the additional nutrient, anion, metals, pesticides and other laboratory analyses requested by the Mexican LRGWQI Partners in 2015. The US Partners agreed to perform these analyses on samples collected at US sites (shaded rows in Table 1-24). Mexican monitoring personnel accompanying US monitoring teams collected additional water samples at US sites for analysis of other parameters of interest to the Mexican LRGWQI Partners (i.e., parameters in unshaded rows in Table 1-24 which are not included in Table 1-22). Sub-section 3.1.1.2 of this dissertation describes in detail how the data collected during the LRGWQI synoptic surveys were used to parameterize and calibrate the LRGWQI models of water quality in the Lower Rio Grande/Río Bravo.

Compilation and Processing of In-stream Flow, flow contributions, flow Diversions and Meteorological Data

In addition to the physical, biochemical and bacteriological data collected during the synoptic surveys of water quality conducted in 2014, 2015 and 2016 the author and his collaborators used meteorological, instream flow, flow diversions, and self-reported effluent data measured and reported or provided by TWDB, TCEQ, USEPA, USIBWC, CILA and CONAGUA. Regional pan evaporation data were supplied by CILA (for locations in Mexico). Pan evaporation were also downloaded from the TWDB's web site https://waterdatafortexas.org (for US locations). Time series of average daily in-stream flow, measured by the IBWC, at nine hydrometric stations located on the Lower Rio Grande/Río Bravo and two major tributaries, the Río Alamo and the Río San Juan were supplied to the BTWG by USIBWC. Daily average flow, by month, measured by CILA at six major agricultural drains that contribute flow to the Lower Rio Grande/Río Bravo were supplied to the BTWG by CILA. Time series of monthly flow diversions (i.e., authorized withdrawals of water from the river for municipal and agricultural purposes) were supplied by the TCEQ (Rio Grande Water Master program), USIBWC, CILA and

CONAGUA. Daily average effluent discharge data, by month, reported by US wastewater treatment facilities were downloaded from USEPA's ICIS database. Sub-section 3.1.1.2 of this dissertation describes in detail how these data were used to parameterize and calibrate the LRGWQI models of water quality.

Characterization of Steady state Nonpoint Sources of Pollutants

A model is most useful to decision makers when it incorporates as many aspects of the decision domain and the decision situation as is possible. The LRGWQI's focus on water quality in the Lower Rio Grande/Río Bravo dictates that the tools developed to support the initiative's decision-making process be designed to address the sources of water quality impairment in the river in a comprehensive manner. In addition to providing important empirical information for parameterizing and calibrating the LRGWQI water quality model, the synoptic data and historical data described in previous sections of this chapter, along with the inherent capabilities of the LA-QUAL model, allow the user to simulate quantitative changes in pollutant loadings associated with point sources in the watershed. However, these data provide only limited information about the steady state nonpoint sources of pollution affecting water quality in the river. In order to construct a decision support tool that simulates the effects of steady state nonpoint sources on water quality in the river, additional information should be incorporated into a model. Any model, or the decision support tool of which it is a part, must have the capability of simulating changes in nonpoint sources of pollution.

To characterize steady state nonpoint sources in the Lower Rio Grande/Río Bravo watershed the author used a modified version of the geospatial analysis method developed by Lynch (2012). The information presented in the following sections details the geospatial analysis methods used by the author and his collaborators to characterize and quantify the steady state nonpoint sources of pollutants addressed by the LRGWQI. For all steady state pollutant nonpoint source types investigated as part of the LRGWQI, the author and his collaborators applied the geospatial methods described in this section to the area within the LRGWQI watershed. The LRGWQI watershed was derived from a synthesis of the transboundary watersheds of the Rio Grande/Río Bravo developed by the USGS, SEMARNAT and INEGI. Development of the LRGWQI watershed is described in more detail in the following section.

Dividing the LRGWQI watershed into smaller sub-basins was necessary to allow users to vary the input of steady state nonpoint sources of pollutants. Each sub-basin corresponds to the model reach to which it contributes steady state nonpoint source pollutant loading. The creation of model sub-basins is described in more detail in the following sections. It should be noted that the GIS work involved with the creation of the LRGWQI sub-watersheds was performed by Adam Torres of the TCEQ. The author adapted the methods for creating the model sub-watersheds from established GIS techniques involving the manipulation of digital elevation raster grids (Environmental Science Institute [ESRI], Technical Article 000012346, 2013).

Binational Watershed Delineation

One of the first technical tasks undertaken by the LRGWQI's BTWG was the delineation of the transboundary watershed for Lower Rio Grande/Río Bravo. This task was important for defining of the geographic limits of the LRGWQI study for project management and administrative reasons. The geospatial analyses also allowed the author to quantify steady state pollutant loadings for input and calibration of the LRGWQI water quality models.

Creating a Harmonized Binational Watershed

The watershed for the Lower Rio Grande / Río Bravo represents the land area that drains into the river. The watershed encompasses some 924,300 km^2 and includes areas in 3 US states and 4 Mexican states. Using digital elevation models (DEMs) that cover most of North America at a scale of 1:24,000, the USGS, under its National Hydrographic Dataset (NHD) Program, has delineated the watersheds of US surface water bodies, including the Rio Grande/Río Bravo. The USGS designates Hydrologic Unit Codes (HUCs) for the watersheds it delineates at different levels of detail. Watershed delineations become better defined and smaller in size as HUC levels increase with stream order. At the coarsest, basin wide level, the USGS assigns HUCs with only six-digit numbers (HUC Level 6); at the sub-basin level, the HUCs are eight digits (HUC Level 8). Figure 1-49 and Figure 1-50 shows the Lower Rio Grande/Río Bravo watershed at resolutions of HUC Level 6 and HUC Level 8, respectively. At these resolutions, the transboundary watersheds for the Lower Rio Grande/Río Bravo are available from the USGS. The effort to define the Lower Rio Grande/Río Bravo watershed for the LRGWQI began with the aggregation of HUC Level 12 (catchment level) watersheds on the US side, downloaded from the USGS' NHD website (Figure 1-51).

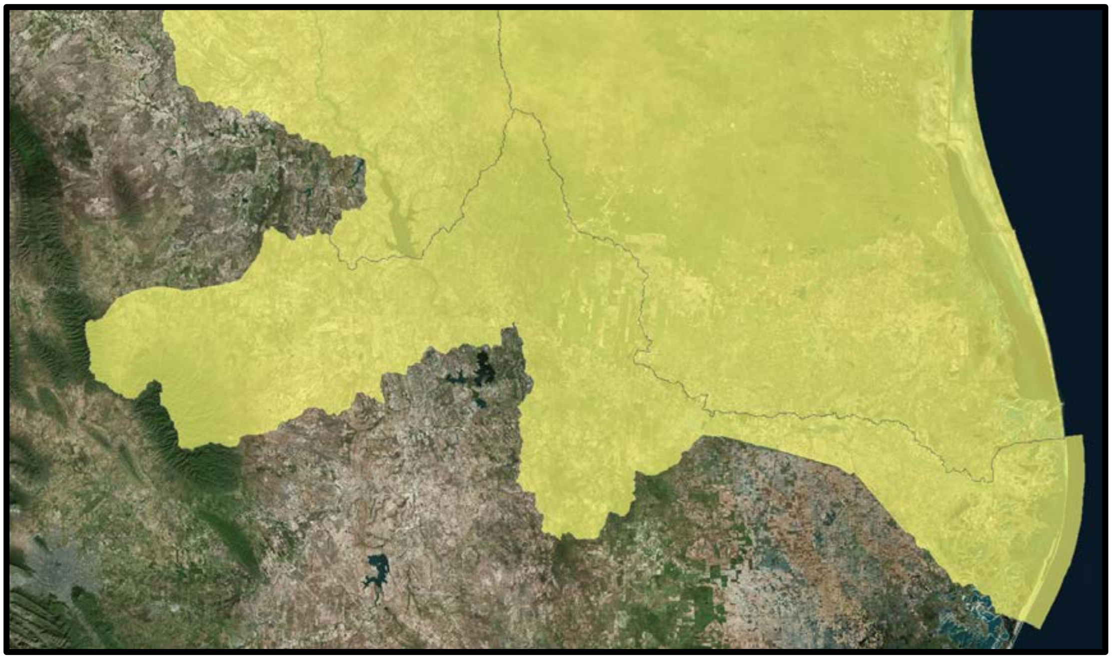

Figure 1-49. Lower Rio Grande/Río Bravo Watershed, NHD Hydrologic Unit Code Level 6.

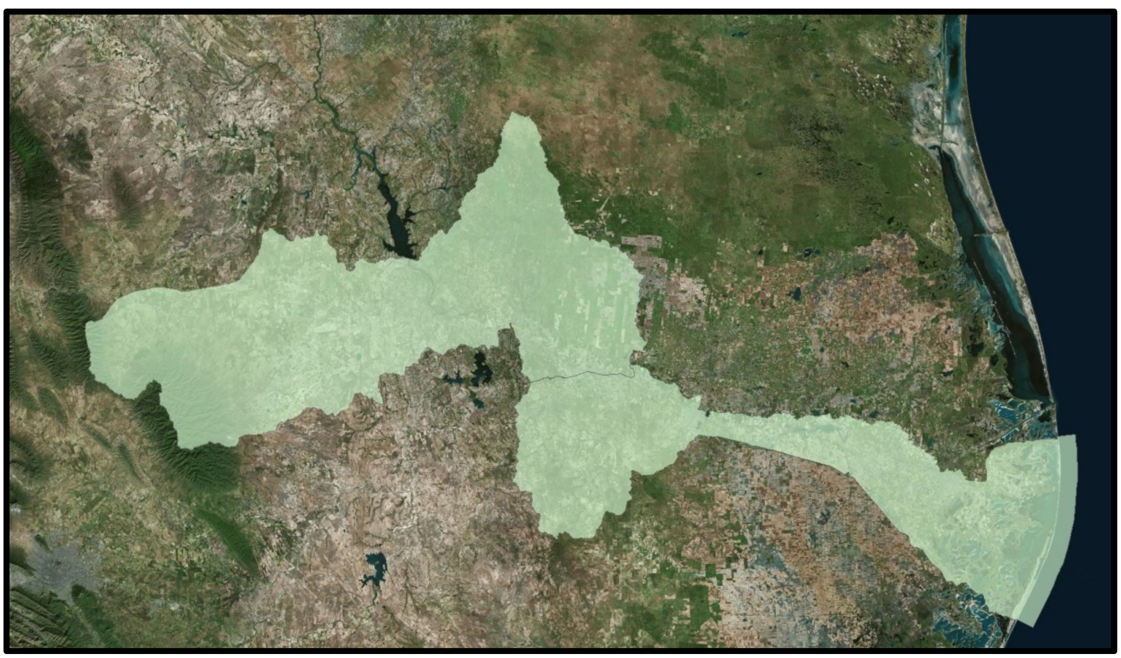

Figure 1-50. Lower Rio Grande/Río Bravo Watershed, NHD Hydrologic Unit Code Level 8.

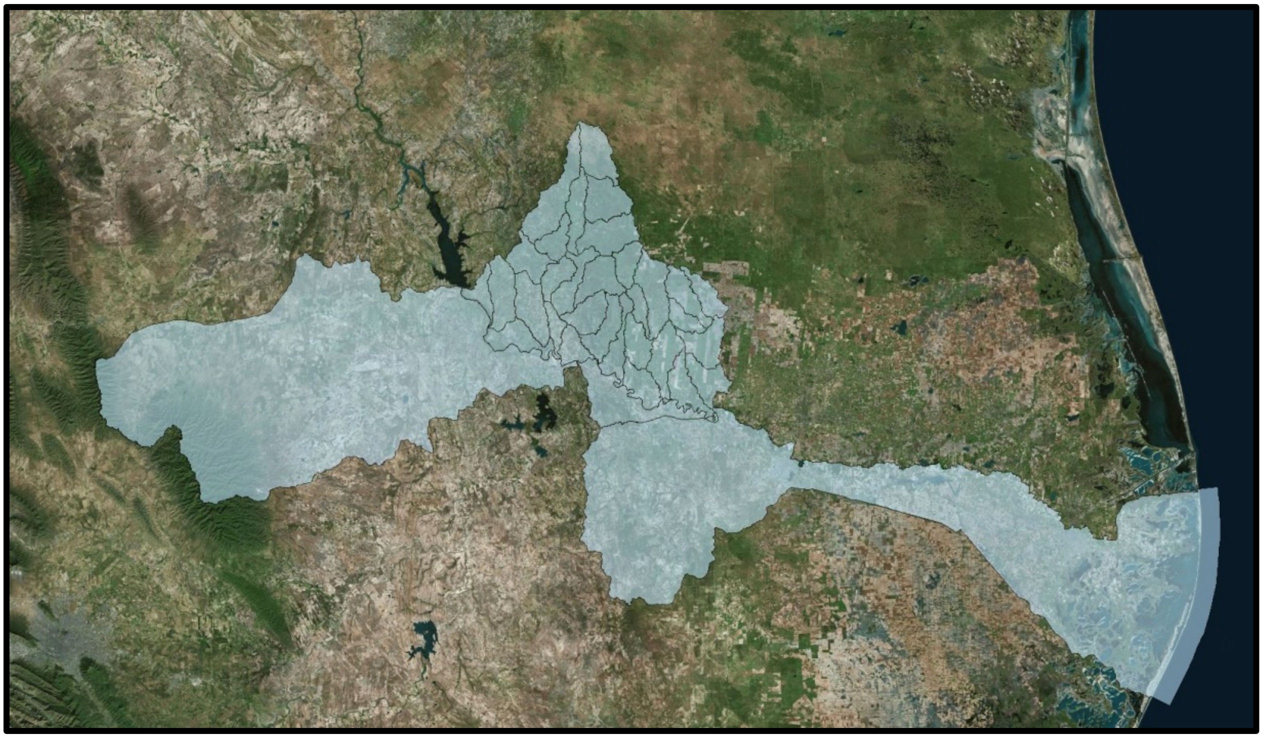

Figure 1-51. Lower Rio Grande/Río Bravo Watershed, NHD Hydrologic Unit Code Levels 12 (US side) and 8 (Mexican side).

Like the USGS, Mexico's federal environmental agency, SEMARNAT has delineated watersheds for surface water bodies in Mexico using 1:250,000 scale DEMs. Figure 1-52 shows the southernmost portion of the watershed delineated by SEMARNAT for the Rio Grande/ Río Bravo (INEGI, 2007). The initial outline of the Mexican portion of the Lower Rio Grande/Río Bravo watershed was a synthesis of USGS HUC Level 8 boundaries and SEMARNAT's 1:250,000 Cuenca Hidrográfica Río Bravo boundary (Figure 1-53). The international boundary downloaded from the USGS' BEHI website was used to provide a common boundary for the US and Mexico watersheds.

During binational deliberations in 2013, the BTWG agreed to limit the LRGWQI watershed by excluding the area of the watershed upstream of Marté Gómez dam on the Río San Juan, which is already excluded from the NHD HUC Level 12 watershed, and upstream of Las Blancas dam on the Río Álamo. Also, given the disparities in the shape of the NHD (HUC Level 8) and SEAMARNAT (1:250,000) watersheds, the BTWG also decided to re-examine the

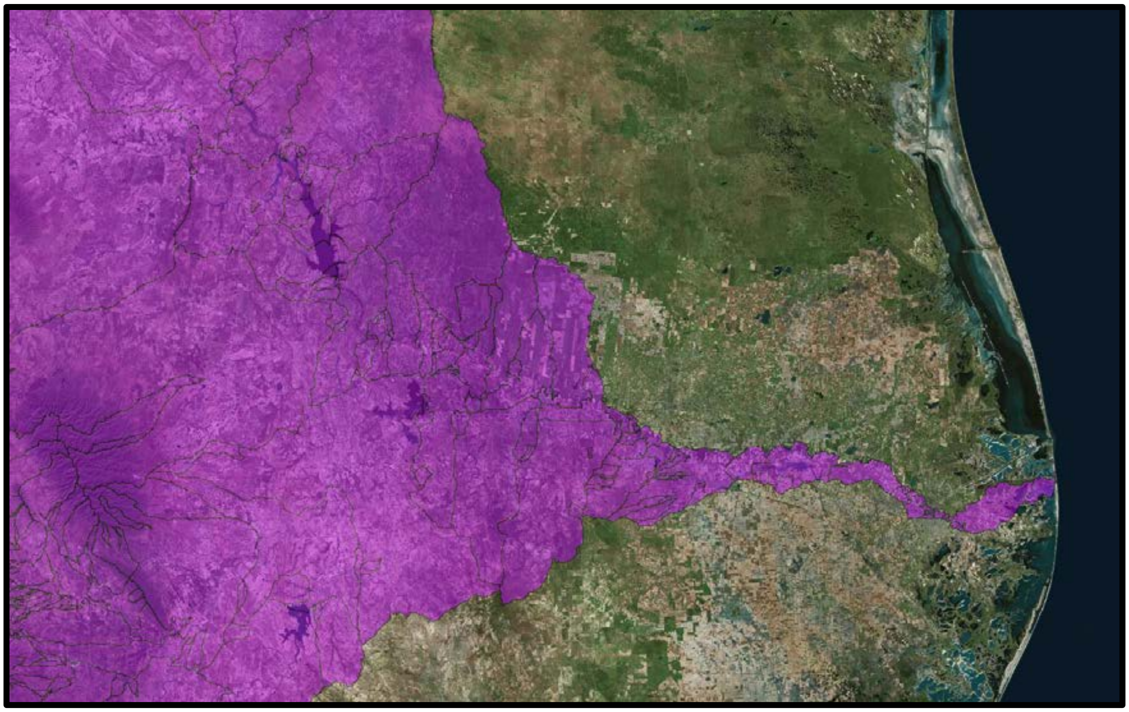

Figure 1-52. Lower Rio Grande/Río Bravo Watershed Delineated by SEMARNAT (1:250,000). Source: INEGI 2007.

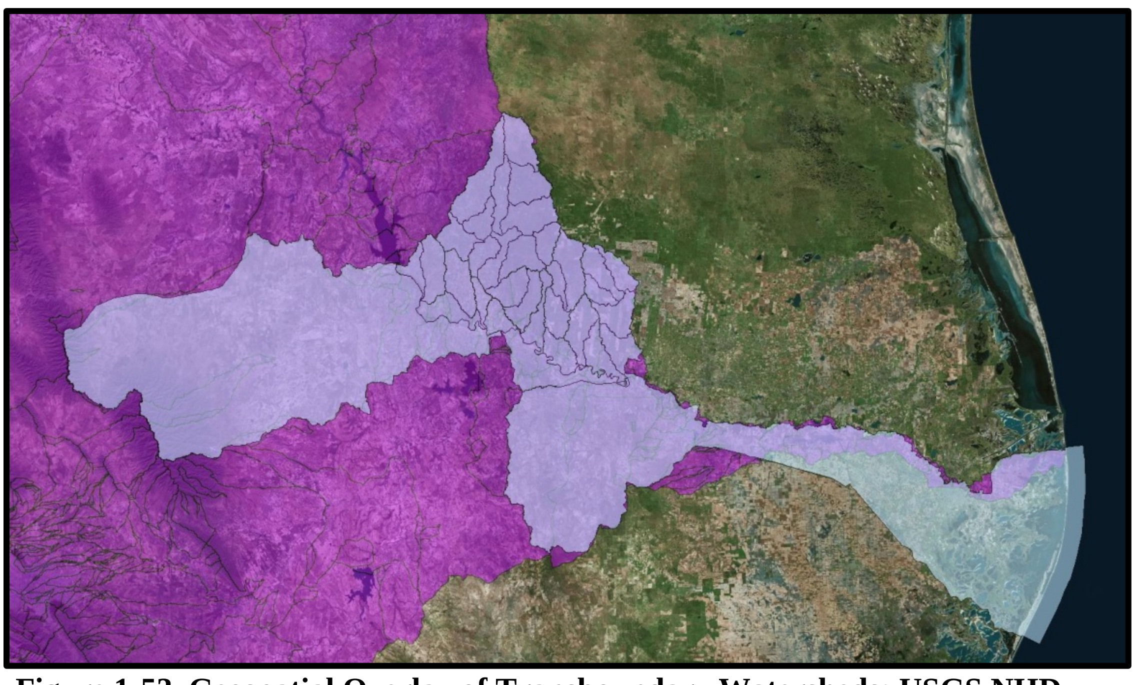

Figure 1-53. Geospatial Overlay of Transboundary Watersheds; USGS NHD HUC Levels 8 and 12 and SEMARNAT's 1:250,000 Cuenca Hidrográfica Río Bravo.

hydrography of the coastal plain in the southeastern portion of the watershed. To verify or modify the southeastern portion of the watershed, the LRGWQI Mexican Partners suggested using INEGI's Simulador de Flujos de Agua de Cuencas Hidrograficas (SAITL), a flow direction model developed by INEGI for use in drainage area analyses (INEGI, 2015). Using a LiDAR-based DEM provided by the USIBWC (Figure 1-54), the SAITL model (Figure 1-55), and the watershed delineation methods described in ESRI Technical Article 000012346 (ESRI, 2003), the TCEQ modified the Mexican portion of the synthesized watershed. The TCEQ used the ArcGIS 10.1 software with the Spatial Analyst extension, both from ESRI, to synthesize and revise the binational watershed. Figure 1-56 shows the watershed resulting from the synthesis of the USGS NHD and SEMARNAT watersheds and the modifications requested by the BTWG. The watershed shown in Figure 1-56 is the final transboundary watershed used for the LRGWQI.

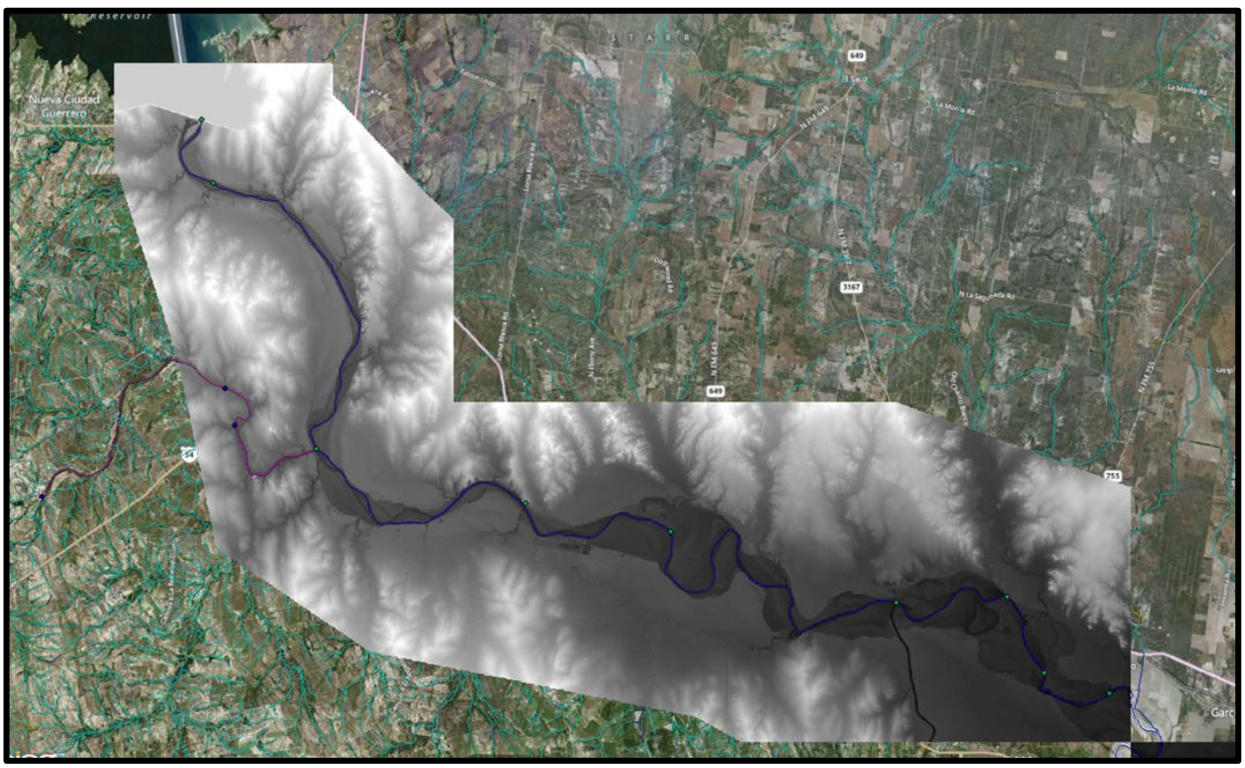

Figure 1-54. Bare Earth LiDAR Layer of the Lower Rio Grande/Río Bravo Watershed. Source USIBWC.

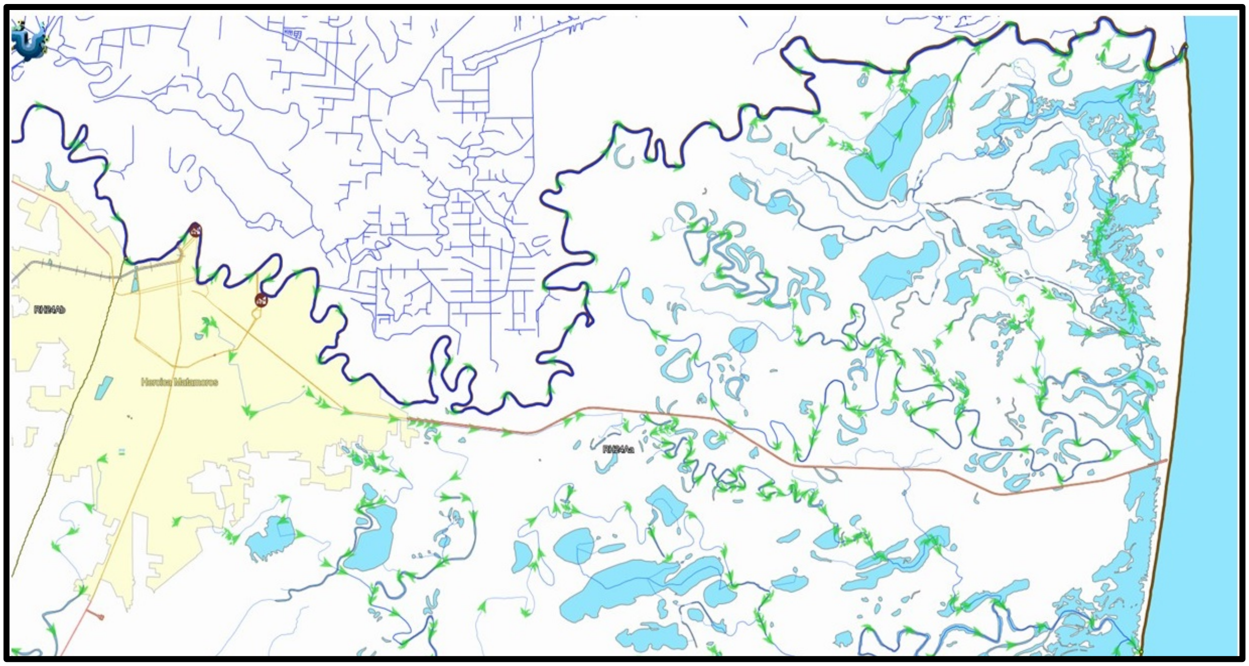

Figure 1-55. Image of Simulador de Flujos de Agua de Cuencas Hidrograficas (SAITL). Source: INEGI.

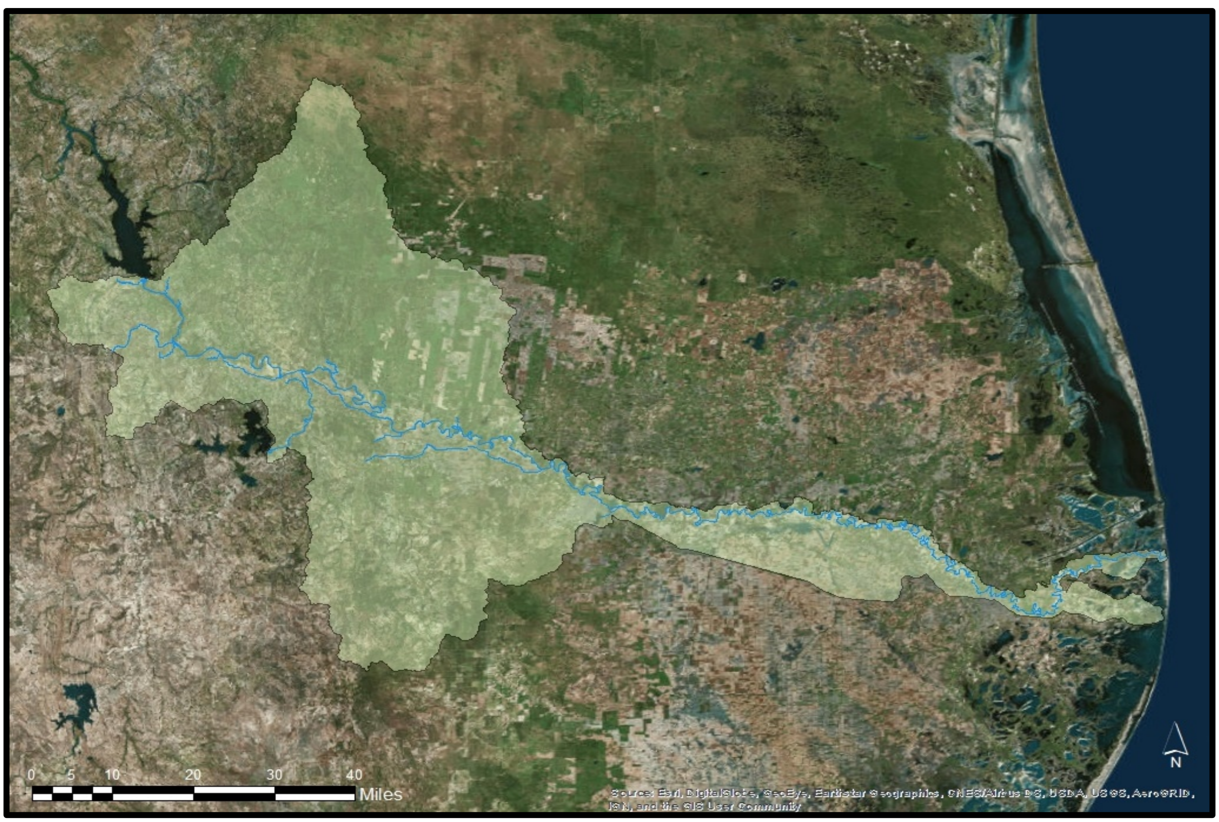

Figure 1-56. Final Transboundary Watershed of the Lower Rio Grande/Río Bravo Used in the LRGWQI.

Binational Hydrography for the LRGWQI

Of equal importance to the development of a harmonized transboundary watershed was the development of a harmonized binational hydrography of the Lower Rio Grande/Río Bravo for the LRGWQI. Like the watershed development process, the development of a binational hydrography layer for the LRGWQI involved manipulation and revision of existing GIS layers guided by the binational deliberations of the BTWG. The process is described in this sub-section for the purpose of explaining the division of the LRGWQI watershed into sub-basins for input of steady state nonpoint sources into the LRGWQI models of water quality. The development and discretization of binational hydrography for the LRGWQI was also integral to developing the LRGWQI model of water quality for reasons beyond the input of steady state nonpoint sources.

The starting binational hydrography layer for this effort was downloaded by the author from the USGS' BEHI web site (USGS, 2009). The BEHI binational hydrography layer integrates medium resolution (1:100,000 and 1:250,000) streams from USGS' NHD and INEGI's Red Hidrográfica, where these were available. In areas where medium resolution streams were not available, the BEHI consortium used lower resolution hydrography layers from USGS' National Atlas 1:2,000,000 and INEGI's 1:1,000,000 scale hydrography layers. An important advantage of using the BEHI binational hydrography layer as the starting hydrography layer for the LRGWQI was the fact that the layer had already been vetted by both national governments (USGS, 2009). Figure 1-57 shows the BEHI binational hydrography layer clipped to the NHD HUC 12 Lower Rio Grande/Río Bravo watershed.

Developing the LRGWQI Model Hydrography

The LA-QUAL software requires a user to discretize the water body being modeled into distinct computational elements of a size specified by the user. The length of elements depends on the definition and accuracy desired in the model. Shorter element lengths provide more accurate results, but more of them are needed for simulation, which requires longer computation times. In the LA-QUAL software, computational elements are numbered and grouped into reaches, which are also numbered. Computational element numbers increase from the most upstream point in the stream system to the most downstream point.

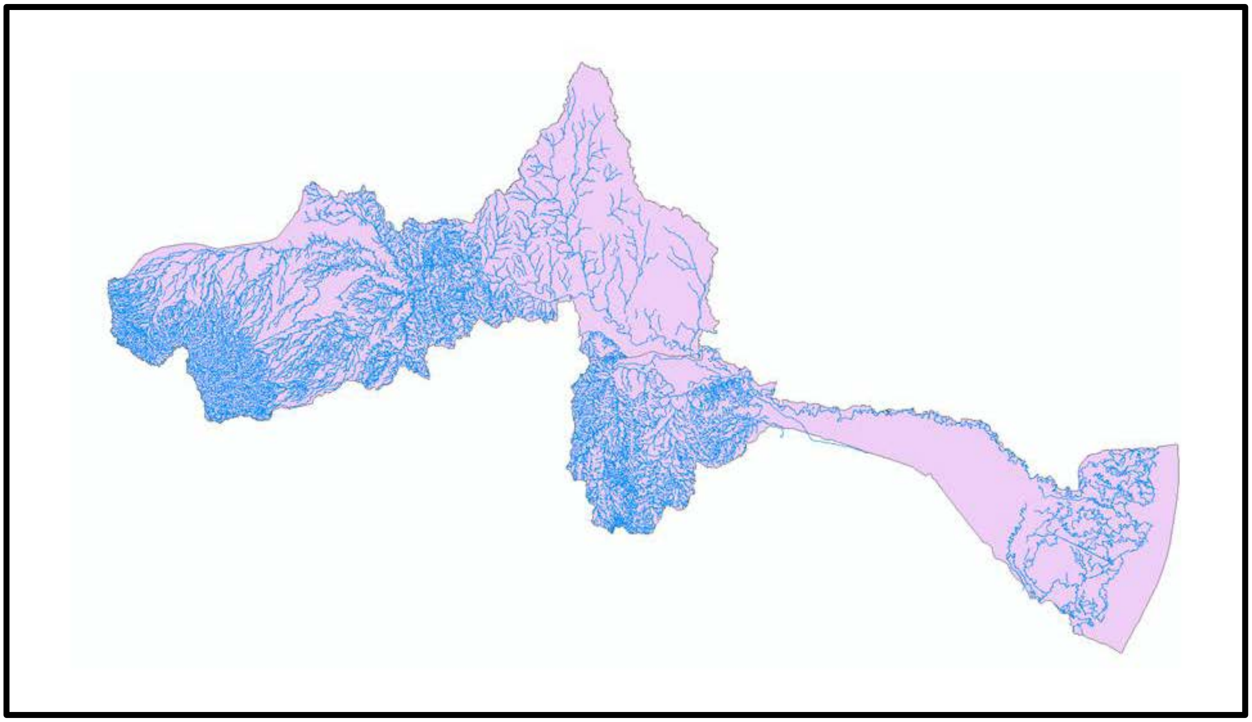

Figure 1-57. Binational Hydrography of the Lower Rio Grande/Río Bravo. Source: BEHI (USGS 2009).

LA-QUAL reach numbers also increase in a downstream direction. When a tributary junction is reached, the numbering order is continued from the most upstream point of the tributary. When a junction is encountered, the upstream reach must end and a new reach must begin immediately below the junction. The LA-QUAL program is dimensioned for a maximum of 4,000 computational elements and a maximum of 200 reaches.

Figure 1-58 shows a portion of the LA-QUAL schematic for the LRGWQI models of water quality in the Lower Rio Grande/Río Bravo, which is composed of 1895 computational elements in 147 reaches. Reach numbers are shown in the small boxes centered at the top of each reach bracket. Computational element numbers are on the right side in the subdivisions of each reach bracket. The stream distance from the headwater element of each waterbody represented in the model schematic is shown on the left side of each computational element, outside the reach brackets. Reach, calibration points, and landmark descriptions are shown to the right of the computational element in which they are located, outside the reach brackets.

The model schematic shown in Figure 1-58 was developed concurrently with the development of the LRGWQI model hydrography through a collaborative process involving binational deliberations of the BTWG via email communications, simultaneous translation conference calls and face-to-face meetings held in 2014, 2015 and 2016 in Mercedes, Texas and Austin, Texas. Due to the dimensional restrictions of the LA-QUAL software, only a portion of the BEHI binational hydrography could be discretized for use in the LRGWQI model (Figure 1-59). The simplification of the BEHI binational hydrography (i.e., the selection of tributaries, drains and ditches to include in the model), as well as the selection of computational element lengths, reach dimensions, landmarks, and model calibration locations was a deliberative process involving all members of the BTWG. The author produced the final model schematic and the associated GIS hydrography and point location layers using the ArcGIS 10.1 software from ESRI.

Discretizing the LRGWQI Model Hydrography and Developing of the LA-QUAL Model Schematic

In assigning computational elements, the author proposed dividing the portions of the Lower Rio Grande/Río Bravo and tributaries, drains and ditches selected by the BTWG for modeling, into 147 reaches consisting of 1895 computational elements. The author determined the length of the computational elements, reach segmentation and location of landmarks and calibration points in accordance with the decisions of the BTWG. In ArcGIS 10.1, the author first split the LRGWQI hydrography polyline segments into individual LA-QUAL reaches, each with its own attributes, by intersecting it with a point layer of reach boundary points. The author then split each reach into computational elements using the ArcGIS Data Management command “Split a line in equal parts.” Figure 1-60 shows the resulting point and polyline layers.

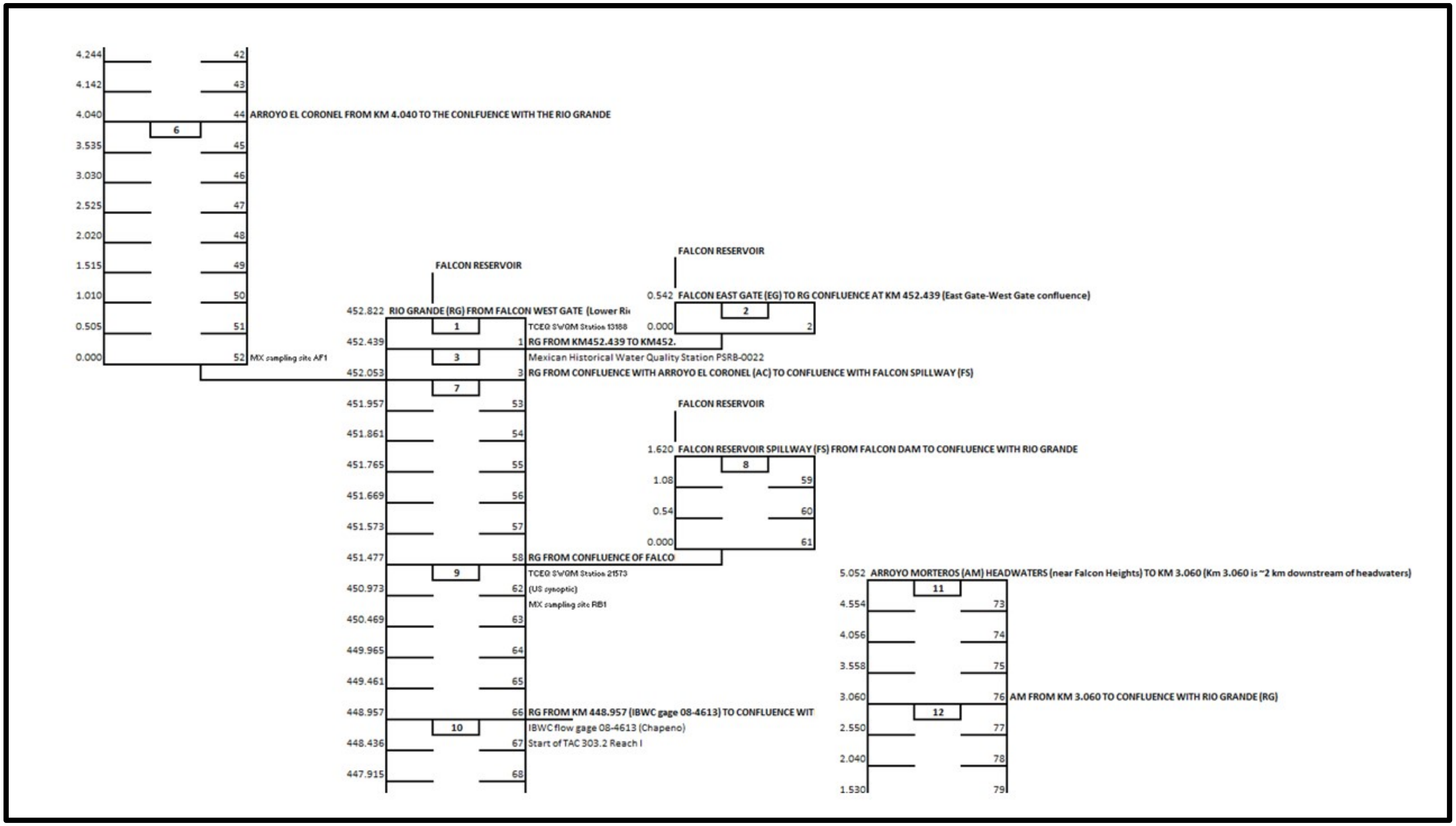

Figure 1-58. A Portion of the LA-QUAL Model Schematic of the LRGWQI Model of Water Quality in the Lower Rio Grande /Río Bravo.

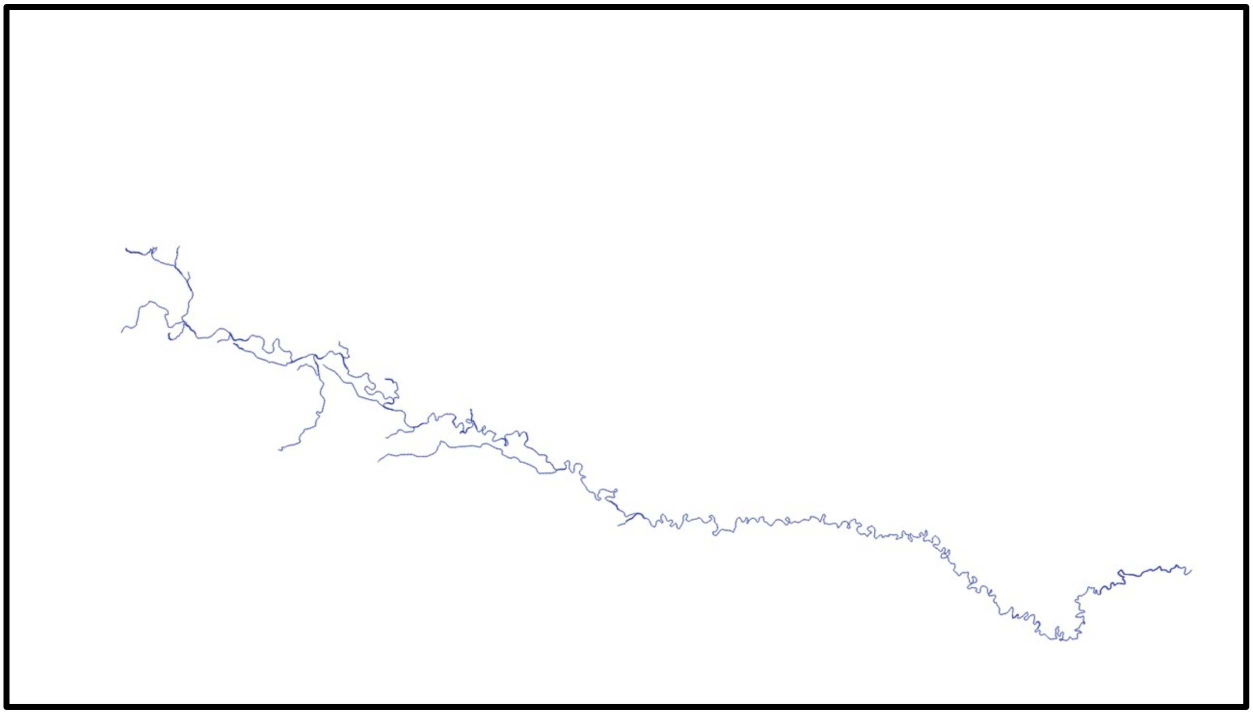

Figure 1-59. Simplified Hydrography of the Lower Rio Grande/Río Bravo Showing the Tributaries, Drains, and Ditches Selected by the LRGWQI's BTWG. Original Hydrography Source: BEHI (USGS 2009).

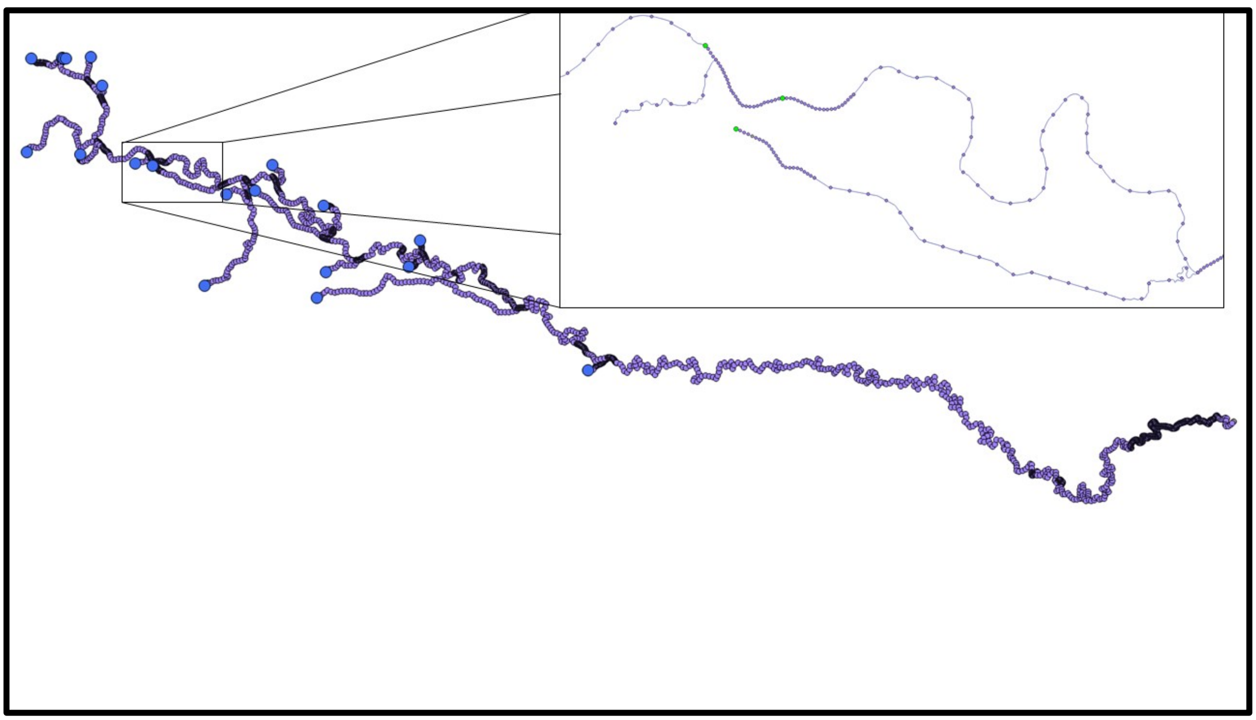

Figure 1-60. LRGWQI Hydrography Discretized for Use in the LA-QUAL Water Quality Modeling Software.

Note the difference in computational element sizes in different reaches of the river (see inset in Figure 1-60). Balancing simulation accuracy, which requires tighter element spacing, and economy of elements, to stay within the 2000 model element maximum, the BTWG agreed to make model element spacings of 0.5 km downstream of known point source outfalls, dams, and tributary junctions. The BTWG agreed to use larger element sizes (1-2.5 km) in other portions of the LRGWQI model.

Dividing the LRGWQI Watershed into Sub-basins based on LA-QUAL Model Reaches

The LA-QUAL water quality modeling software requires that all flow and pollutant inputs to the model be associated with specific spatial locations represented in the model as computational elements and reaches. Point source inflows (i.e., headwaters and wastewater outfalls) and outflows (diversions and withdrawals) must be associated with specific computational elements in the model. Referred to as "Wasteloads," point source inputs consist of a flow component and a pollutant concentration at the point source outfall; headwaters are handled in the same manner. By contrast, nonpoint source pollutant inputs to LA-QUAL are associated with the model reaches and affect all computational elements within a reach equally.

Some nonpoint sources, such as irrigation return flows, can be input into LA-QUAL as "incremental inflows," for which flows and pollutant concentrations are specified on a reach basis. Other nonpoint sources of pollutants, for which flow is negligible or for which no flow can be specified, such as leaking septic systems or direct, or indirect, fecal deposition, are input into LA-QUAL by specifying a pollutant loading, in units of mass (i.e., kg or lbs), also entering the model on a reach basis. Steady state nonpoint source inputs must be estimated for each LA-QUAL reach of the model, including irrigation return flows, as incremental inflows with associated water quality, and human and animal loadings as mass-based nonpoint source inputs. To do this, each model reach must be associated with a watershed area in which the pollutants are generated and introduced into the reach. The process of dividing the LRGWQI watershed into smaller sub-basins is therefore linked to the discretization applied to the LRGWQI hydrography. As previously mentioned, the division of the LRGWQI watershed into LRGWQI model sub-basins was performed by Adam Torres of the TCEQ.

Using the upstream boundaries of the LA-QUAL model reaches (omitting headwaters) as the “pour points” for each sub-basin, flow direction and flow accumulation grids were created for each reach using a LiDAR-based DEM provided by the USIBWC and the watershed delineation methods described in ESRI Technical Article 000012346. Due to the limited coverage of the USIBWC’s LiDAR layer some adjustment was necessary to the upper and lower boundaries of the binational sub-basins. This was done using the 30-meter DEMs available from the USGS for the US HUCs and INEGI’s SAITL model for the Mexican portion of the watershed. The upstream boundaries to all sub-basins were clipped to the LRGWQI watershed. Subsequently, the main stem of the Rio Grande/Río Bravo, selected from the LRGWQI hydrography, was used to split (intersect) the binational sub-basin polygon layer into two sub-basin layers, a US LRGWQI Sub-basin layer and a Mexican LRGWQI Sub-basin layer. Figure 1-61 shows the pour points for each of the 147 reaches LA-QUAL reaches of the LRGWQI models and the sub-basins delineated for each. The inset in Figure 1-61 shows a closeup of the area of the river near its confluence with the Gulf of Mexico where sub-basins are relatively short and relatively narrow.

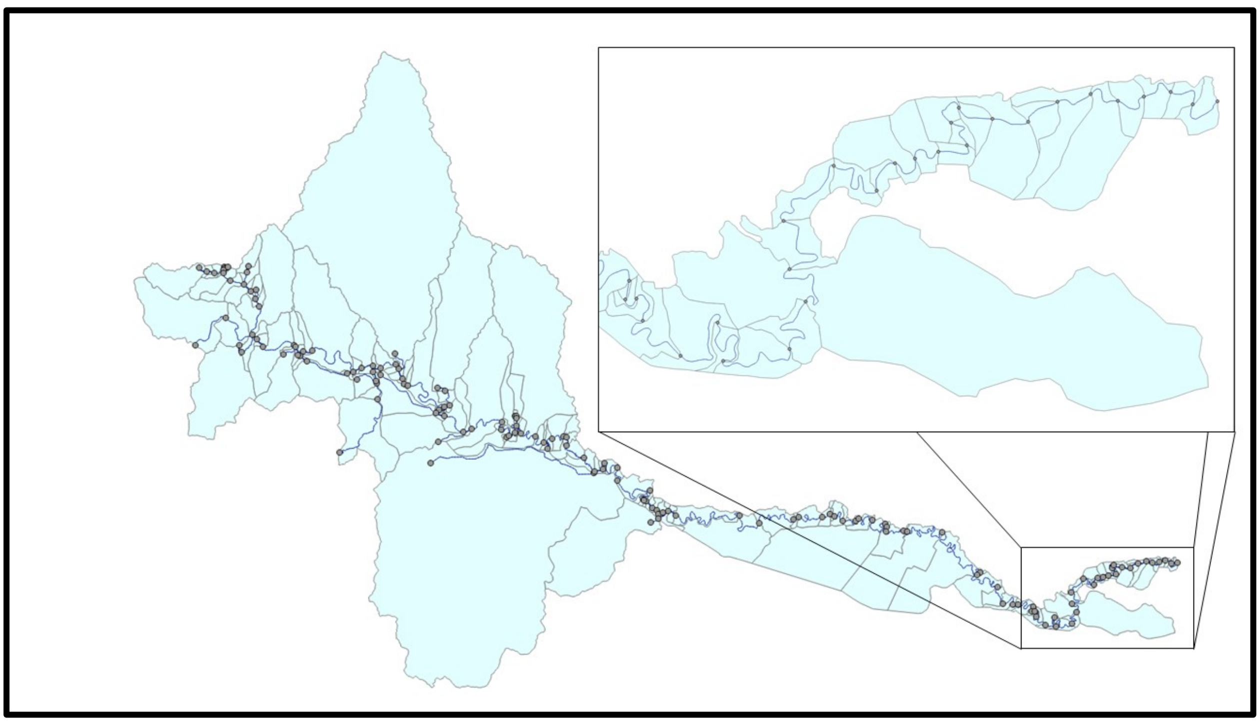

Figure 1-61. Pour Points and Associated Sub-Basins Delineated for LA-QUAL Reaches of the LRGWQI Model of Water Quality.

Estimation of Residential Nonpoint Sources

In accordance with the LRGWQI's TOR, rainfall runoff is omitted from consideration as a pollutant transport mechanism. The consensus within the BTWG, however, was that residential nonpoint sources of pollution affect surface water quality during steady state conditions through direct deposition of wastes into surface waters or through transport by concomitant aqueous waste streams (e.g., sewage and gray water from residential and commercial activities). In view of this consensus, members of the BTWG agreed to limit the analysis to residents living in very close proximity to the Lower Rio Grande/Río Bravo or one of its contributing tributaries, drains or ditches. After binational deliberations, the BTWG agreed, to quantify pollutants contributions for residents living within a 500-meter riparian buffer around the Lower Rio Grande/Río Bravo or one of its contributing tributaries, drains or ditches.

The amount of raw sewage per capita reaching surface waters in riparian communities is dependent on the levels of sanitation that exist in those communities. Therefore, to account for disparities in sewage collection and treatment services, the BTWG agreed on three main residential categories to quantify, (1) residents currently being provided centralized wastewater services, (2) residents using onsite sewage facilities (OSSF) and, (3) residents with no wastewater treatment. The associated geospatial analysis conducted by the author and his collaborators is described below. The resulting US and Mexican riparian population values, categorized by wastewater treatment type, are used in the Human Loadings component of the Nonpoint Sources module of the LRGWQIDSS.

To conduct the analysis, the author and his collaborators in the BTWG first quantified the number of watershed residents living within a 500-meter buffer of Lower Rio Grande/Río Bravo or one of its contributing tributaries, drains or ditches and then segregated this population based on ancillary information available from other sources. The data used to make these estimates was a combination of the spatial LRGWQI sub-basin boundaries previously described and spatial census data from the 2010 Decennial Census of the United States (US Census Bureau, 2010), the Border Colonia Geographic Database (State of Texas Office of Attorney General, 2016), GIS layers and information about water and wastewater service areas in the Rio Grande Valley (obtained from local utilities), and Mexico's 2010 Censo de Población y Vivienda (INEGI, 2010). To estimate per capita pollutant contributions, the author used typical per capita wastewater production values used by the BECC (now NADB) for US and Mexican border residents and literature values of pollutant concentrations in raw sewage from Metcalf and Eddy (1991).

US Residential Nonpoint Sources

Figure 1-62 shows an image of 2010 US Census Blocks located within the Lower Rio Grande/Río Bravo watershed. Using the census block polygon layer for the state of Texas, available from the US Census Bureau, the author extracted the census blocks included only within the US portion of the Lower Rio Grande/Río Bravo watershed. The author then determined the number of residents living within each of the US LRGWQI sub-basins of the Lower Rio Grande/Río Bravo watershed by summing the number of residents in the resulting subset of US Census Blocks within each of the US sub-basins. For census blocks intersected by the sub-basin boundary, the author determined the total watershed population in those blocks by applying the relative proportion (i.e., ratio) of the census block area within the sub-basin to the total area of the intersected census block.

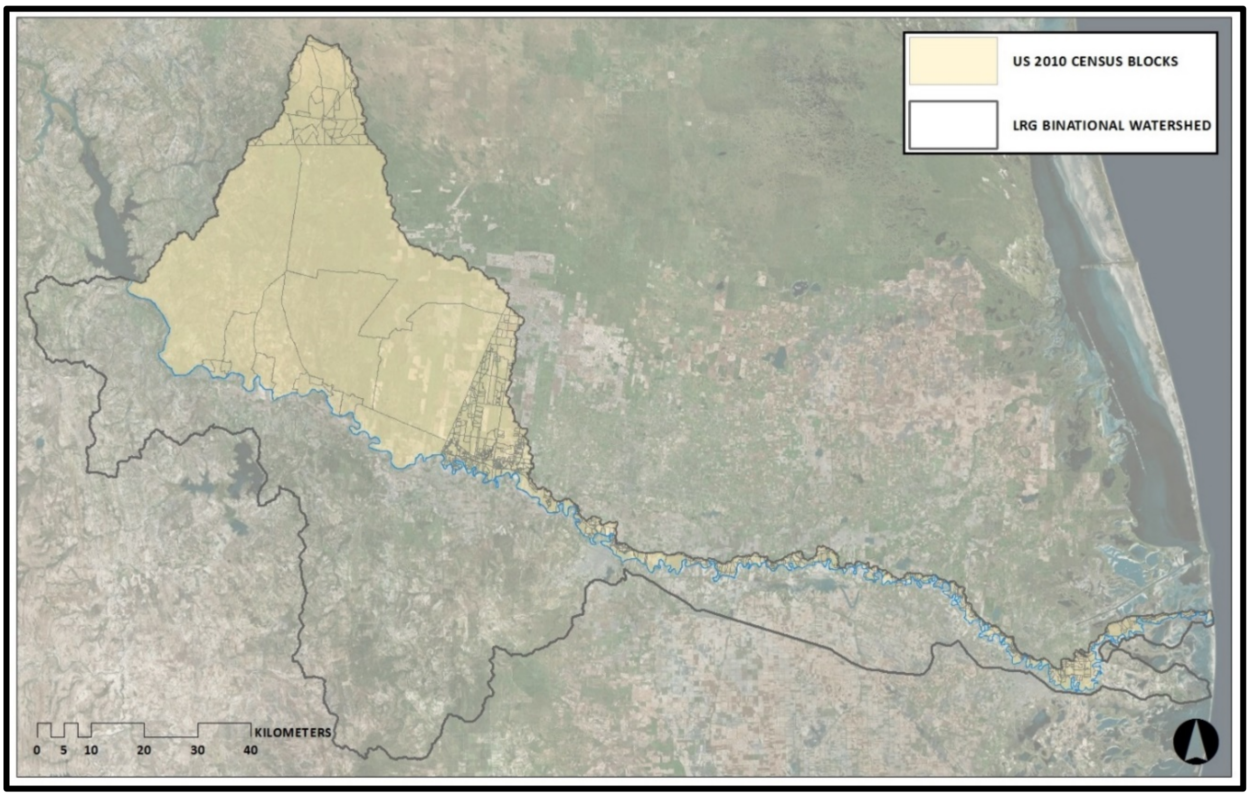

Figure 1-62. US Census Blocks within the Lower Rio Grande/Río Bravo Watershed.

Using GIS layers of wastewater service areas in the US sub-basins of the LRGWQI watershed, the author then estimated the number residents living in the US sub-basins with access to centralized wastewater treatment systems, by estimating the number of residents living in the watershed census blocks that also lived within wastewater service areas.

Next, the author used the Texas Attorney General's Border Colonia Geographic Database, which contains information about unincorporated communities within the Texas side of the US-Mexico border region, known as "colonias," where residents lack centralized wastewater treatment services, including residents with no form of sanitation, to determine the number of residents living in US census blocks within the LRGWQI watershed sub-basins who lacked any type of wastewater treatment (Figure 1-63).

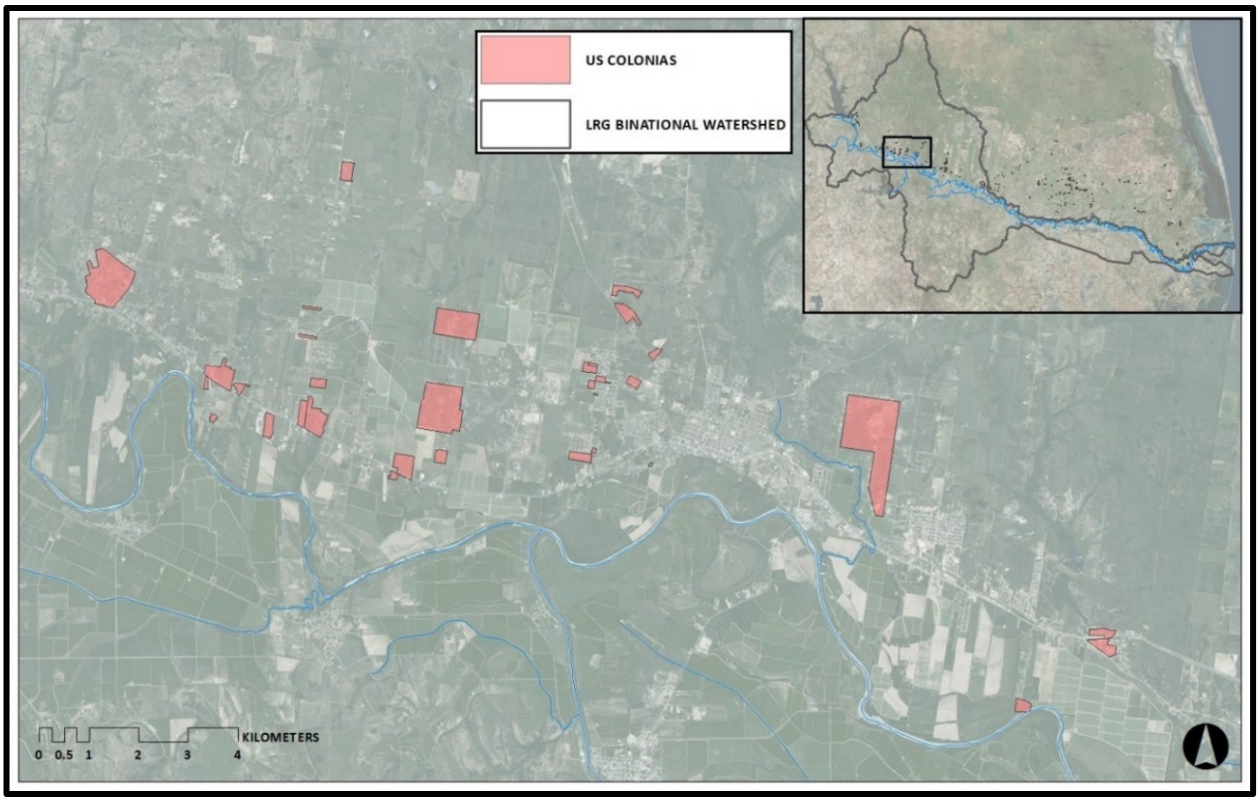

Figure 1-63. Unincorporated US Communities, Known as "Colonias," which Lack Centralized Wastewater Treatment.

As with the geospatial analysis determining total watershed population, the author used census block area ratios to determine the resulting 2010 population values for intersections of census blocks and colonia areas. The author assumed that the remaining population living in the

US LRGWQI watershed sub-basins census blocks, that is, the US watershed census block population living neither within a service area nor within a colonia lacking sanitation, consisted of US watershed residents with OSSFs. The final step in the geospatial analysis was to determine the sanitation-dependent subsets of residents, living within the 500-meter riparian buffers; that is, riparian buffer residents with (1) access to centralized sewer services, (2) access only to onsite wastewater treatment systems and (3) no access to wastewater treatment systems. The author accomplished this by intersecting or "clipping" the subsets of the different residential populations in each sub-basin using a 500-meter riparian buffer polygon (Figure 1-64). Figure 1-65 shows an example of the resulting GIS layers produced by the geospatial analysis.

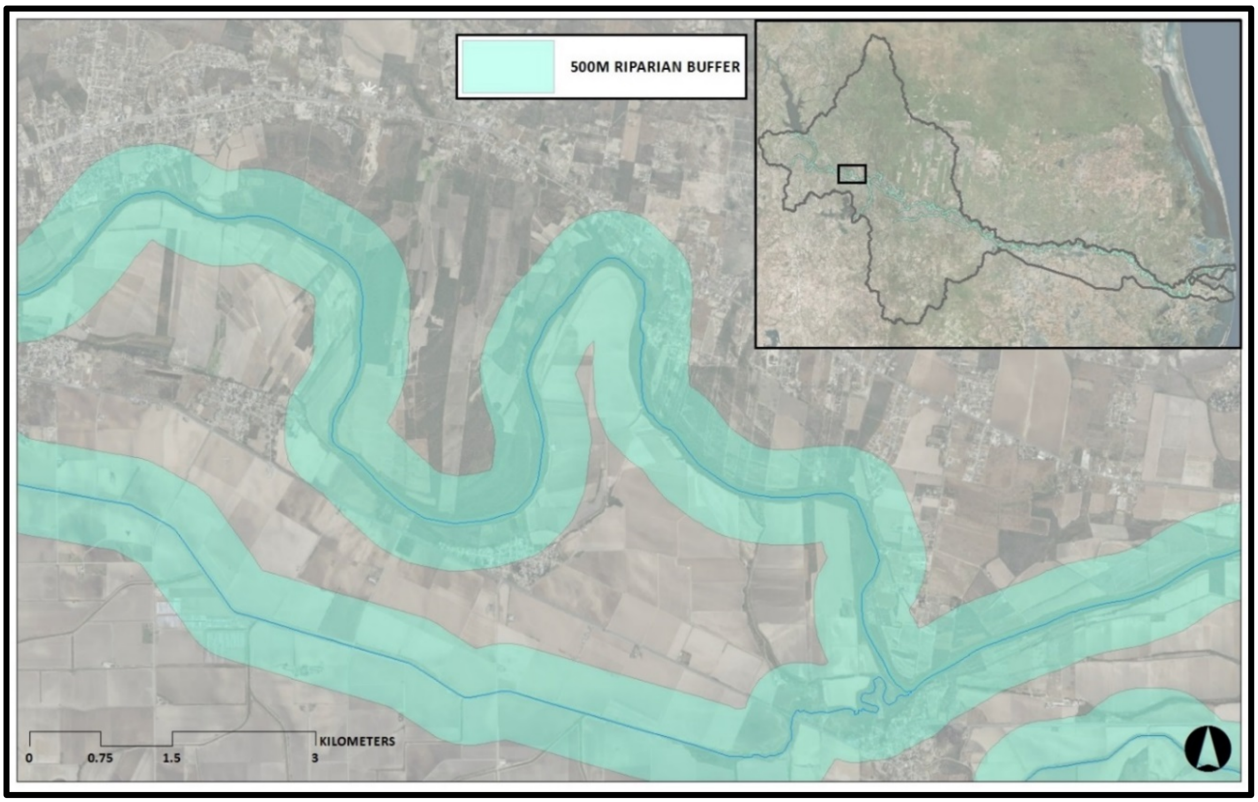

Figure 1-64. 500-Meter Riparian Buffer Applied to the LRGWQI Hydrography Layer.

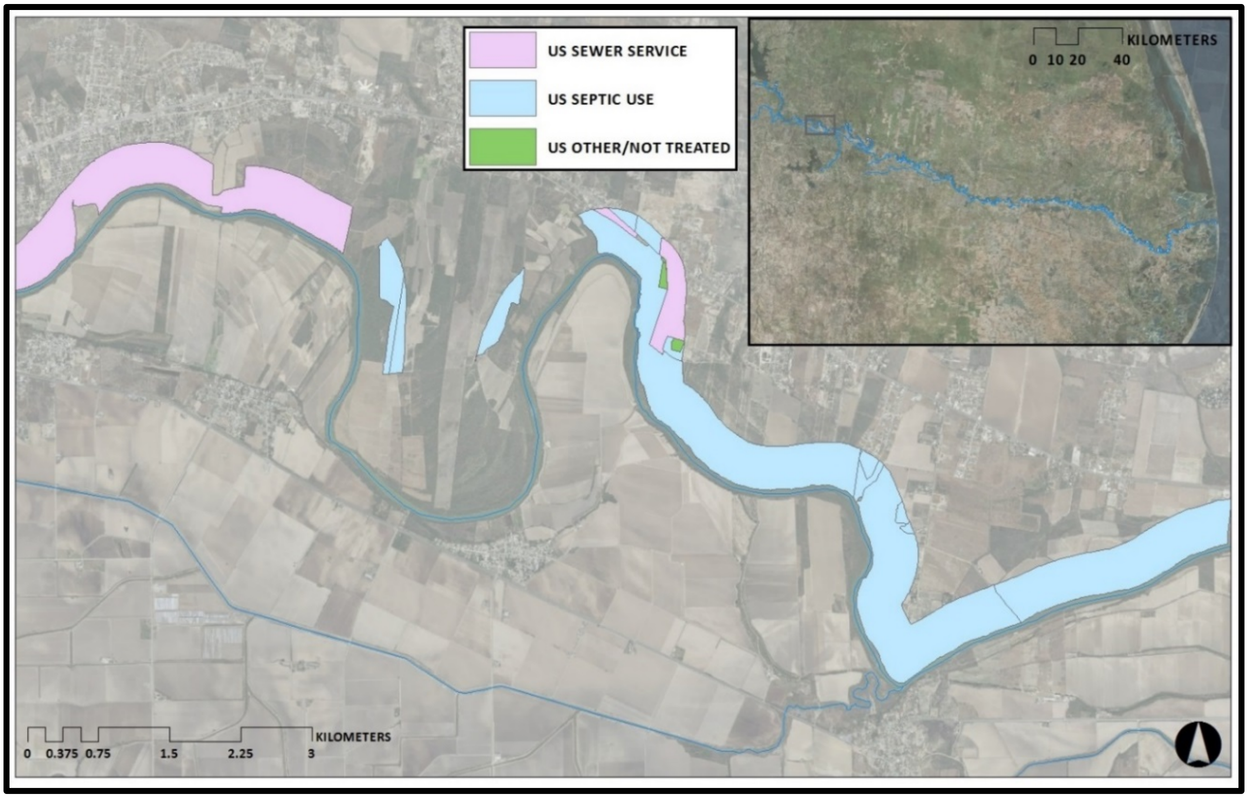

Figure 1-65. Geospatial Analysis of US Residential Nonpoint Sources in the Lower Rio Grande/Río Bravo Watershed.

The author adapted the method developed by Lynch (2012), for calculating residential nonpoint source pollutant loadings to each of the LA-QUAL model reaches using the population estimates for the two population subsets contributing residential steady state nonpoint source pollution to the river, (1) residents with no wastewater treatment and (2) residents using OSSFs. The method, described in more detail in the following sections, is an important part of the Human Loadings component of the Nonpoint Sources module of the LRGWQIDSS.

Mexican Residential Nonpoint Sources

While similar to the geospatial analysis conducted to estimate population values associated with US residential nonpoint sources, the geospatial analysis used by the author and his Mexican collaborators to estimate population values associated with Mexican residential nonpoint sources differed in several important aspects. First, the author and his Mexican collaborators used data from INEGI's 2010 Censo de Población y Vivienda at two separate levels: (1) the municipio level, and (2) the localidad level. Second, unlike the 2010 US census data, the 2010 INEGI census data contained sanitation and drainage information useful in categorizing the type of wastewater treatment received by residents living on the Mexican portion of the Lower Rio Grande/Río Bravo watershed.

The 2010 INEGI census data, aggregated at the municipio level, categorizes municipio residents according to the type of sewage disposal available to them. The categories include, (1) public sewer, (2) septic systems, (3) piping directly to a crevice or cliff, (4) piping directly to surface water bodies, and (5) no "drainage." However, the coarse aggregation of municipio level data renders it inadequate for estimating the number of Mexican municipio residents living within a 500-meter riparian buffer of a receiving water body. The 2010 INEGI data aggregated at the localidad level, Principales Resultados por Localidad (ITER), available as a GIS point layer from INEGI (INEGI 2010c), provides sufficient geospatial detail for the analysis (Figure 1-66).

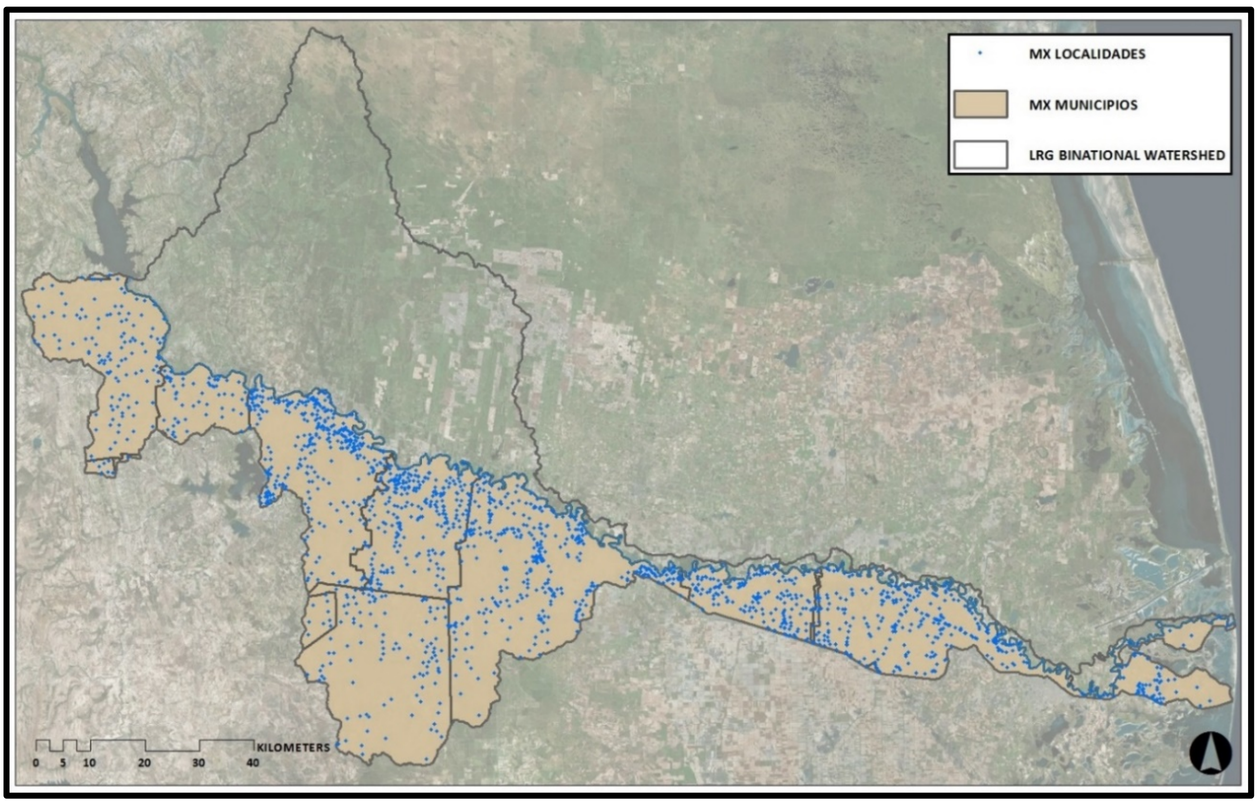

Figure 1-66. Mexican Localidades and Municipios within the Lower Rio Grande/Río Bravo Watershed.

However, these data include information on whether "drainage" is available to the residents but do not provide detailed information about the type of sewage disposal available to the residents of each localidad. To estimate the distribution of residents living within the 500-meter riparian buffer, by sewage disposal type, in each of the Mexican LRGWQI sub-basins, the author and his Mexican collaborators applied the proportions of municipio residents falling under each sewage disposal category to the numbers of residents of localidades within each municipio that were also located inside the 500-meter riparian buffer (Figure 1-67). This calculation yielded values for Mexican riparian populations classified under one of the five sewage disposal categories available for the municipio level Mexican census data. To represent Mexican riparian populations lacking wastewater treatment services, the last three categories, (3) piping directly to a crevice or cliff, (4) piping directly to surface water bodies, and (5) no "drainage, were combined for each Mexican LRGWQI sub-basin to represent residents with no sanitation (i.e., other).

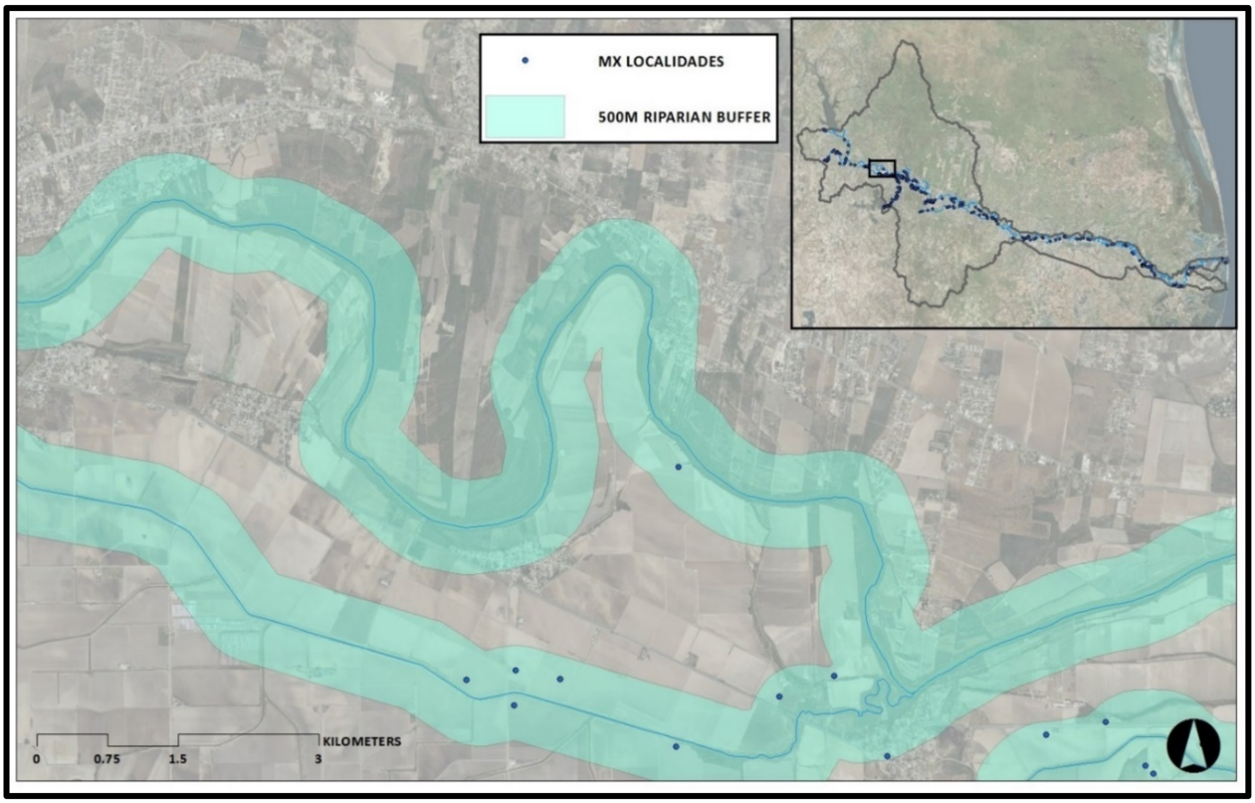

Figure 1-67. Geospatial Analysis of Mexican Residential Nonpoint Sources in the Lower Rio Grande/Río Bravo Watershed.

Pollutant Loading Estimates for Residential Steady State Nonpoint Sources

Using the estimated number of US and Mexican riparian populations (i.e., living within 500 m of the Lower Rio Grande/Río Bravo, a tributary or a contributing drain or ditch) that (1) use

OSSFs for sewage treatment and (2) that lacked any wastewater treatment, the author estimated the potential daily loading of pollutants of concern from residential steady state nonpoint sources to each of the LRGWQI model reaches by applying average per capita wastewater production rates and typical concentrations of constituents in untreated domestic wastewater of weak strength, from Metcalf and Eddy (1991), to the population estimates in each LRGWQI sub-basin. Based on information found in BECC project certification and environmental impact assessment documents for NADB projects in the Rio Grande/Río Bravo watershed, the author used different per capita wastewater production rates for US and Mexican residents (245 L/person/day for US residents and 184 L/person/day for Mexican residents). The value for typical fecal coliform concentrations in untreated wastewater was obtained from Schueler (2000). This method of estimating pollutant loadings from US and Mexican riparian populations, categorized by wastewater treatment type, is coded into the LRGWQIDSS and forms the basis for the Human Loadings component of the system's Nonpoint Sources module.

AGRICULTURAL NONPOINT SOURCES

Within the context of the LRGWQI, steady state agricultural nonpoint sources in the Lower Rio Grande/Río Bravo watershed can be subdivided into two main categories, (1) pollutant contributions from livestock and domestic animals (2) pollutant contributions from irrigation return flows. These two types of nonpoint sources of pollution result from distinctly different agricultural activities and their characterization requires different data sources and data analysis methods.

Irrigation Return Flows

The data sources used to characterize irrigation return flows in the Rio Grande/Río Bravo watershed include (1) the LRGWQI watershed boundary and (2) the binational land use/land cover GIS layer developed as part of the BEHI (USGS, 2009). These GIS layers were used to estimate the hectares of irrigated agricultural land in the US and Mexican LRGWQI sub-basins. It should be noted that the GIS work associated with this effort was conducted by Adam Torres of the TCEQ. The author estimated seasonal irrigation return flow yields per hectare of irrigated agricultural land using the daily average flow, by month, measured by CILA at five major agricultural drains that contribute irrigation return flows to the Lower Rio Grande/Río Bravo (supplied to the BTWG by CILA). The locations of CILA's hydrometric stations in these drains are less than 1 kilometer from the confluence with the Rio Grande/Río Bravo (or, in the case of the Los Fresnos Drain, the Río San Juan). Finally, the author estimated the average concentrations of LRGWQI pollutants of concern in return flows from irrigated agricultural land in the LRGWQI sub-basins using the average values reported in a 2012 study of the effectiveness of agricultural best management practices (BMPs) conducted by Texas Water Resources Institute on irrigated agricultural fields in the Rio Grande Valley (Enciso, 2012).

Estimating Irrigated Agricultural Land Areas

The Binational land use and land cover data obtained from the BEHI is an integrated binational land cover dataset developed from the 2001 USGS National Land Cover Database and INEGI's 2001 Uso de Suelo y Vegetacion Serie III (1:250,000 Land Use Series 3) raster datasets. To integrate the datasets, the BEHI harmonized the land use and land cover (LULC) categories from each dataset into eight common categories: developed, agriculture, forest, shrub, water, barren, grass/pasture, and wetland. Figure 1-68 shows the BEHI binational landuse cover clipped to the LRGWQI watershed.

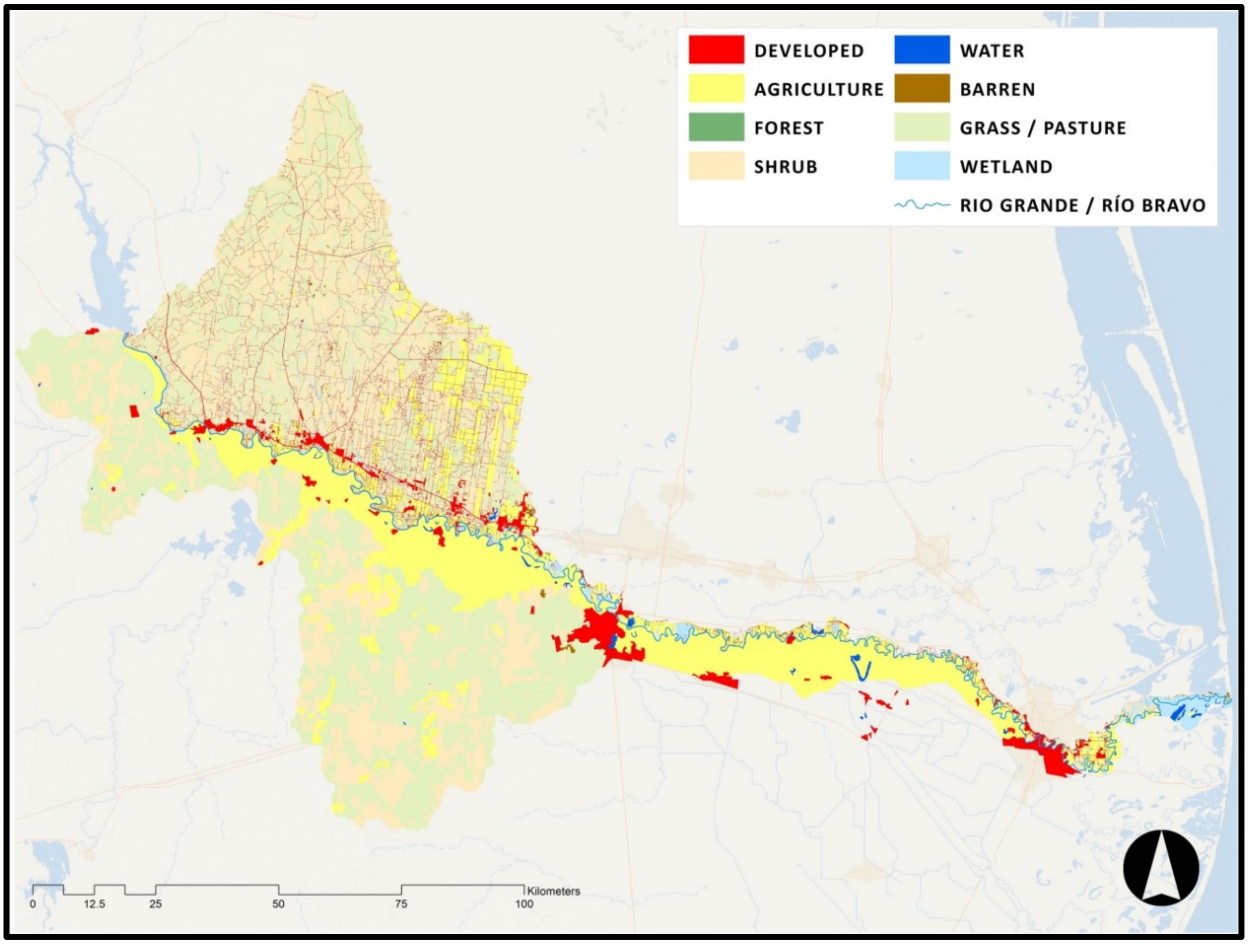

Figure 1-68. Binational Land Cover Layer of the Lower Rio Grande/Río Bravo Watershed. Source: BEHI (USGS, 2009).

To isolate the areas of irrigated agricultural land in the LRGWQI watershed, the BEHI land use layer, clipped to the LRGWQI watershed, was sorted by the data value field corresponding to the agriculture code ID using ArcGIS 10.1. This resulted in the binational agricultural land use layer (Figure 1-69).

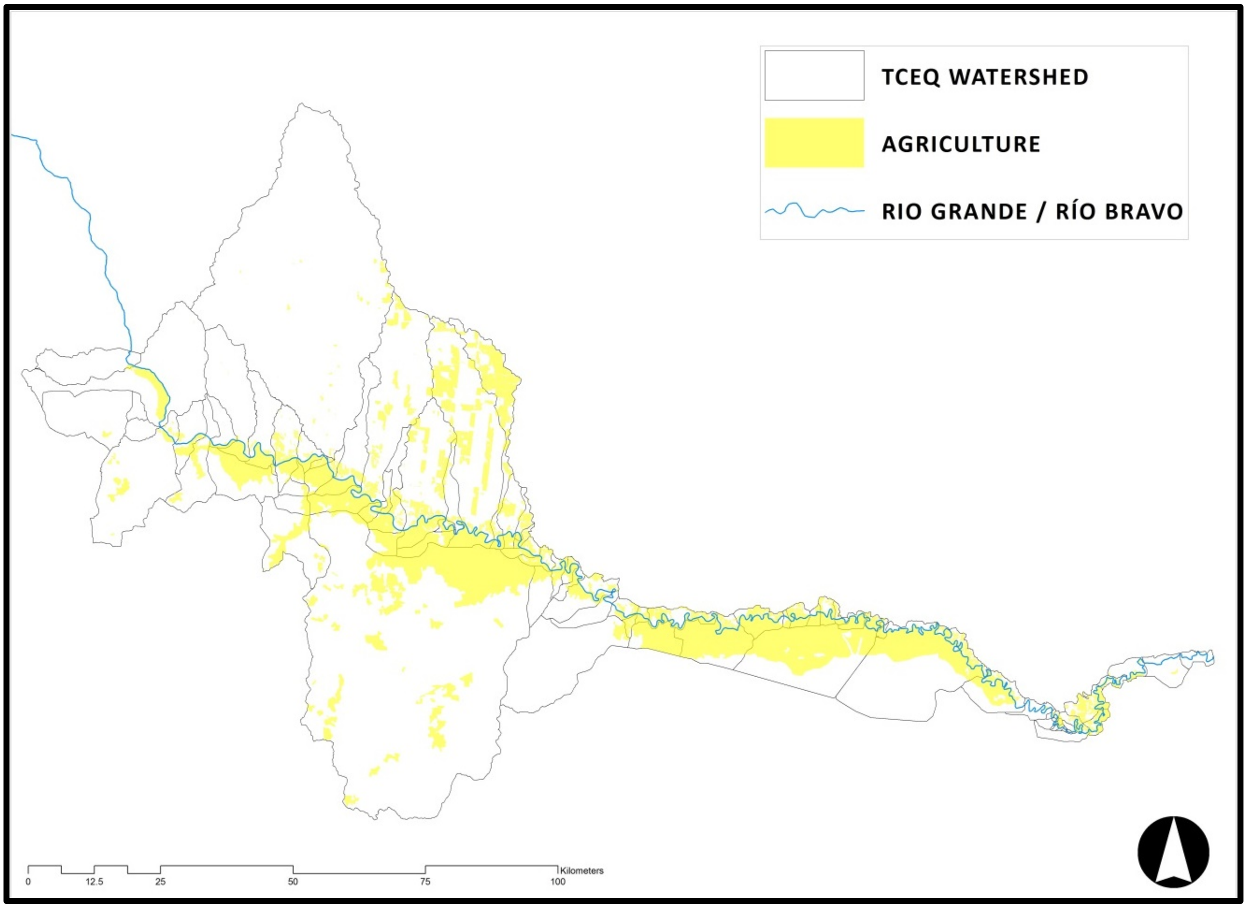

Figure 1-69. Agricultural Land within the LRGWQI Watershed. Source: BEHI (USGS, 2009).

To calculate the area (in hectares) of irrigated land within each LRGWQI sub-basin layer, it was necessary first to distinguish between irrigated agricultural land and non-irrigated agricultural land in the binational agricultural land use layer. This was accomplished simply by assuming that most of the irrigated agricultural land contributing irrigation return flows to the Lower Rio Grande/Río Bravo is found adjacent, or in close proximity, to the Lower Rio Grande/Río Bravo or one of its tributaries or drains.

Torres extracted the irrigated agricultural land within the binational agricultural land use layer by selecting (i.e., "clipping"), land areas located only within a 30 km buffer of the Lower Rio Grande/Río Bravo or one of its tributaries or drains. Thirty kilometers was the distance agreed upon by the BTWG as the consensus buffer around the Lower Rio Grande/Río Bravo, Río Álamo, Río San Juan, and the Rancherías, Los Fresnos, Puertecitos Huizaches and El Morillo agricultural drains, in which agricultural land was likely to be irrigated within the LRGWQI watershed (Figure 1-70). For quality assurance, the resulting binational watershed irrigated land use layer was checked against satellite imagery to verify that prevalence of furrow irrigation in the areas designated as irrigated land use.

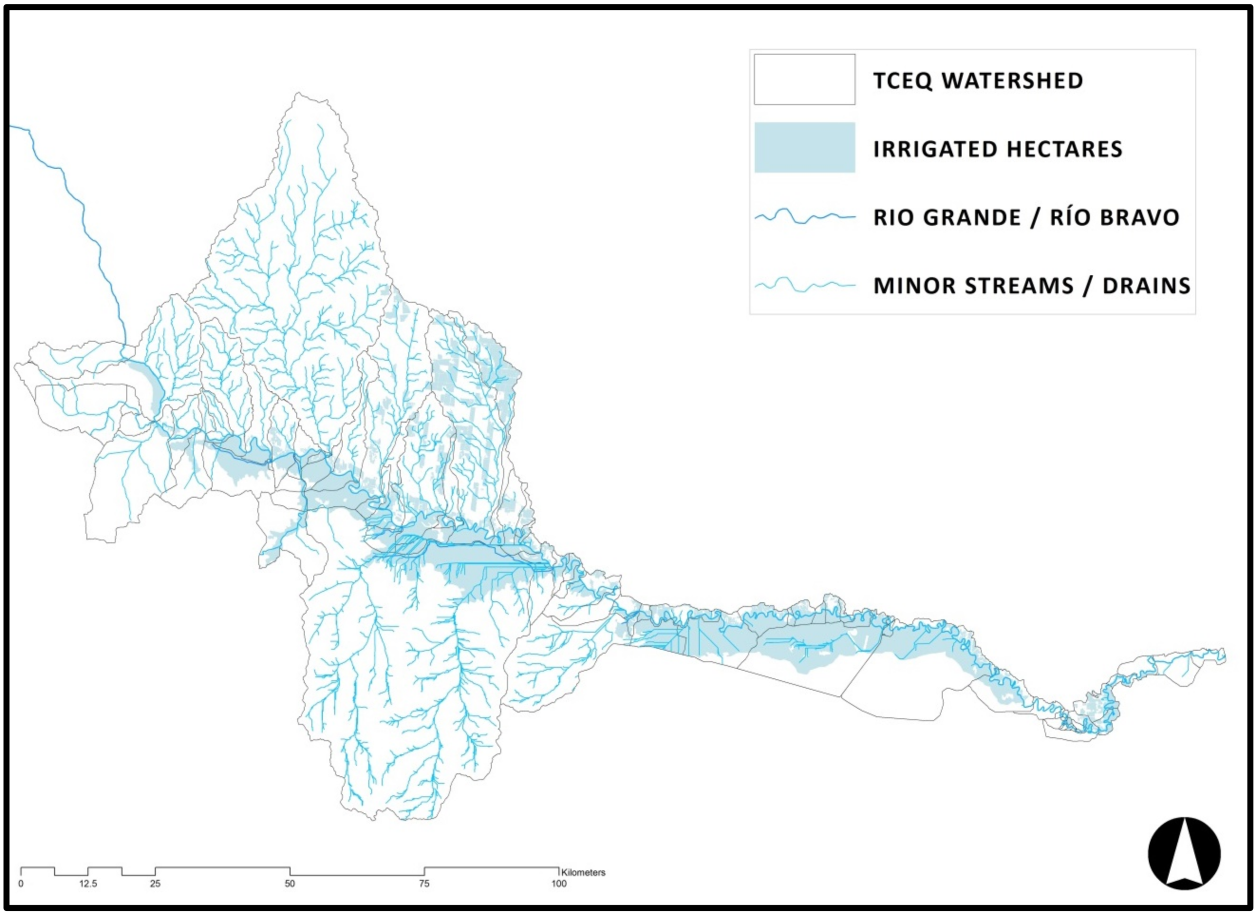

Figure 1-70. Irrigated Agricultural Land within the LRGWQI Watershed.

Once the binational irrigated land use layer was cross-checked with satellite imagery, the areas (in hectares) of irrigated agricultural land within each of the US and Mexican LRGWQI sub-basins were estimated. The first step was to "split" the binational irrigated land use layer with the US and Mexican LRGWI sub-basins, using the ArcGIS geoprocessing tools. Then, from the attribute table of the resulting layer, the "Calculate Geometry" function was used to calculate the areas of irrigated agricultural land in the individual US and Mexican LRGWQI sub-basins (Figure 1-71).

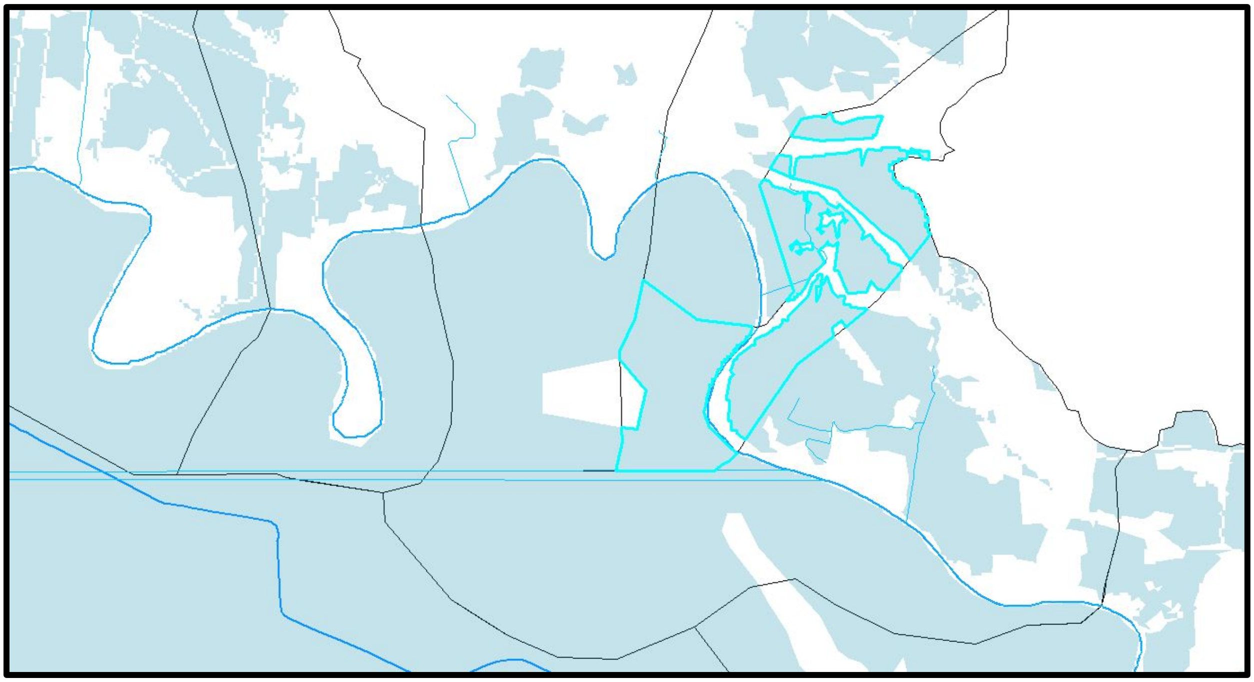

Figure 1-71. Splitting of Binational Irrigated Land Use Layer Using the LRGWQI Sub-basins Layer.

The hectares of irrigated agricultural land determined for each of the US and Mexican LRGWQI Sub-basins using the methods described in this section are an essential part of the Agriculture Loadings component of the Nonpoint Sources module of the LRGWQIDSS.

Determining LRGWQI Sub-basin Irrigation Return Flow Yields

Determining the yield of irrigation return flows (in liters per hectare) for each of the US and Mexican LRGWQI sub-basins is important for two reasons. First, it facilitates the modeling of irrigation return flows as “incremental inflows” in LA-QUAL. Second, it enables the simulation of the effects, on flow and water quality, of implementing agricultural BMPs in the LRGWQI sub-basins. As a starting point for estimating sub-basin yields, the author used the average daily flow values in the drains monitored by CILA, for the months in which the LRGWQI synoptic surveys of water quality were conducted, and divided these values by the area of irrigated land in the sub-basins corresponding to each of the Mexican drains in which the flow data was measured. In some instances, the author used flow measured and reported by IMTA during the synoptic surveys for this purpose.

The author extrapolated the irrigation return flow yields calculated for the Mexican agricultural drain sub-basins to other LRGWQI watershed sub-basins by assigning drain-derived yield values to agricultural land located in the portions of the LRGWQI watershed bounded by one of the six IBWC hydrometric stations on the Lower Rio Grande Río Bravo. For example, the yields estimated for the Puertecitos drain sub-basin were assigned to sub-basins located between the IBWC hydrometric stations located at Rio Grande City and at Los Ebanos. The (LA-QUAL) "incremental inflow" input into a particular LA-QUAL model reach is the product of the hectares of irrigated agricultural land in the sub-basin associated with that LA-QUAL reach and the "per hectare" return flow yield assigned to the LRGWQI sub-basin associated with that LA-QUAL reach. Some of the sub-basin yield values were adjusted during hydrologic calibration of the LA-QUAL model. It should be noted that sub-basin irrigation return flow yields vary seasonally, as reflected by the CILA flow data used to estimate them. Since the LA-QUAL model developed for the LRGWQI was calibrated using data collected during five different synoptic survey events (July 2014, March, August and November of 2015 and April of 2016), the author estimated five different sets of sub-basin yields using flow data measured during the months coinciding with the five synoptic survey events.

The sub-basin irrigation return flow yields estimated using the methods described in this section are coded into the LRGWQIDSS. To simulate the application of irrigation-related agricultural BMPs, the LRGWQIDSS applies factors to the sub-basin irrigation return flow yields of the land being treated in the US and/or Mexican LRGWQI sub-basins. These factors, derived from the technical literature, are associated with the expected percent reduction in irrigation return flow production resulting from the application of one of two irrigation BMPs, land leveling and the use of polypipe. Additional details about the Agriculture Loadings component of the Nonpoint Sources Module of the LRGWQIDSS is provided in Section 3.2.1.6 of this dissertation.

Assigning Pollutant Concentrations to Irrigation Return Flows

Irrigation return flows are simulated as "incremental inflows" in LA-QUAL, so pollutant concentrations must be assigned to "incremental inflows" into each of the LA-QUAL reaches in the LRGWQI model. The pollutant concentrations in irrigation return flows, used in the LRGWQI model of water quality, were derived from Enciso (2012). To evaluate the effectiveness of agricultural BMPs, Texas A&M Agrilife Researchers documented the differences in the flow volume and concentrations of several pollutants of concern in irrigation return flows collected at the edge of several irrigated agricultural fields in the Arroyo Colorado watershed, a watershed adjacent to the Lower Rio Grande/Río Bravo on the US side. The author and his collaborators made some adjustments of the initial literature-derived concentrations during the calibration of the LRGWQI models of water quality.

Table 1-15 lists estimates of pollutant loads to the Lower Rio Grande/Río Bravo from irrigation return flows, as calculated by the author using the LA-QUAL output of the LRGWQI model. The author averaged the load of pollutants of concern generated by the model for the calibration periods associated with the five synoptic surveys of water quality conducted in 2014, 2015 and 2016 to represent the average daily load of pollutants of concern from irrigation return flows.

Livestock and Domestic Animals

The spatial analysis method used by the author and his Mexican collaborators to characterize livestock and domestic animal populations in the US and Mexican LRGWQI sub-basins was modified from Lynch (2012). The method relies on county and municipio level agricultural census values for animal populations of interest, which include cattle, horses, sheep and goats. As decided by the BTWG, domestic pigs, chickens, ducks and geese were excluded from the analysis; unlike grazing livestock animals, these species are generally confined to areas where direct steady state nonpoint source pollutant contributions to surface waters do not occur (e.g., pens and coops). The resulting estimates of livestock and domestic animal populations in the US and Mexican LRGWQI sub-basins, categorized by species, are used in the Animal Loadings component of the Nonpoint Sources module of the LRGWQIDSS.

For each of the counties included in the US portion of the LRGWQI watershed, the author calculated the densities of the cattle, horses, sheep and goats per square kilometer using the county-level animal population values reported in the USDA's Census of Agriculture (USDA, 2007) and the area of each LRGWQI county. The author then calculated the area of land, that supports grazing, in each the US sub-basins of the LRGWQI watershed. Lynch (2012) defines grazing animal habitats as being the forest, shrub, and grass/pasture land use categories, which were the land use categories in the BEHI binational land use layer used by the author (Figure 1-72). Using municipio-level Mexican agricultural census data (INEGI 2007a, INEGI 2007b), IMTA technical representatives used the same procedure to determine the density of animals in the Mexican municipios included in the Mexican portion of the LRGWQI watershed and they calculated the area of land, that supports grazing, in the Mexican sub-basins of the LRGWQI watershed using the BEHI binational land use layer.

The author and technical representatives of IMTA used equation 1 (modified from Lynch, 2012) to calculate the total number of grazing animals in US and Mexican LRGWQI sub-basins. The equation multiplies the area of grazing habitat in each sub-basin by the density of each of the four types of grazing animal in the county/municpios in which the sub-basins are located.

$$AN_j = AR_j * \rho_{ij} \qquad (1)$$

Where AN_j is the total number of animals in each sub-basin j (animal count), AR_j is the total area of grazing habitat (km^2) in Sub-basin j, ρ_i is the density of animals in county/municipio i in which sub-basin j is located (animal count/km^2). The resulting counts of the five domestic animal species (cattle, horses, sheep and goats) are included in the Animal Loadings component of the Nonpoint Sources module of the LRGWQIDSS.

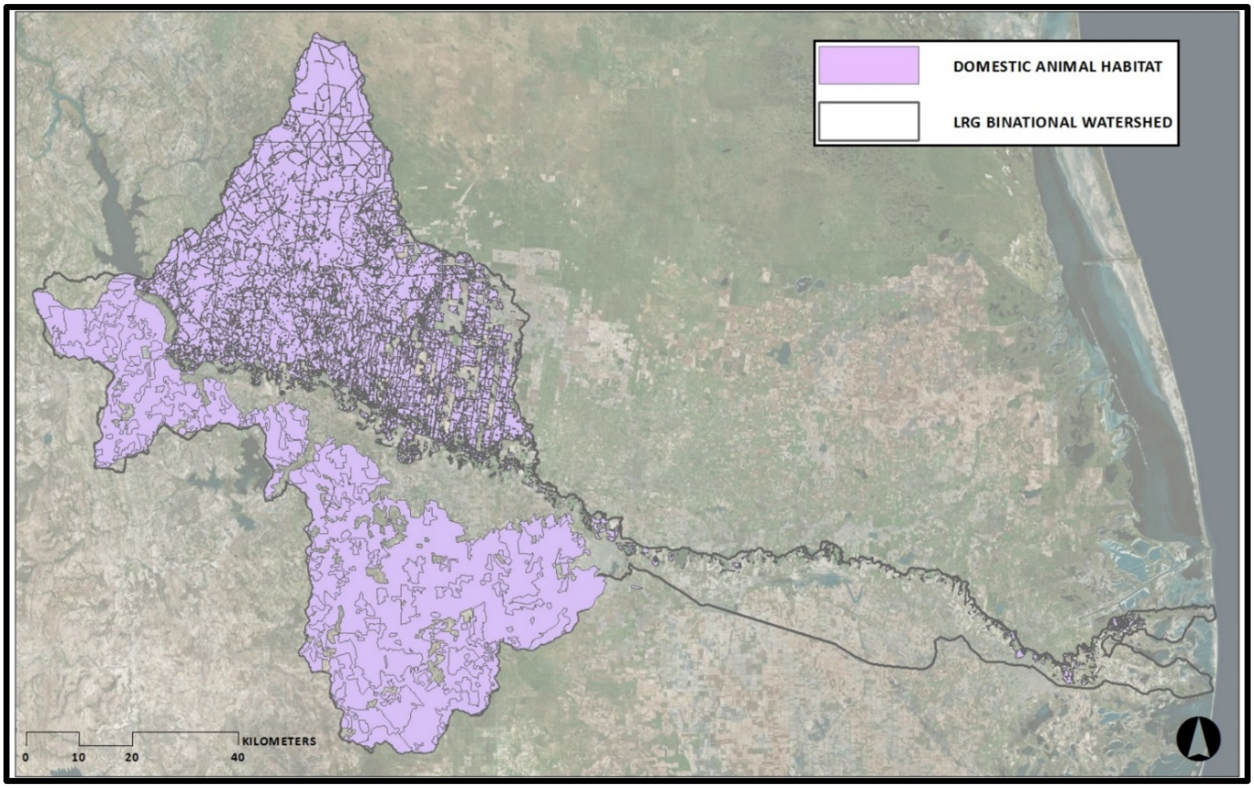

Figure 1-72. Grazing Habitat for Livestock and Domestic Animals in the Lower Rio Grande/Río Bravo Watershed (i.e., Forest, Shrub, and Grass/Pasture Land Use Categories in the Binational Land use/land cover GIS Layer Developed as Part of the BEHI [USGS, 2015]).

Pollutant Loading Estimates for Livestock and Domestic Animals

Using the number of livestock and domestic animals estimated in each US and Mexican LRGWQI sub-basin, the author calculated the potential daily loading of pollutants of concern from livestock and domestic animals to each of the LRGWQI model reaches by multiplying the animal counts estimated for each LRGWQI sub-basin by daily pollutant production rates estimated from literature-derived manure (urine and feces combined) production rates and manure pollutant composition values for each domestic animal species. The manure production rates and manure composition values used in the calculations were derived from the American Society of Agricultural Engineers (ASAE) Standard D384.2 (2005). For pollutants not listed in the ASAE standard D384.2, such as TSS, TDS and total nitrogen, the author used conversions of total solids values and stoichiometric ratios of pollutants to biochemical oxygen demand (BOD), respectively, found in ASAE (2005).

Since the LRGWQI characterizes water quality in the Lower Rio Grande/Río Bravo under steady state conditions, the initiative considered loadings of pollutants of concern from livestock and domestic animals in situations where direct deposition of these pollutants is occurring (i.e., direct defecation and urination into the river or one of its contributing tributaries, drains or ditches). This assumes that livestock and domestic animals spend a small fraction of their time directly in or very near the water, estimated in Lynch (2012) to be 1.4% of the time. Following the method adapted from Lynch (2012), the author applied an attenuating factor, to the total daily pollutant loading values, equal to the maximum amount of time livestock and domestic animals are likely to spend directly in the Lower Rio Grande/Río Bravo or one of its tributaries (estimated). The author and his collaborators adjusted this attenuation rate during the LRGWQI model calibration process. This method of estimating pollutant loadings from livestock and domestic animals, is coded into the LRGWQIDSS and forms the basis for estimating steady state nonpoint source contributions from livestock and domestic animals in the Animal Loadings component of the LRGWQI's Nonpoint Sources module.

WILDLIFE NONPOINT SOURCES

Like livestock and domestic animals, wild animals also contribute pollutants to the Lower Rio Grande Río Bravo. While the magnitude of the wild animals' potential contribution to water quality degradation is generally smaller than those of other pollution sources, pollutant contributions from wildlife must be taken into account to construct an accurate model of water quality in the river. The analysis methods used by the author and his Mexican collaborators to characterize the populations of wild animals in the US and Mexican LRGWQI sub-basins was modified from Lynch, 2012. The data sources used include the binational land use GIS layer developed as part of the BEHI (USGS, 2009) and estimates of wildlife population densities from (1) Texas Parks and Wildlife Department (TPWD, 2010), (2) The Institute of Renewable and Natural Resource at Texas A&M University (Texas A&M, 2011), and (3) Smith, 2002**.** Three wildlife species were chosen by the BTWG for the analysis, deer, feral hogs and migratory waterfowl, based on their abundance and impact on water quality.

Deer and Feral Hogs

Unlike livestock and domestic animals, which graze openly and can often access surface water bodies at will within their grazing areas, wild animals tend to concentrate in riparian corridors. Following Lynch (2012), LRGWQI the author defined a 300-foot (91 meter) riparian wildlife corridor to account for this tendency. The author assumed a standard density of wild animals of interest in all the LULC types in which the species are typically found. Following Lynch (2012), the author assigned the land use categories of forest, shrub, grass/pasture, agriculture, and wetlands as the habitats for both deer and feral hogs. The author selected these land use categories from the BEHI binational land use layer and combined them into a single deer and feral hog habitat layer (Figure 1-73).

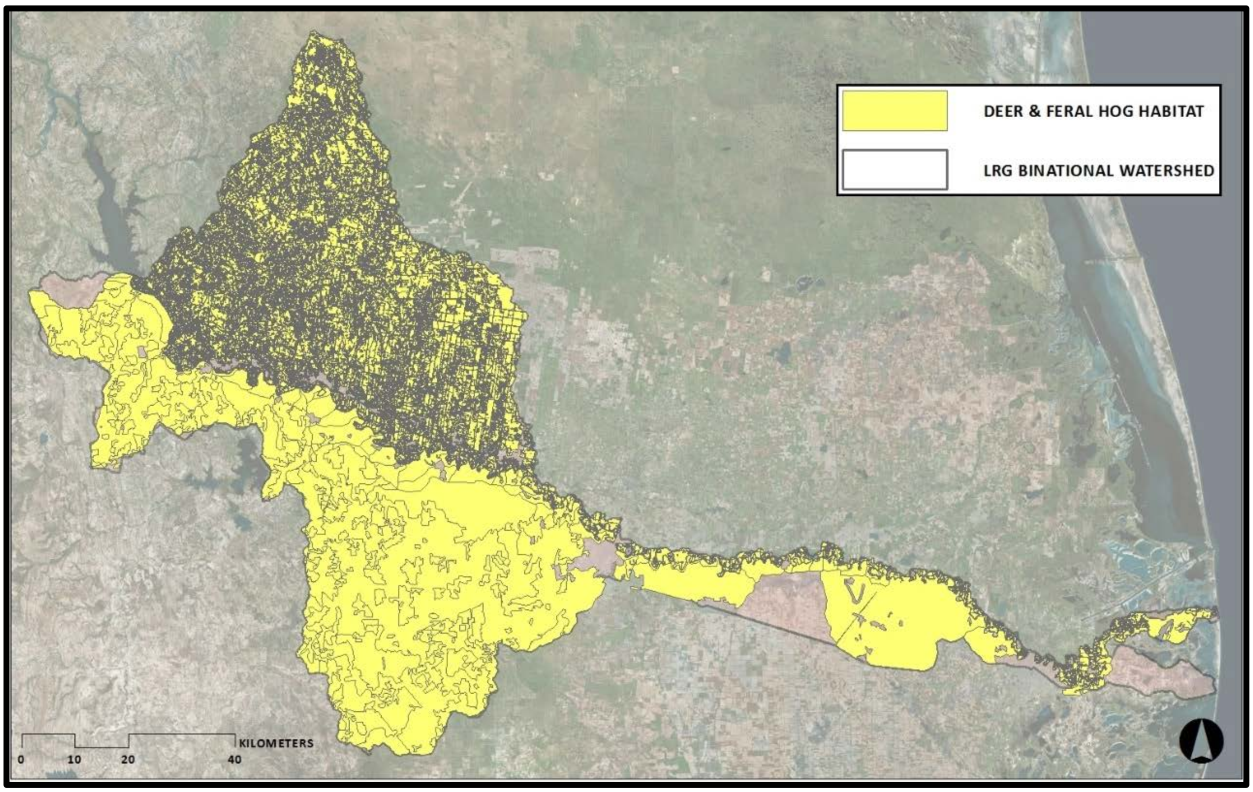

Figure 1-73. Dear and Feral Hog Habitat in the Lower Rio Grande/Río Bravo Watershed. Source: BEHI (USGS, 2015).

The spatial analysis used by the author to estimate deer and feral hog populations in the riparian wildlife corridors of each of the LRGWQI sub-basins required the intersection of three polygon layers, the combined binational land use layer obtained from the BEHI, intersected by the

91-meter riparian wildlife corridor buffer, and the resulting layer intersected by the LRGWQI sub-basins polygon layer, which imputed the wildlife populations as attributes to the LRGWQI sub-basins layer.

In Texas, deer populations are monitored according to Range Management Units, which are units of land in which deer concentrations are surveyed by the Texas Parks and Wildlife Department. Resource Management Unit Number 8 includes the US portion of the Lower Rio Grande/Río Bravo watershed. From the most recent surveys available at the time of analysis, 2009 and 2010, the TPWD estimated that Resource Management Unit Number 8 had a deer density of 3.21 deer per square kilometer (TPWD, 2010). For Feral Hog population densities, the author used values derived from Texas A&M University's Institute of Renewable and Natural Resource, which estimates densities of feral hogs in Texas ranging between 0.51-0.95 hogs per square kilometer (Texas A&M Institute of Renewable Natural Resources, 2011). The author used a value of 0.95 hogs per square kilometer in the analysis.

Equation 2 calculates the total number of deer and feral hogs in the riparian corridors of a given LRGWQI sub-basin (US and Mexican) as the product of the total area of suitable habitat for each animal of interest (deer or feral hogs) within the riparian corridors of that sub-basin and the population density of that species in TPWD Wildlife Management area 8.

$$ANW_j = HB_j * \rho' \qquad (2)$$

Where ANW_j is the total number of wildlife animals of interest in the riparian corridors of sub-basin j (#), HB_j is the total area of suitable habitat in the riparian corridors of sub-basin j (km^2), and ρ' is the wildlife animal of interest population density ($\#/km^2$). For deer, ρ' is the animal density in TPWD in management unit 8 (which encompasses the entire US portion of the LRGWQI watershed). For feral hogs, ρ' is the animal density estimated by Texas A&M University's Institute of Renewable and Natural Resource (2011). Since no deer or feral hog population estimates were available for the Mexican side of the LRGWQI watershed, the author used US wildlife animal population densities for the same suitable habitats in the riparian wildlife corridors of the Mexican LRGWQI sub-basins.

Waterfowl

The Texas Gulf Coast is an important location for seasonal waterfowl migrations. Many of the waterfowl in the Texas Gulf Coast stay in the wetland areas of the Rio Grande delta, defined by Tunnel (2002) as the area which divides the Laguna Madre in Texas from the Laguna Madre de Tamaulipas; from the coast to approximately the Brownsville/Matamoros urban area (Tunnel, 2002). The area is the favored wintering grounds for many types of wild geese, as well as mottled ducks and green-winged teal ducks. Other types of migratory and coastal waterfowl can also be found in the Lower Rio Grande/Río Bravo watershed. However, the dominant waterfowl species in the Lower Rio Grande/Río Bravo watershed are wild geese and ducks (Lynch, 2012).

Following the method described in Lynch (2012), the author estimated population densities for waterfowl in the LRGWQI watershed using the percentages of the most abundant species in the Rio Grande Delta, from Smith (2002), and multiplying them by the waterfowl population in the Lower Texas Coast area, a value derived from a survey conducted by the USFWS during the 1980-81 winter season (USFWS, 1981), and the four county area comprising Rio Grande Delta. The author then used the resulting population densities, 31.77 #/km^2 for wild geese and 34.54 #/km^2 for wild ducks, in the analysis of waterfowl species in the Rio Grande Delta area.

The land uses included in waterfowl habitat in the LRGWQI watershed are water and wetlands (Lynch, 2012). As with the spatial analysis to characterize deer and feral hog habitats, the author selected these land use categories from the BEHI binational land use layer and combined them into a single waterfowl habitat layer (Figure 1-74). The spatial analysis to characterize waterfowl populations also required the intersection of three polygon layers, the combined water and wetland land use layer from the BEHI binational land use layer, intersected by the 91-meter riparian wildlife corridor buffer, and the resulting layer intersected by the LRGWQI sub-basins polygon layer, which imputed the waterfowl populations in each sub-basin as attributes to the US and Mexican LRGWQI sub-basins layers. Of the approximately 197 km^2 total water and wetlands area in the Lower Rio Grande/Río Bravo watershed, the author estimated a total of 22.4 km^2 of suitable habitat for waterfowl within the riparian corridors (91m buffer) in the Lower Rio Grande/Río Bravo watershed.

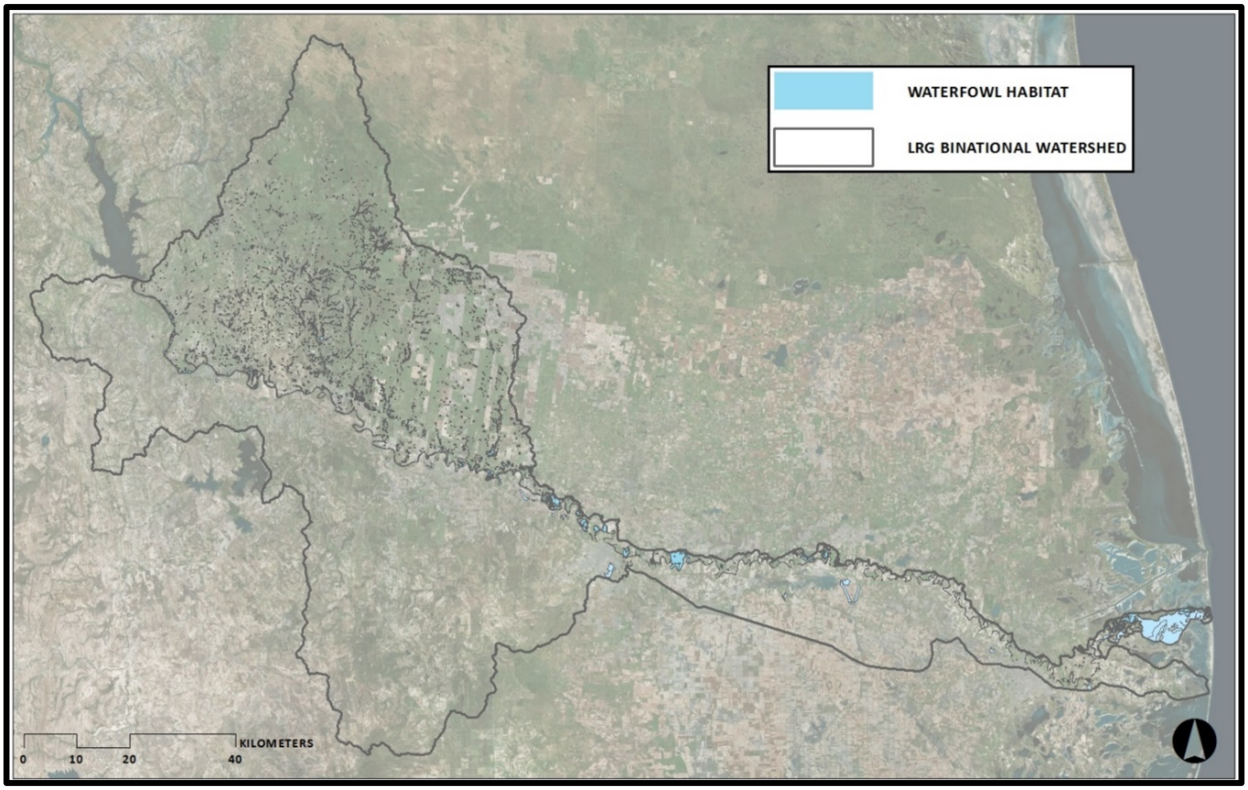

Figure 1-74. Waterfowl Habitat in the LRGWQI Watershed.

Unlike the assumption of even population densities across suitable habitats made for the population analysis other wildlife species, spatial densities of waterfowl are considered more variable. Following the method described in Lynch (2012), the author incorporated a migratory corridor distance factor, which decreases the population densities of wild geese and wild ducks with distance from the coast using an inverse distance weighting factor based on the distance from the Rio Grande Delta area (i.e., decreasing population densities from east to west). The author applied the variable densities of waterfowl (geese and ducks) to the LRGWQI sub-basins based on the distance of the sub-basin centroids to the Gulf of Mexico coast.

Equation 3 calculates the total number of waterfowl species in the riparian corridors of a given LRGWQI sub-basin (US and Mexican) as the product of the total area of suitable habitat for each animal of interest (wild geese or wild ducks) within the riparian corridors of that sub-basin and the population density of that species in (31.77 #/km^2 for wild geese and 34.54 #/ km^2 for wild ducks) adjusted based on the distance of the sub-basin centroid to the Gulf of Mexico Coast (i.e., the distance from Falcon Dam to the Gulf Coast divided by the distance from the sub-basin centroid to the Gulf coast).

$$NWF_j = HB_j * \rho * k_j \qquad (3)$$

Where NWF_j is the total number of waterfowl of interest in the riparian corridors of sub-basin j (#), HB_j is the total area of suitable habitat in the riparian corridors of sub-basin j (km^2), ρ is the density of waterfowl species in the Rio Grande/Rio Bravo Delta area ($\#/km^2$), and k_j is the migratory corridor distance factor (unitless) for sub-basin j. Figure 1-75 shows a visual example of the results of the geospatial analysis conducted by the author to estimate the number of domestic and wildlife animals of interest in the Lower Rio Grande/Río Bravo watershed.

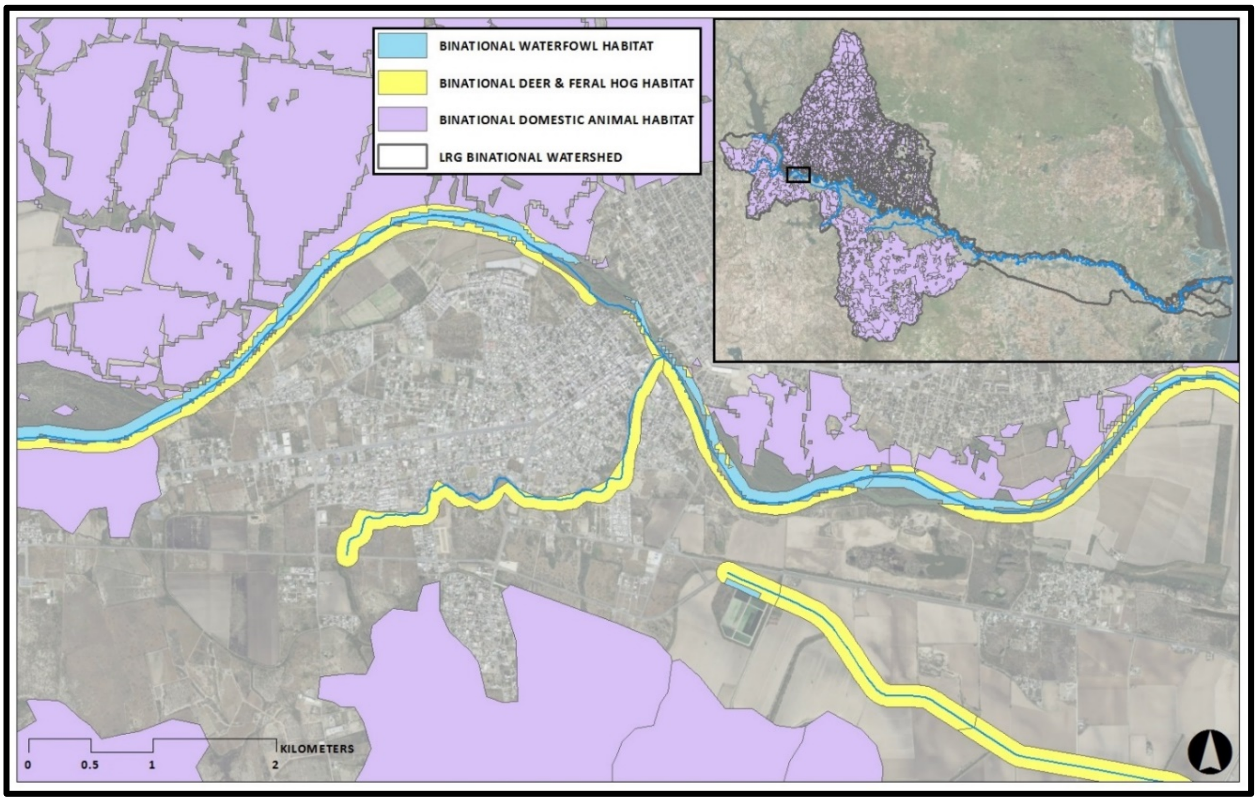

Figure 1-75. Geospatial Analysis of Domestic and Wildlife Animal Populations in the Lower Rio Grande/Río Bravo Watershed.

Pollutant Loading Estimates for Wildlife

Using a method identical to that used for livestock and domestic animals, the author used the population numbers of wildlife species of interest found within the riparian corridors (91m) of the US and Mexican LRGWQI sub-basins in combination with best professional estimates of wildlife excrement composition and production rates to calculate the potential daily average loading rates of constituents of concern to the LRGWQI model reaches. Since the author could not find excrement composition or production rates in the technical literature for deer, feral hogs and waterfowl, he used manure composition and production values associated with sheep and ducks, from ASAE Standard D384.2, as surrogates. The author used sheep manure production rate and composition to represent deer and feral hogs. However, the author multiplied sheep manure production rate values by a factor of 1.5 for use in feral hog loading calculations. This was based on the assumption that feral hogs produce more excrement per day than sheep. Similarly, the author used half of the ASAE domestic duck manure production values to calculate daily loading rates of pollutants of concern for waterfowl based on the assumption that migrating waterfowl produce approximately half the waste produced by domestic ducks.

As with the calculation of livestock and domestic animal loadings, the author assumed that deer and feral hogs spend only a small fraction of their time directly in the water, where direct defecation can occur under steady state conditions. To account for this, the author applied the same attenuation factor, to the total constituent loading calculations as he did to livestock and domestic animal loading estimates (0.014). The author and his collaborators adjusted to these attenuation rates moderately during the LRGWQI model calibration process. The use of surrogate excrement composition or production values in the calculation of constituent loading rates for wildlife species introduces a higher level of uncertainty in these loading estimates. Consequently, the results of these calculations contain a higher level of uncertainty than the results of similar calculations associated with residential and agricultural nonpoint sources. Fortunately, the number of deer, feral hogs and waterfowl thought to contribute pollutants of concern to the Lower Rio Grande/Río Bravo is small compared to the number of contributing livestock, domestic animals and residential nonpoint sources of pollution to the river. This is reflected in the population and loading values estimated in Tables 1-18 and 1-19 (Page 93). The method for estimating steady state nonpoint source pollutant loadings to the Lower Rio Grande/Río Bravo from wildlife, described in this section, is coded into the LRGWQIDSS and forms the basis for estimating pollutant contributions from these animals in the Animal Loadings component of the LRGWQI's Nonpoint Sources module.

CHAPTER 2: TRANSBOUNDARY WATER QUALITY MANAGEMENT AND DECISION SUPPORT

2.1 Transboundary Water Quality Management

Water quality management is an important component of the broader field of water resources management. Traditionally, water resources management's focus on water quality has been on ensuring the suitability of the resource for its intended uses, such as agriculture, industry, or human consumption, which entails evaluating the quality of source waters and protecting water resources from natural and anthropogenic sources of pollution. With increasing industrialization, a growing urban population, and increasing scarcity of fresh water resources throughout the world, national governments and international institutions have placed a greater emphasis on water quality protection in recent decades. In transboundary situations water resources management is complicated by issues associated with national sovereignty. In some instances, depleted and degraded transboundary water resources may cause social unrest within and between countries. To deal with the problems posed by the management of transboundary water resources, an integrated approach based on legal and institutional frameworks and shared benefits and costs, must be developed and implemented (United Nations Water Program [UN-Water], 2018).

According to the UN-Water, there are 263 transboundary lake and river basins spread out over almost half the Earth's surface; 145 nations have territory in these basins and there are approximately 300 transboundary aquifers helping to serve 2 billion people who depend almost entirely on groundwater from these aquifers (UN-Water, 2018). Since 1948, 295 international water agreements were negotiated and signed, including the UNECE Water Convention, a legal framework for transboundary water cooperation worldwide; initially available only to countries in the pan-European region but globally available since 2003. Approximately two-thirds of the world's transboundary rivers currently do not have a cooperative management framework (UN-Water, 2018).

International agencies have consistently suggested a strong link between successful transboundary water resources management frameworks and the equitable governance of transboundary water bodies. For example, the UN cites effective and resilient institutional frameworks as a key factor in sustainable transboundary water resources management efforts (UN-Water, 2018).

2.1.1 TRANSBOUNDARY WATER RESOURCES MANAGEMENT FRAMEWORKS

The legal and institutional frameworks under which transboundary decision-making is conducted dictate, at least in part, the operational boundaries under which transboundary water resources management occurs. Therefore, it stands to reason that a review of transboundary water resources management agreements might yield valuable information about institutional factors that influence transboundary decision domains such as that of the LRGWQI. It also stands to reason that the information obtained as a result of such efforts, in turn, could be useful in designing a transboundary DSS for water quality management such as the LRGWQIDSS. A number of water resources management frameworks and protocols have been developed that incorporate institutional dimensions; some of these frameworks have been applied to transboundary water bodies.

2.1.1.1 Integrated Water Resources Management (IWRM)

First proposed in 1992 as a best practice concept for water resources management at the World Summit on Sustainable Development in Rio de Janeiro – Agenda 21, IWRM is based on the so-called “three pillars” of sustainable resource management (also known as the 3E principle): Economic Efficiency, Equity, and Environmental Sustainability (Figure 2-1). Simply stated, the IWRM concept is based on the notion that water should be used to provide economic well-being to people, without compromising social equity and environmental sustainability (Hassing et al., 2009). The emergence of IWRM was largely in reaction to increasing scarcity and pollution in surface and subsurface fresh water systems all over the world and to the demonstrated linkage of these problems to fragmented and isolated sectoral water management practices.

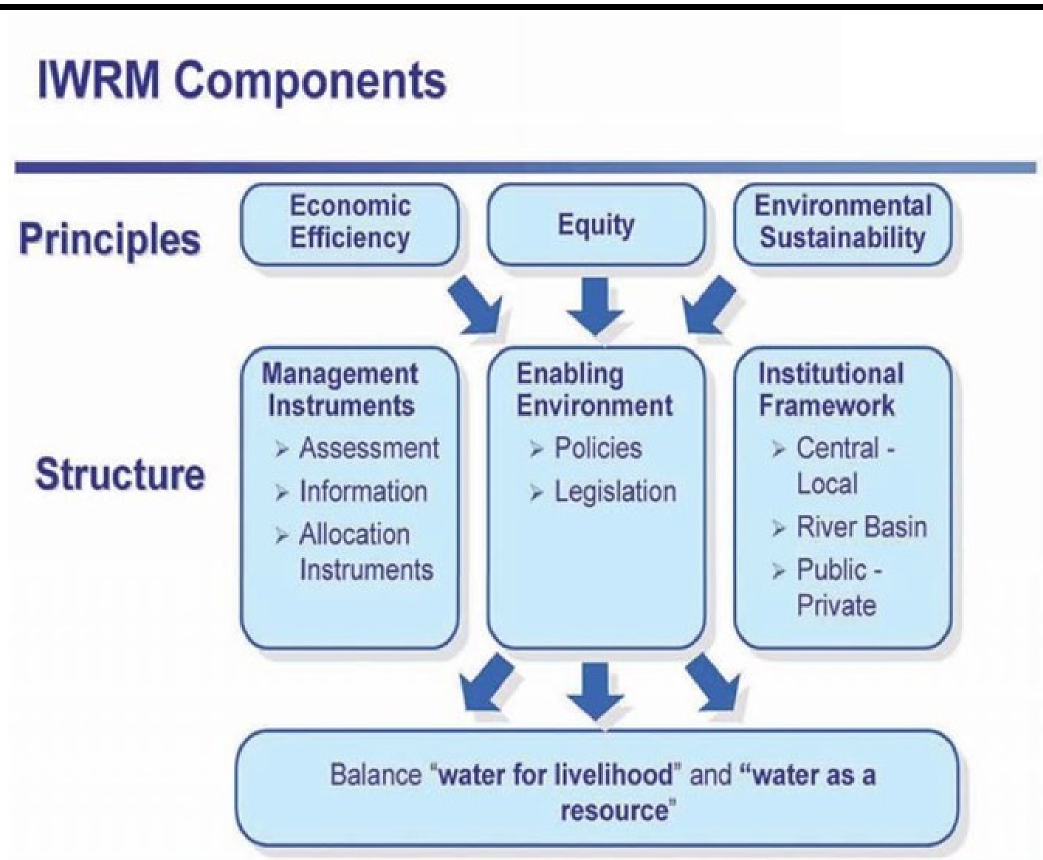

Figure 2-1. Integrated Water Resources Management Component "Pilars." Source: Modified from Hassing et al., 2009.

Thus, beyond the broad 3E conceptual principals, IWRM advocates for the management of water resources in a basin-wide or aquifer-wide context, with robust stakeholder participation and under the prevalence of good governance. Currently, IWRM is universally promoted by the environmental and resource conservation organizations of the UN as *the* framework for water resources planning and management efforts at virtually any jurisdictional scale, including transboundary settings. The UN Environment Programme (UNEP) tracks the implementation of IWRM through its IWRM Indicator 6.5.1 database, which it makes available to the public (http://iwrmdataportal.unepdhi.org/).

According to UNEP, to implement IWRM, a collective action environment must first be established in which appropriate policies, strategies and legislation can be enacted. This is followed by the building of an institutional framework through which these policies, strategies and legislation can be implemented. Next, the management institutions and instruments can be established and empowered. The concept is to combine the best land and water management practices through broad-based stakeholder participation to effect multiple co-benefits to stakeholders in a multitude of sectors and economic levels (UNEP-DHI, 2009). Monitoring of progress is an important part of the IWRM process along with assessment, reform and adaptation to particular situations. Though not explicitly stipulated in the literature, international guidelines for the implementation of IRWM promote the creation of river basin organizations, which are conducive to cooperation and encourage a holistic approach to water resources management.

Despite concerted efforts, on the part of international organizations such as the UN, to promote the implementation of IWRM, the feasibility of the approach in transboundary settings has been questioned by some water resources management experts. In the view of some researchers, the IWRM concept is overly broad and theoretical, making it difficult to implement. Some scholars regard IWRM's attempt to simultaneously cover all water-related activities under one management structure as problematic in that orchestrating a system comprised of units having responsibilities for multiple aspects of water use is, at best, challenging and potentially infeasible in practice (Mohile, 2005). Also, the competition for water among different sectors such as agriculture, industry, domestic use, navigation, and recreation is severe in many river basins. In these situations, environmental and ecological considerations can be relegated to secondary priorities until these concerns begin to visibly affect the sustainability of the resource. In transboundary river basins, IRWM becomes even more challenging, as the competing interests of the riparian governments come into play.

In many cases IWRM plans are developed cooperatively by transboundary basin organizations only to encounter serious lags in implementation. Researchers have suggested that implementation of IWRM plans covering multiple sectors and a wide variety of actors requires appropriate institutional capacities and a proper consideration of the political environment in the particular river basins where the plans are to be implemented (Mehtonen, Keskinen & Varis, 2008). For this reason, the establishment of effective and adaptable national and transboundary institutions is fundamental to the IWRM process in any transboundary river basin.

In transboundary settings, implementation of IWRM is often handled by transboundary commissions, which are tasked with coordinating the planning, management and financing activities among riparian countries, financial organizations and donor countries. According to UNEP (2009), cooperation between the riparian countries, which is a prerequisite for IWRM in transboundary river basins, is possible only through the establishment of effective transboundary institutions.

2.1.1.2 Community Based Natural Resource Management (CBNRM)

Imbedded within the broader concept of IWRM, CBNRM seeks to address the apparently perennial problem of stakeholder disenfranchisement within centralized water resources management structures and especially in marginalized communities that have little or no political representation. Proponents of CBNRM argue that community empowerment in the management of natural resources results in more effective and efficient institutional structures. In this aspect, CBNRM is in line with the principal tenets of Institutional Rational Choice theory (Ostrom, 1990), which maintains that common pool resources are best managed by community-based collective choice arrangements and not by higher levels of government or the free market. CNBRM builds on the IWRM concepts of economic efficiency, equity and environmental sustainability, but incorporates an institutional approach that favors the empowerment of local communities, encouraging the participation of local people in the identification of problems that affect their communities as well as in the design and development of strategies to address these problems.

Most applications of CBNRM have been documented in developing countries, especially in the countries of southern Africa and the Ivory Coast, where CBWRM, has been successfully integrated and aligned with the national development and planning policies of the countries where the user communities are located (Jones, 2007; Tantoh & Simatele, 2015). However, very few examples exist of CBWRM application to transboundary water resources. Mohamed (2016) proposed a form of CBWRM for the Tigris-Euphrates Basin using the principles of the Human Integrated Management Approach (HIMA). Interestingly, the approach proposed by Mohamed (2016) focuses on implementing CBWRM in a limited portion of the transboundary basin, the Kurdistan region in the headwater area of the basin. This geographically limited approach is a departure from the basin-wide IWRM approach. Nevertheless, Mohamed (2016) argues that

CBWRM can play an important role in transforming how water resources are managed in the Tigris-Euphrates Basin. Schultz (2012) documented several community-based participation initiatives introduced by existing transboundary river basin organizations. Although, it is unclear if the initiatives Schultz studied can be accurately classified as CBWRM, the study showed the willingness of established transboundary water resources management institutions to engage local communities in decision-making.

2.1.1.3 Non-Integrated Water Resources Management Aproaches

While the principles of IWRM are grounded in solid research into the factors that affect the effectiveness of policies and management strategies used to sustainably develop water resources, a growing number of scholars have criticized the rigidity by which international development organizations and financial institutions promote IWRM. Their arguments are based mainly on case studies in which alternative methods have yielded functional management systems and, conversely, on case studies in which IWRM has failed to adequately manage water resources either by failing to provide access to the resources equitably or by failing to do so in a sustainable manner.

Contextual Transboundary Water Resources Management

Contextual Water Resources Management portends that, while the principles of IWRM are indisputably effective in developing water resources in a sustainable manner, implementation of IWRM rarely occurs in a “blank slate” water resources management situation. In most cases, the community of water users in catchments, watersheds, river basins and aquifers around the world have developed some form of water governance system which has evolved through time. In some cases, the systems are not equitable, or protective of the resource, or resilient enough to manage their water resources sustainably. In other cases, water quality management systems are effective and efficient enough to warrant careful consideration of the existing institutions, local knowledge, socioeconomics, and political and environmental conditions. Therefore, advocates of Contextual Water Resources Management support a more flexible approach to IWRM implementation, including in transboundary situations.

Some arguments for Contextual Water Resources Management challenge long held principles of IWRM. For example, Shah (2014) argues that, while involving local input is advantageous in reaching consensus about a particular management approach, sometimes local participation is not necessary for achieving viable solutions to the management of water resources. As an example, Shah cites the outcome of a central government intervention in China's Hubei Province, where increased water allocation to urban centers was offset by the construction of ponds to capture runoff in rural areas. These actions also reduced the overall amount of water farmers used for irrigation, albeit out of necessity. As a result, water production increased in rural areas of the province along with rice production. An alternative approach, such as the involvement of local farmers in decision making, may or may not have yielded such benefits to both of the sectors involved. The system appears sustainable as long as water reallocations continue to be offset by other actions that help competing sectors.

Another argument for Contextual Water Resources Management involves the differing levels of economic modernization of riparian countries. Developed countries tend to have water systems that work within well-defined legal and regulatory frameworks. Less developed countries may have informal "water economies" that are poorly regulated and are influenced by socio-economic barriers to development (i.e., low education levels, government corruption, etc.). Proponents of Contextual Water Resources Management suggest that formal approaches to water management, such as those advocated by IWRM through laws and higher-level institutions, do not work well in less developed countries without first establishing a basic level of infrastructure and intermediation (Giordano & Shah, 2014). This point is especially important in transboundary situations where one or more developed countries share water resources with less (or more) economically developed riparian neighbors.

Proponents of IWRM often argue for the river basin to be the natural management unit for water resources management, especially in transboundary settings. However, of the 450 international water treaties signed since 1820 only about a quarter of all treaties cover the entire basin to which they apply (Giordano et al., 2013). In theory, the lack of participation of one or more riparian countries in a transboundary agreement can undermine the collective efforts of all riparian nations to manage the water resources of a shared water body. From a practical perspective, sustainable development of water resources can be achieved in a variety of settings without a governance structure or agreement covering an entire river basin.

Giordano and Shah (2014) make this argument by pointing to case studies in which bilateral and multilateral treaties have achieved success in managing water resources without covering the entire transboundary river basin. Perhaps the case study most germane to the Lower

Rio Grande/Río Bravo is that of the Columbia River, a boundary water that crosses the US and Canada border. Seven different agreements have been signed between the two nations regarding the management of boundary waters that straddle both countries. Arguably, since 1944, the management of water allocation, hydroelectric power generation, navigation and environmental quality have been handled sustainably in the Columbia River Basin, despite the fact that the transboundary agreements signed by the US and Canada cover storage within the Canadian portion of the Columbia basin in general but are limited in the United States to the Columbia main stem and to a lesser extent the Kootenay tributary of the Columbia River (Giordano & Shah, 2014).

It is important to reiterate that Contextual Transboundary Water Resources Management proponents do not argue against the principles of IWRM. Their argument is to recognizethe inflexibility by which international organizations, world financial institutions, and donor countries implement the concept in practice. They propose a more thoughtful consideration of the socio-economic, cultural, and political situations existing in the riparian countries in which IWRM implementation is contemplated. The ability of an existing institutional system or "water economy" to incrementally develop a management style that adheres more closely to the principles of IWRM is dependent on many factors, one of them being the ability of IWRM practitioners to develop a flexible approach to implementing IWRM.

American Society of Civil Engineers / Environmental and Water Resources Institute (ASCE/EWRI) Standard 33-09

Within the realm of transboundary water resources management approaches that do not adhere strictly to the principles of IWRM are a number of suggested guidelines for developing bilateral and multilateral agreements for cooperation on the management of shared water resources. These guidelines, while often comprehensive, sometimes allow the flexibility to develop agreements focusing on a particular aspect of water resources management or on a limited geographic area. One such set of guidelines with particular relevance to the LRGWQI is the ASCE/EWRI Standard 33-09, "Comprehensive Transboundary Water Quality Management Agreement with Guidelines for Development of a Management Plan, Standards and Criteria." Originally published in 2001 as ASCE/EWRI Standard 33-01, the standard was revised in 2013 to include guidance on the development of water quality management plans for transboundary water bodies.

ASCE/EWRI Standard 33-09 provides a comprehensive framework which can be adopted or modified by riparian governments seeking to undertake comprehensive, or more narrow approaches to, water resources planning and management of shared water resources. Based on the concept of "shared sovereignty," the standard offers a template for developing legal agreements, between sovereign governments, to manage water resources in cooperation with one another. The intent of the standard is to be sufficiently flexible to be used across borders of sovereign governments in a variety of geopolitical settings. Although ASCE/EWRI Standard 33-09 itself is comprehensive in its scope, addressing all aspects of water resources management and advocating a basin-wide approach where appropriate, the standard offers the riparian governments involved the flexibility to define the geographic extent of the transboundary waters subject to the agreement, as well as the flexibility to define a limited purpose and scope for the agreement.

At the conceptual center of ASCE/EWRI Standard 33-09 are several ideas that guide the development of transboundary water resources management agreements. One of these ideas is the notion of bilateral/multilateral data collection and information sharing. Riparian governments adopting the standard agree to "…provide sufficient data to the other Parties to verify beneficial use. The [standard for the] Agreement suggests that information acquisition costs be apportioned so that data collection, environmental assessment, and inventories of basin water user efforts should be systemic in nature…" (ASCE/EWRI 2009). The standard further suggests an analysis be conducted prior to, or concurrently with, the development of the agreement to examine the factors that influence water resources management, including the identification of current and potential future sources of pollution and their impacts on transboundary water quality. According to the standard, the analysis and supporting data are to be updated and shared among the parties to the agreement.

Another central concept of ASCE/EWRI Standard 33-09 is the joint exercise of sovereignty over shared water resources (i.e., shared sovereignty). Commonly, transboundary agreements reserve the sovereign right of each signatory to develop its own water resources, including transboundary waters. However, a number of these agreements allow for some level of level of cooperation with allowances for certain uses that affect the industrial and commercial privacy of the signatory country or its national security. Some scholars have pointed to the de facto establishment of shared governance of transboundary waters as an adaptive management process that evolves with time under an existing international agreement, as the parties to the agreement develop a requisite level of trust and establish a good working relationship (Sherratt & Davies, 2018). Article 1, Section 2 of ASCE/EWRI Standard 33-09 encourages parties to transboundary water resources management agreements to establish the institutional framework needed to build the trust and cooperation necessary for the evolution of shared sovereignty over transboundary water resources.

ASCE/EWRI Standard 33-09 also provides guidelines for the development of water resources management plans, which it promotes as the basis for management of transboundary water resources. As a subset of these guidelines, the standard provides a stepwise procedure for establishing a water quality management strategy (Figure 2-2).

The procedure outlines the general steps that are to be taken to assess water quality, develop water quality goals, devise a plan to implement controls, monitor water quality and develop enforcement mechanisms. As a general guide for strategy development, Standard 33-09 guidelines do not provide details on how a transboundary water quality management plan should be developed. However, the commentary included in the standard alludes to several important tools for decision support, including joint data collection, data sharing, and joint analysis. It is in the crucial third step of the process outlined in Figure 2-2 that decision support tools would be most valuable.

An important concept introduced in ASCE/EWRI Standard 33-09 is the concept of Total Maximum Daily Load or TMDL. As mentioned in Section 1 of this dissertation, TMDLs are essentially limits on the amount of pollutants allowed to enter a water body on a daily basis. Introduced for the first time in the US federal Clean Water Act, TMDLs are essentially an estimate of the capacity of a water body to assimilate pollutants. In this respect, TMDLs can be considered a beneficial use of a water resource which can be allocated much like flow or water volume. Accordingly, the ASCE/EWRI Standard 33-09 treats TMDLs essentially as an allocable component of transboundary water resources that must be negotiated in a manner similar to water allocation. While TMDLs for some pollutants can be estimated using simple analytical methods, the analyses necessary to make these estimates can be technically complex, even for conventional pollutants such as fecal indicator bacteria or dissolved oxygen in ambient water. Estimates of TMDLs typically involve the use of water quality models to predict water quality resulting from specific pollutant loading levels.

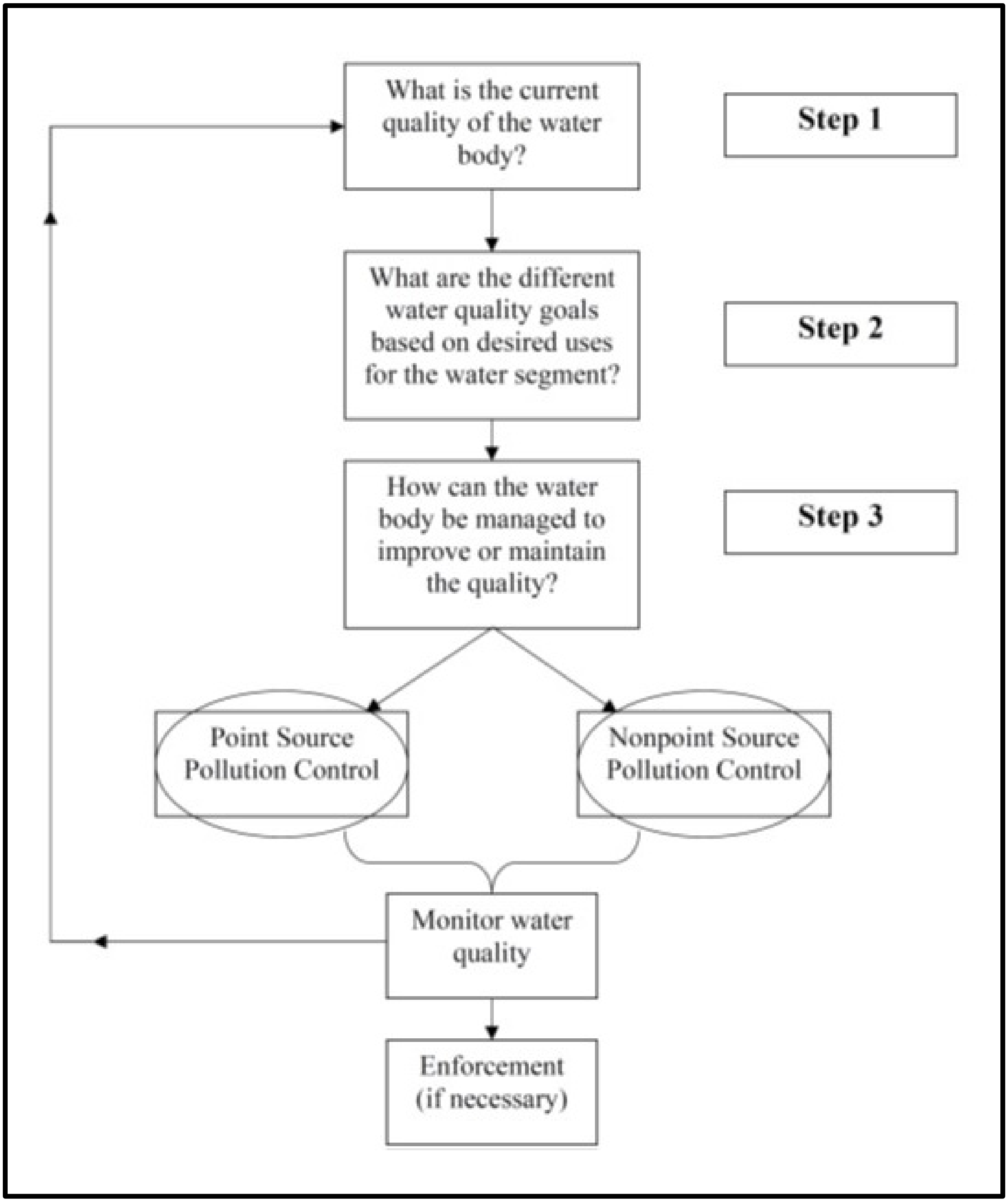

Figure 2-2. Guidelines for Transboundary Water Quality Management. Source: ASCE/EWRI, 2009.

Although flexibility is built into the ASCE/EWRI Standard 33-09, the standard is designed for transboundary water bodies which currently lack bilateral or multilateral water resources management agreements. Much of the standard is devoted to outlining the institutional structure suggested for transboundary water resources management and the obligations and authorities associated with those institutional entities and associated organizations (i.e., Treaties, Agreements, and Commissions). In the case of the LRGWQI, some of these components of transboundary water resources management have existed for over a century. Nevertheless, the flexibility incorporated into ASCE/EWRI Standard 33-09, and the background it provides as an instrument that evolved from existing transboundary agreements, makes the standard a good template for developing a binational water quality management agreement under the LRGWQI.

2.1.2 REVIEW OF TRANSBOUNDARY WATER RESOURCES MANAGEMENT AGREEMENTS[4]

As part of the LRGWQIPRP, described in Sub-section 1.0.11.1 of this dissertation, the author reviewed summaries of 450 international, freshwater-related agreements, covering the years 1820 to 2012. The main source of the summaries and ancillary information was the International Freshwater Treaties Database, a comprehensive database of international treaties, protocols, and agreements on the use, allocation, and stewardship of transnational streams and lakes compiled and maintained by Oregon State University's (OSU's) Program in Water Conflict Management and Transformation (OSU, 2011). Most transboundary river treaties in the OSU database are negotiated agreements on boundary disputes, water allocation, fishing, flood control, irrigation, hydro-electric power, or navigation of shared waters. While the number of transboundary water treaties and agreements in the OSU database is extensive, the number of treaties that address transboundary water quality issues is very limited. Of the 450 agreement summaries reviewed, cooperation on water quality was mentioned as a component or activity in only 90 agreements and very few examples where evident of two or more nations planning and/or implementing water quality improvements cooperatively. The most common examples of bi-national collaboration

[4] The content of this sub-section of Chapter 2 draws, in part, from the research conducted in support of the 2013 Report titled "International Water Quality in the Lower Rio Grande/Rio Bravo," co-authored by David Eaton and Roger Miranda. (See UT-LBJ, 2013a)

were limited exclusively to information exchange and bilateral and multilateral communications regarding unilateral efforts.

Nevertheless, binational and multinational treaties and collaboration efforts can be considered case studies used to assess the effectiveness of various binational and international institutional arrangements in protecting transboundary water resources. More importantly, these case studies can provide insight into the institutional factors that influence binational and multinational decision-making in transboundary water resources management.

The author selected 6 case studies to examine in detail, from the 90 transboundary water agreements in the OSU database, in which cooperation on water quality was mentioned as a component or activity. To develop the case studies, the author conducted additional research on the aspects of the selected transboundary agreements that shed light on the institutional factors affecting the decision domains in each transboundary situation and which are most relevant to the decision domain and decision situation represented by the LRGWQI.

2.1.2.1 Case Studies

The following sections describe seven selected cases in which nations manage transboundary rivers under international agreements that include some provision for water quality management. The river basins in the case studies represent a wide spectrum of industrial, economic and political conditions existing in developed nations, such as the European nations of the Rhine and Danube River valleys, and also of developing nations, such as those of the Lempa watershed, and the Mekong, Nile and Zambezi River Basins. Some of the knowledge gained from these case studies informed the design and development of the LRGWQIDSS.

CASE STUDY 1: THE LEMPA WATERSHED (CENTRAL AMERICA)

The Lempa is the longest river in Central America and one of the most important water resources for the people of the region (Lopez, 2009). Located in the humid, tropical Trifinio region of Central American, at the intersection of El Salvador, Honduras, and Guatemala, the headwaters of the Lempa are located in the mountainous and volcanic region of southeastern Guatemala where four rivers, the Río Chacalapa, Río Tepoctún, Río La Planta, and Río Olopita come together over a 30 km portion of an extensive tropical rain forest system that covers nearly the entire watershed (Figure 2-3).

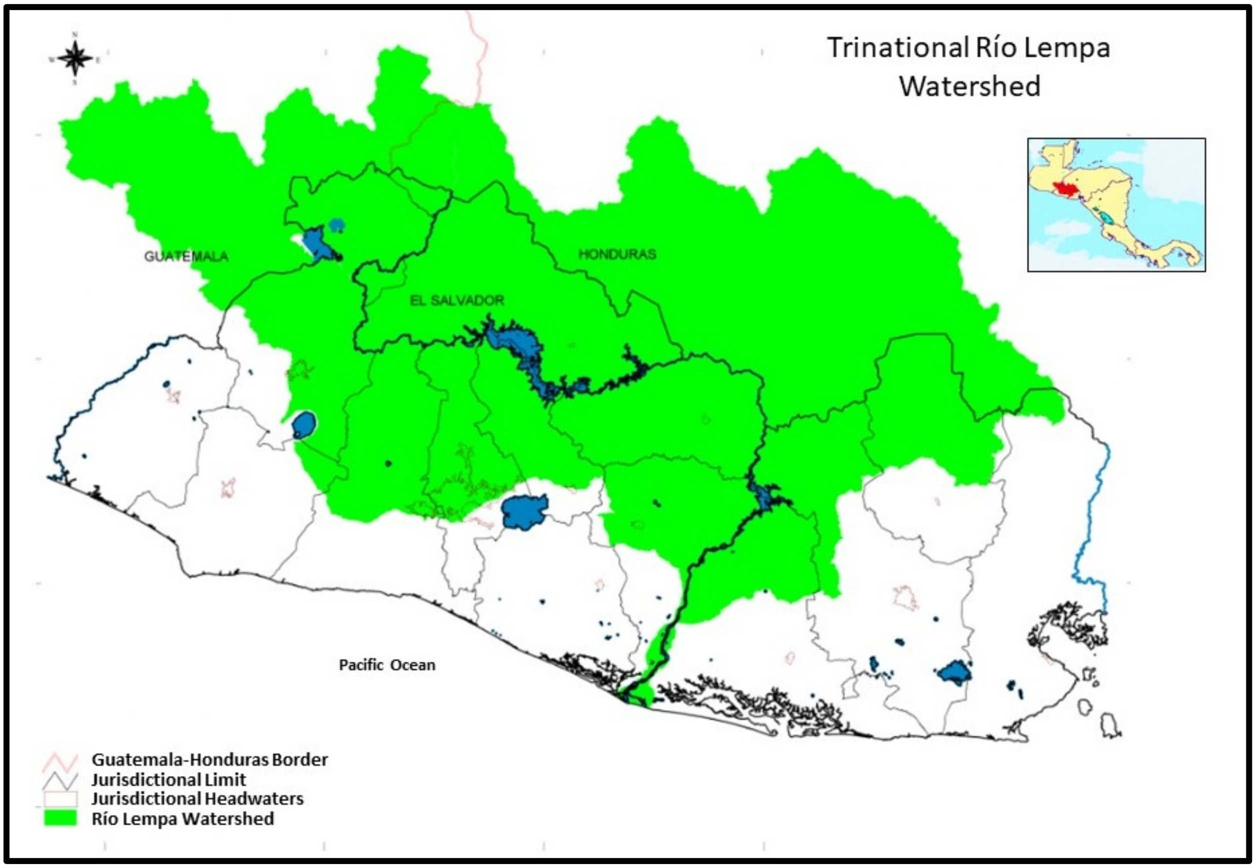

Figure 2-3. The Lempa River Watershed. Source: Modified from Ríos Del Planeta (2016); http://riosdelplaneta.com (Original Source: Ministerio de Medio Ambiente y Recursos Naturales de El Salvador).

Through its 462 km journey to the Pacific Ocean, the Lempa crosses into Honduras and then into El Salvador where, over a 39 km stretch, it forms the border between these two countries after having traversed approximately 200 km through northern El Salvador. The river then flows south through mainly agricultural land in El Salvador to the Pacific Ocean.

A tri-national agreement among the governments of El Salvador, Guatemala, and Honduras, the Trifinio Plan Treaty established a Trinational Commission, composed of the vice presidents of the Republics of Guatemala and El Salvador, to oversee the implementation of the Trifinio Plan and its permanent updates with administrative, financial, technical and legal status. The Trifinio Plan began in 1986 as a pilot project for the reforestation of 6,000 hectares of the

Trifinio Ecological Zone, which was ravaged by the civil war in El Salvador. Initially funded by the European Union, the plan was developed in phases and has been revised twice, in 1992 and 2004. Formalized by the creation of the Trinational Commission of the Trifinio Plan (the Commission), the trinational treaty that codified the institutional framework of the commission was ratified by all three governments in April 1999. In addition to the Trinational Trifinio Plan Commission, the institutional framework of the Trifinio Plan includes a Trinational Technical Unit, a Consultative Committee of the region's mayors, and a consortium of nongovernmental organizations from all three countries who assist the Commission in implementing the Plan. The number of stakeholders involved with the Trifinio Plan has increased over the years, especially during the processes of revising the plan.

The plan revisions completed in 2004 identify specific pollution problems in the watershed. The plan cites inadequate waste control and lack of education as significant risk factors to the health of residents in both urban and rural areas of the watershed. Access to basic sanitation (water and waste disposal) is an especially pervasive problem in rural areas, which contributes to high levels of fecal coliform contamination. The most recent Trifinio Plan revision includes goals for economic growth, infrastructure, social development, institutional development, and the support of ecosystem and watershed environmental needs through pollution control measures. Specifically, the plan revision listed the following additions as components of the plan in 2004:

- Promotion of measures to reduce and control pollution of soil, water and air
- Facilitation of pollution control in the three Trifinio countries and raising awareness to bring about change in attitudes towards the environment
- Identification and implementation of technical and economic solutions for disposal of liquid waste, solid and gas concentrations generated by urban and industrial and mining activities
- Construction of water and sewage treatment plants in rural and urban areas
- Installation of solid waste disposal sites for major urban centers in the Trifinio Region

Since 1987, the Trifinio Plan Tri-national Commission has approved and sought financing for 28 tri-national studies and projects outlined in the Plan. Funding for the projects has come from a variety of sources, including the Inter-American Development Bank, the United Nation's Revolving Fund for Natural Resources Exploration, the Organization of American States (OAS), the International

Union for Nature Conservancy, the Norwegian Agency for Development Cooperation, the German Technical Cooperation Agency, the Japan Special Fund, the Central American Bank for Economic Integration, and the governments of the United States, Sweden, Spain, the Netherlands, Germany, Canada, and Japan. Some funding for Trifinio Plan projects has come from the three Trinational Commission Governments, but the bulk of the funding for plan projects has come from loans and grants received from external sources.

By all accounts, the Trifinio Plan has improved transboundary cooperation on water resources management among El Salvador, Guatemala, and Honduras. The cooperation has, in turn, increased transnational stakeholder involvement, a fact widely credited with having helped the plan become more successful over time (Artiga, 2003). While strides have been made in habitat conservation in the watershed, empirical assessments of water quality have shown little change in pollutant levels in the Lempa river since the Trifinio Plan was implemented. An assessment of the Trifinio Plan Treaty conducted by the Global Water Partnership (GWP) in 2016 concluded that the Trifinio experience "exposes the limitations of top-down processes not accompanied by strategies designed by local actors" (GWP, 2016). The GPW assessment found a lack of efficiency and sustainability in the actions of the Trinational Commission and faulted the a top-down approach and centralized management structure, which relied solely on the decision-making of the national ministries involved.

Institutional Factors with Potential Relevance to LRGWQIDSS Design – Case Study 1

The Trifinio Plan Treaty case study highlights several institutional factors with potential relevance to the LRGWQIDSS design, even though the setting in the Lempa river watershed differs in many ways from that of the Lower Rio Grande/Río Bravo. For example, the treaty is a trilateral agreement between three developing countries with weak, unstable governments in nations which suffer from social unrest. However, the decision situation shares some similarities with the LRGWQI, including a major pollutant of concern from a similar source (i.e., fecal bacteria from inadequate sanitation), a segment of the river that demarcates an international boundary between two countries, and a transnational commission that implements an established international treaty. According to the assessments reviewed as part of the case study, three main institutional factors are pointed out as influencing decision making that affects the sustainability and the effectiveness of Commission actions, (1) involvement of top-level government officials, (2) scant involvement of stakeholders at the local level, and (3) financial viability of proposed actions, which has attracted outside investment. Especially relevant to the LRGWQI, is the criticism the Trifinio Plan Tri-national Commission has received for its top-down management practices, which is cited as contributing to unsustainable outcomes.

CASE STUDY 2: THE NILE BASIN (EAST-CENTRAL AND NORTHEAST AFRICA)

The Nile River has been cited as one of the longest rivers in the world (Liu et al., 2009). Fed by the Central African highland streams that sustain it, Lake Victoria has historically been cited as the headwaters of the iconic Nile River. However, the hydrology of the Nile headwaters is much more complicated and includes a chain of smaller lakes and reservoirs connected by tributaries, including the Rutshuru, Semeliki, Albert Nile, and Victoria Nile Rivers which flow into the "Mountain Nile" portion of the White Nile in South Sudan. The Blue Nile, a major tributary to the Nile, originates in the highlands of Ethiopia and joins the White Nile in Sudan at the capital city of Khartoum. In all, the Nile River Basin includes territory in 12 countries, including Burundi, Chad, the Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda (Figure 2-4). In 1999, the ministries of water affairs (to use a generic term) of 10 of the 12 countries formed the Nile Basin Initiative (NBI), with Eritrea in an observer capacity; Chad did not participate in the agreement.

The NBI is led by the Nile Council of Ministers and is assisted by a Technical Advisory Committee and a Secretariat based in Entebbe, Uganda. The shared vision, as stated in its charter, is "achieving sustainable socio-economic development through the equitable utilization of, and benefit from, the common Nile Basin water resources." Motivated primarily by pervasive disputes over water appropriation, the original focus of the NBI was on establishing trust and building capacity among the participating governments. With collaboration on large-scale storage, conveyance and hydroelectric projects as its main initial goal, the Initiative's scope has expanded to include conservation, environmental protection, and socio-economic projects of mutual interest to participating riparian nations. For example, the NBI's Transboundary Environmental Action Project, proposed in 2003, established programs for basin-wide water quality monitoring.

Figure 2-4. The Nile River Basin. Source: Nile Basin Initiative (2010) http://www.nilebasin.org

As part of this effort, a set of common water quality indicators were developed, and baseline water quality assessments were conducted in the upper portions of the Nile and its tributaries. In 2013, The NBI developed an Environmental and Social Policy Document, which outlined the initiative's social and environmental policies and described the specific institutional arrangements ensuring environmental protection, including the role of the national agencies of the riparian nations in these efforts. The document also declared that national-level measures, while playing critical roles in their own right, could not sufficiently address basin-wide and transboundary full-scale impacts and threats, which it stated must be addressed through cooperative efforts (NBI, 2013).

Indeed, water quality remains an important concern in various parts of the Nile River and its tributaries. Despite impressive efforts, recent evidence points to the ecological situation in the Nile Basin becoming more precarious than ever before (Paisley, 2017). Water quality in the Lower Nile is especially poor, with assessments showing high levels of nutrients, including excessive levels of ammonia, BOD, and metals being among the most pervasive pollutants (Badr, El-Sonbati & Nassef, 2013). Some researchers have pointed to Egypt's one-sided domination of the hydropolitics in the basin as a cause for deteriorating cooperation and commensurately deteriorating of water quality (Swain, 2002).

The NBI has been successful in its ability to fund important collaborative studies and projects. Early in its development the NBI formed the Nile Basin Initiative Development Partnership, which included 17 bilateral and multilateral donors. The Partnership is coordinated by the World Bank, which provides financial support and also facilitates the project development process. To meet the complex needs of the NBI, the World Bank and other national and international organizations use a range of financial mechanisms to support the Initiative's activities and projects, including an existing $100 million multi-donor trust fund administered by the World Bank, in addition to direct unilateral and multilateral support (World Bank, 2016).

Included among those projects is the development in 2013 of a state-of-the-art DSS and data warehouse. The NBDSS is a multicriteria, environmental DSS with multiple water resources and socio-economic modeling capabilities. The uses of the NBDSS, documented by the NBI, include supporting the development of the Lake Tana Basin Integrated Water Resources Plan in Ethiopia, modeling of the Sebeya dam for flood control in the Sebeya River Catchment of

Rwanda, addressing water management issues in the Nyando catchment in Kenya, and supporting the development of a water permitting system in the Mukungwa catchment of Rwanda. Of the documented uses of the NBDSS, only the Lake Tana Plan involves aspects of water quality management and protection, and only within Ethiopia.

Institutional Factors with Potential Relevance to LRGWQIDSS Design – Case Study 2

Perhaps more so than with Case Study 1 (Trifinio Plan of the Lempa River Watershed), the setting in the Nile River Basin differs in many ways from that of the Lower Rio Grande/Río Bravo. The number of riparian countries and water resources issues associated with the NBI makes it a poor institutional analogue to the LRGWQI. While water quality issues appear important enough to have been addressed in detailed policy and institutional arrangements, they do not seem to have been the impetus for the formation of the initiative and appear to be secondary to other water resources management issues, especially development. Nevertheless, some institutional factors in Case Study 2 do appear to have some relevance to the LRGWQI. Like Case Study 1, the involvement of top-level, ministerial, officials and the financial viability of studies and projects are also evident in the Nile River Initiative operation. The NBI, however, does not seem to place much emphasis on local stakeholder involvement. Egypt's power asymmetry with other riparian nations (Swain, 2002), which may arguably be a factor in the failure to mitigate water quality problems in the Nile River, as described by other researchers studying the relationship between riparian states sharing transboundary waters (e.g., Jägerskog & Zeitoun, 2009). The disparity in economic power and global political status between the United States and Mexico also is a factor when evaluating the decision situation associated with the LRGWQI and in the design of the LRGWQIDSS.

The most useful element of Case Study 2 is the NBDSS which was used to develop the Lake Tana Integrated Water Resources Plan. The NBDSS is a versatile transboundary decision support tool used by a number of participating riparian nations for a variety of uses, including the development of a watershed plan that includes water quality management and protection (i.e., the Lake Tana Plan). However, within the context of a discussion of the institutional factors incorporated into the design of the NBDSS, two important factors can be highlighted. Although documented uses of the NBDSS are limited to national applications, the NBDSS provides access to a multinational repository of water quality data. The NBDSS development process was preceded by an effort to develop common water quality indices for the Nile River system.

CASE STUDY 3: THE ZAMBEZI RIVER (SOUTH CENTRAL AFRICA)

Zambezi River Basin is the fourth-largest river basin in Africa. The Zambezi River flows 3000 kilometers from its source in the central African highlands to the Indian Ocean. The Basin includes a range of subtropical terrains in eight countries, including Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe (Figure 2-5).

Figure 2.5. The Zambesi River Basin. Source: Modified from Wikimedia Commons (2019) https://commons.wikimedia.org/wiki/File:Zambezi_watershed_plain.png.

A general lack of sanitation and environmental controls in the water courses in the basin fostered a concern on the part of the riparian nations of the Zambezi River Basin in the early 1980s. In 1987, all eight riparian countries of the Zambezi River Basin signed an Agreement on an Action Plan for the Environmentally Sound Management of the Zambezi River. The plan focused on addressing environmental issues identified by the riparian countries of the Zambezi River Basin. Implementation of the Zambezi River Basin Action Plan was very slow and ineffective and did not function to promote environmentally sound management of the river and its tributaries (Nakayama, 1999). Nakayama (1999) attributed political factors for the lack of effectiveness of the plan, including: (1) a reluctance on the part of riparian countries to implement the full plan for fear of negative economic consequences; (2) the plan received only limited support at high government levels; and (3) operational assistance was not given by the donor community. The Zambezi River Basin Action Plan was, however, instrumental in promoting collaboration of the riparian countries in the basin, which inspired the development, in 1998, of the Protocol on Sharing Water Course Systems drafted by the South African Development Council (SADC). The SADC is composed of 16 member countries, including all Zambezi Basin riparian states.

The SADC Protocol was revised in 2000. In July 2004, 7 of the 8 Zambezi River Basin riparian states signed the Agreement on the Establishment of the Zambezi Water Course Commission (ZAMCOM). At the time ZAMCOM was created, Zambia, an important riparian nation, had not signed the agreement and the agreement lacked key institutions such as a Council of Ministers and a Permanent Secretariat. In 2013, the Norwegian Government began financially supporting ZAMCOM. In 2014, Zambia joined the agreement becoming a full member of the Commission. ZAMCOM is composed of a Council of Ministers which provides direction for the ZAMCOM Secretariat, a professional body responsible for the day to day operations of ZAMCOM. A Technical Committee (ZAMTEC) provides technical advice to both the Council of Ministers and the Secretariat. In addition to overseeing Project Implementation Units and Working Groups, the ZAMCOM Secretariat receives input from a Basin-wide Stakeholders Coordination Committee and a National Stakeholders Coordination Committee, acting as a conduit for communication between these committees and the ZAMCOM Council of Ministers.

ZAMCOM manages and develops the water resources of the Zambezi River, including water storage and conveyance and hydroelectric projects. The commission also coordinates water quality monitoring in the water courses of the basin, compiling and disseminating data to riparian nations and the public. However, aside from developing a strategic plan with general recommendations for water quality improvement, ZAMCOM has not conducted studies or implemented projects specifically targeting water quality improvement. In 2010, the World Bank reported that the incidence of waterborne disease attributed to untreated sewage effluent was still widespread in the Zambezi River Basin (World Bank, 2010). There are few indications that this situation has improved in the subsequent decade.

Institutional Factors with Potential Relevance to LRGWQIDSS Design – Case Study 3

As with the previously discussed case studies, the setting in the Zambesi River Basin differs in many of the same ways from that of the Lower Rio Grande/Río Bravo watershed. Again, the number of riparian countries and water resources issues associated with Case Study 3 make comparison to the LRGWQI challenging. The literature available on the Zambezi River Basin Commission Agreement reveals that, while dating back to the mid 1980's, the formation of the institutional framework for transboundary water resources management in the Zambezi River Basin is relatively recent. In contrast, the IBWC has been in existence since 1889. Notably, water quality issues appear to have been a driving force for the ZAMCON agreement, although the first concrete actions of the commission have been water resources development projects. Case Study 3 reinforces the importance of (1) the involvement of top-level, ministerial, officials and (2) financial viability. In the case of ZAMCOM, however, the importance of financial viability is extended to include not only the institution's outcomes (i.e., studies and projects), but of the institution itself.

Of special relevance to the design of the LRGWQIDSS is the creation of the Zambezi Water Resources Information System (ZAMWIS), which is used by ZAMCOM to inform the decision-making and planning processes in the Zambezi Basin. While not described as a DSS, the ZAMWIS is an interactive, web-based data and information system based on contemporary and historical spatial data, hydrological time series, earth observation information, knowledge products and other related information. The system became operational in 2013, enabling riparian states to routinely share data and information, thereby helping to foster basin-wide cooperation. To augment decision support efforts, ZAMCOM is developing a basin-wide Decision Support System (DSS) which will be added to the ZAMWIS system. ZAMCOM describes the functions of the DSS simply as "supporting planning, operations, management and monitoring-related functions." The coupling of an information system with a decision support tool is a feature of ZAMCOM with relevance to the LRGWQI.

CASE STUDY 4: THE DANUBE RIVER (CENTRAL AND SOUTHEAST EUROPE)

Described as Europe's second longest river, the Danube flows for 2,857 kilometers from the Alps to the Black Sea, draining a basin area of 817,000 km². The basin incorporates territories in 19 riparian countries, including Albania, Austria, Bosnia and Herzegovina, Bulgaria, Croatia, the Czech Republic, Germany, Hungary, Italy, Macedonia, Moldova, Montenegro, Poland, Romania, Serbia, the Slovak Republic, Slovenia, Switzerland and Ukraine (Figure 2-6). One of the most international river basins in the world, the Danube River Basin is home to an estimated 81 million people.

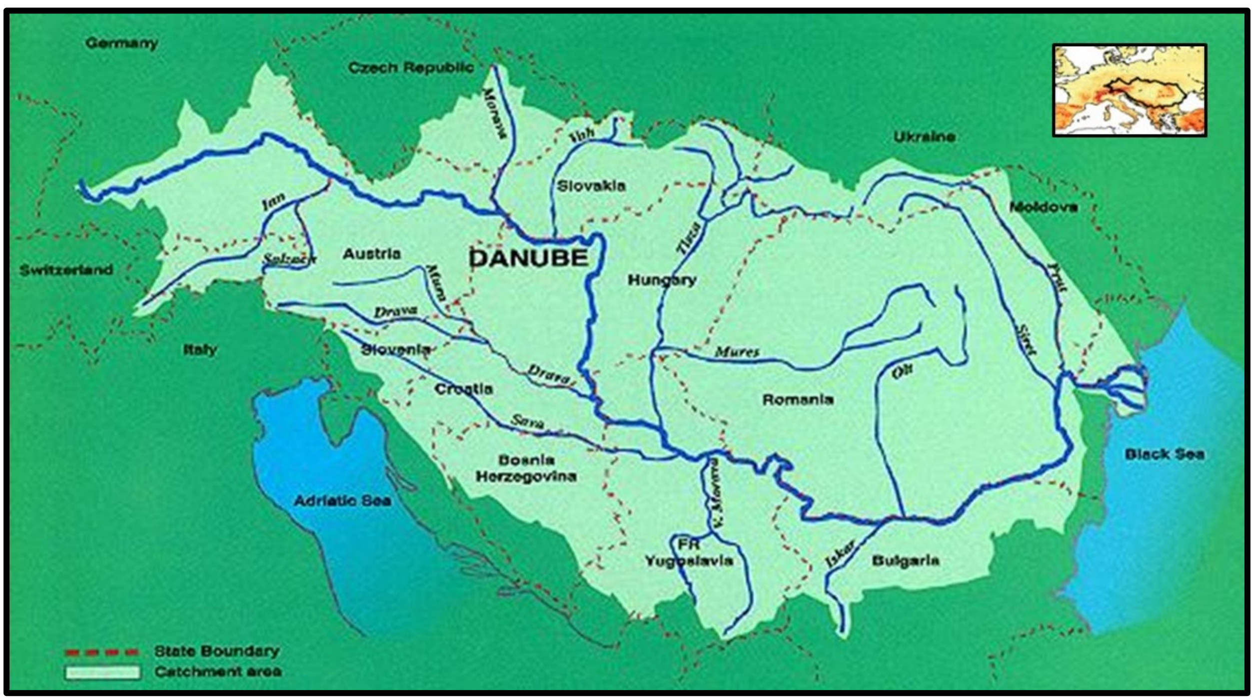

Figure 2-6. The Danube River Basin. Source: Modified from RAMSAR (2015) https://www.ramsar.org/news/new-ecological-expert-group-launched-for-ramsar-management-in-the-danube-river-basin.

By most objective measures, the Danube River is one of the most effectively managed transboundary rivers in the world. Since 1948, 18 international water agreements have been signed for cooperation on water resources in the Danube River Basin (Schmueli, 1999). While many of the agreements have focused on water allocation, flood control and the development of water resources, the institutional framework for environmental and ecological sustainability of water resources has played an incrementally important role in many of the international agreements associated with the Danube River Basin since 1991.

Water quality in the Danube river has been poor in the recent past. A 1997 case study published by the World Health Organization cited serious water quality problems associated with microbiological contamination, oxygen-depleting substances, high nutrient loads and hazardous substances in the Danube Basin (E&FN Spon, 1997). In 1991, the representatives of all Danube River Basin riparian nations, as well as some interested international organizations, developed the Environmental Program for the Danube River Basin to support and reinforce national actions to restore and protect of the Danube River. In 1994, the Danube River basin riparian nations signed the Danube River Protection Convention (DRPC). Four years later, in 1998, the International Commission for the Protection of the Danube River (ICPDR) was formed under the charter of the DRPC. The DRPC provided the wherewithal for "setting priorities as appropriate and strengthening, harmonizing, and coordinating measures taken and planned to be taken at the national and international level throughout the Danube Basin aiming at sustainable development and environmental protection of the Danube River" (Wolf & Newton, 2008).

Involved in the development of the DRPC in 1994 were the European Commission, the European Bank for Reconstruction and Development, the European Investment Bank, the Nordic Investment Bank, the United Nations Development Program (UNDP) and UNEP, the World Bank, the government of the Netherlands, the government of the US, the World Conservation Union, the World Wildlife Fund, the Regional Environmental Center, and the Barbara Guntlett Foundation. Public and NGO participation was an important factor in the development of the DRPC, as it served to reduce confrontations or conflicts among countries. Organizing entities recognized that the link between internal politics among different sectors and political constituents within a nation was influenced by the strength and resilience of an agreement reached in the international realm. The ICPDR continues to rely on the participation of local stakeholders and NGOs in strategic planning and implementation, which has permitted the basin states of the Danube River Basin to move forward rather quickly with several initiatives (Schmueli, 1999).

As part of the DRPC, and with the support of the UNDP Global Environmental Fund, convention members created the Danube Pollution Reduction Program (DPRP) to: define transboundary measures and actions; develop an investment program for national, regional and international cooperation; and control and reduce water pollution and nutrient loads in the Danube River and its tributaries. While the Program outlines several cooperative measures to protect the waters of the Danube, it does not establish specific transboundary water quality standards. Instead, it gives a general framework from which the signatories can devise appropriate water quality objectives and criteria (Schmueli, 1999).

The structure of the ICPDR is similar to that of the transboundary water agreement commissions described for Case Studies 1-3. The commission itself is composed of high-level representatives of the Danube River Basin riparian countries with territories of more than 2000 km^2 within the Danube Basin (referred to as "Contracting Parties"), though some representatives are not ministerial heads. One of the Contracting Parties is the European Union. Representatives of the Contracting Parties meet in what is termed the Ordinary Meeting Group to make "political decisions." The Ordinary Meeting Group is supported by a Standing Working Group, which provides political guidance. Eight Technical Expert Groups provide technical advice and prepare technical background documents. The Technical Expert Groups also oversee the work of technical Task Groups that perform various technical tasks.

The ICPDR has developed an extensive, publicly accessible information system (DANUBIS), which it maintains and shares with all DRPC signatories and the European Union. DANUBIS offers access to information of many types, including detailed GIS data, commission reports, news articles, and other outreach materials. The centerpiece of DANUBIS is the Danube River Water Quality Database, which contains data from ICPDR's Trans National Monitoring Network (TNMN) as well as data collected by DRPC countries and other entities. In addition to data, DANUBIS provides information on long-term trends in water quality and pollution loads in the major rivers in the Danube River Basin. Surprisingly, ICPDR does not use a single machine-based decision support tool, relying instead on a number of models and analytical tools and on expert advice from its internal and external technical and non-technical resources, including a sophisticated system of stakeholder and public involvement in decision making.

Institutional Factors with Potential Relevance to LRGWQIDSS Design – Case Study 4

By far the transboundary water agreement with the most riparian countries of all the case studies presented in this dissertation, the institutional framework of the DRPC focuses intensely on water quality issues, many of which are in common with the Lower Rio Grande/Río Bravo. As is the case with the other transboundary agreements studied for this dissertation, the history and structure of the ICPDR again reinforce the importance of the involvement of top-level officials, though not necessarily at the minister level, and of financial viability. The ICPDR appears to have leveraged its integration of public, local stakeholder and NGO involvement in decision making to reduce controversy and enhance acceptance of commission decisions resulting in accelerated implementation of environmental programs and projects.

An interesting institutional feature of the DRPC, which has an important bearing on the design of the LRGWQIDSS, is the convention's intentional avoidance of specific transboundary water quality standards for water bodies of the Danube River Basin. This feature of the DRPC, as well as other information gathered as part of the qualitative institutional analysis conducted for this dissertation, influenced the content of the TOR for the LRGWQI, which was originally drafted by David Eaton, Ph.D. of the UT LBJ School of Public Affairs, and highlighted the need for a DSS capable of supporting binational decision making related to water quality in the Lower Rio Grande/Río Bravo based on multiple numeric criteria. As is the case with ZAMCOM (Case Study 3), the emphasis placed by ICPDR on data and information availability to decision makers, stakeholders and the general public, seemingly more so than on decision support tools, is also very relevant to the design of the LRGWQIDSS.

CASE STUDY 5: THE RHINE RIVER (WESTERN EUROPE)

Less than half the size of the Danube, the Rhine River flows 1,320 kilometers from its headwaters in the Alps to its confluence with the North Sea on the Dutch shore. The river's 170,000 km^2 catchment is home to 58 million people living in 9 riparian countries of Western Europe, including Austria, Belgium, France, Germany, Italy, Liechtenstein, Luxembourg, the Netherlands and Switzerland (Figure 2-7).

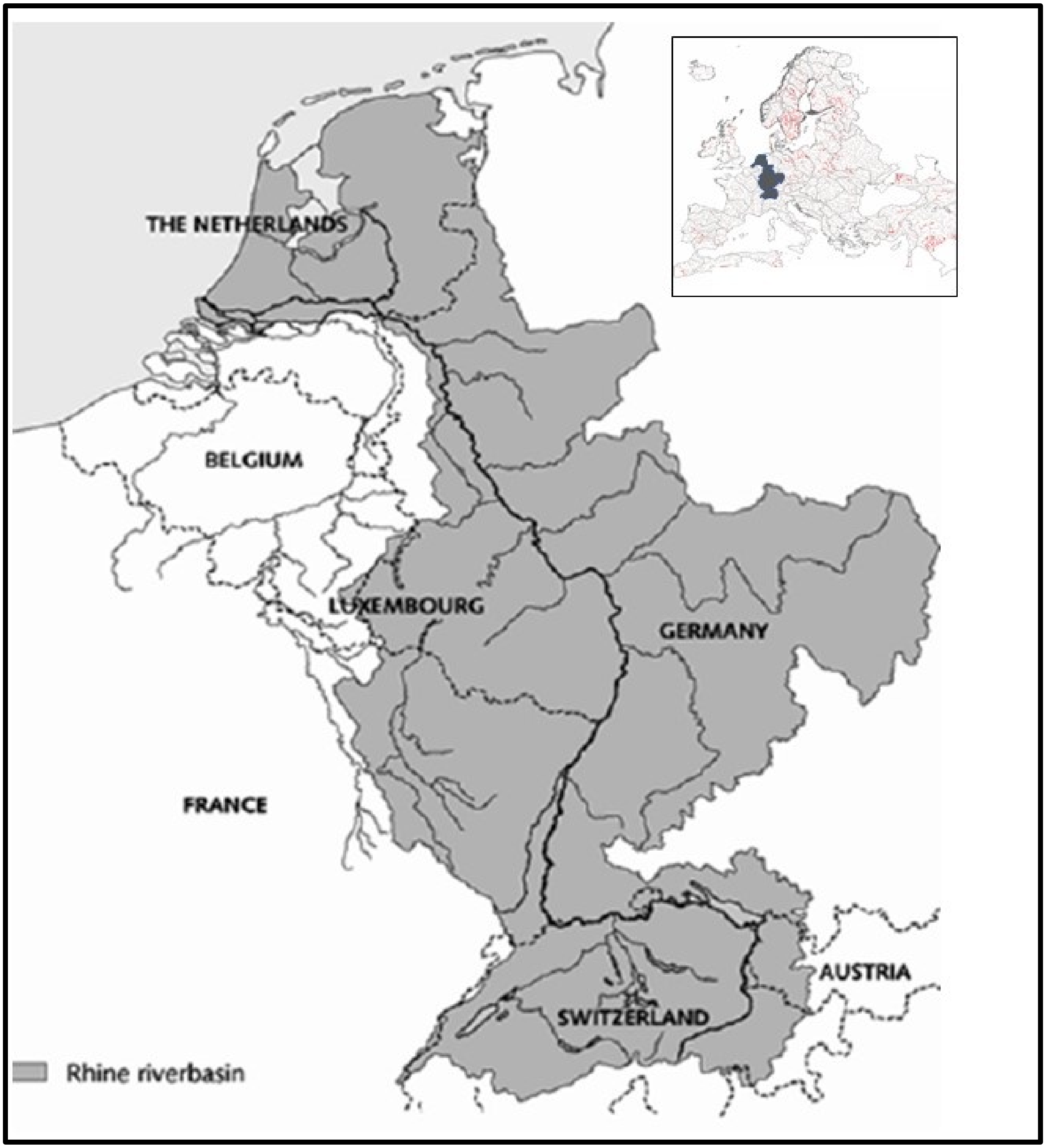

Figure 2-7. The Rhine River Basin. Source: Modified from Frijters & Jan Leentvaar (2003).

High seasonal flow in the Rhine River motivated investment in extensive flood control measures in the basin, such as the construction of dikes along the Upper and Lower Rhine. These actions have resulted in the loss of large stretches of natural floodplain and wetlands. Water from the Rhine is used for industrial production, agriculture, energy generation, municipal wastewater disposal, and drinking water, with more than 20 million people depending on the Rhine for drinking water (Frijters & Jan Leentvaar, 2003). The Rhine is also Europe's most densely navigated shipping route, connecting the world's largest seaport, Rotterdam, in the Netherlands with the world's largest inland port, Duisburg in Germany. Vast industrial complexes were built along the river, such as the Ruhr, Main, and Rijnmond areas and most of Europe's important chemical production plants are located along the Rhine. Conflict between ecological concerns and beneficial uses of the river (above all in hydropower development) have been a common occurrence in the Rhine Basin (Frijters & Jan Leentvaar 2003). Industrialization and population growth in the mid-nineteenth century lead to the discharge of large amounts of organic wastes into the river. After World War II, water quality in the Rhine deteriorated further due to inflows of poorly treated sewage, industrial waste, drainage from salt mines, and agricultural chemicals. Large amounts of hydrocarbons, heavy metals, pesticides, and volatile organic compounds were discharged into the river, causing severe water quality problems in the 1950s and 1960s. Since the 1980s water quality has improved in the Rhine River, although the river and some of its tributaries continue to suffer from water quality problems.

Multinational accords in the Rhine River Basin are some of the oldest transboundary water agreements in the world, with some accords dating as far back as the 1815 Congress of Vienna, which established the Central Commission for Navigation on the Rhine (CCNR). Revised in 1868 through the Mannheim Act and re-chartered in 1963, the CCNR is the oldest active Pan-European organization. The main charge of the CCNR is to "ensure the freedom of navigation on the Rhine and its tributaries and maintain a uniform legal regime governing navigation along the full length of the river." In 1950, Switzerland, the Federal Republic of Germany, France, Luxembourg, and the Netherlands created the International Commission for the Protection of the Rhine against Pollution (ICPR) and, in 1970, the riparian countries of the Rhine Basin formed the International Commission for the Hydrology of the Rhine Basin (CHR) to develop joint hydrological measures for sustainable development of the Rhine Basin. The three commissions operate independently of each other, but coordinate activities, cooperating on policy development and collaborating on projects.

Within the context of the LRGWQI, the ICPR is the institution with the most relevance to the LRGWQI, as it was formed specifically to address water quality concerns in Rhine Basin surface waters. By design, the ICPR is only an adviser to the governments of the riparian countries of the Rhine Basin and the European Union. The ICPR: formulates investigations into the type, source, and extent of Rhine pollution; recommends appropriate measures to reduce it; and prepares agreements between the participating countries. Implementation and funding of measurements and activities are the responsibilities of the individual basin states. The ICPR consists of the highest water officials from the different member states (Contracting Parties), which meet annually in a Plenary Assembly to decide on programs, finances, and formal procedures. Every three years, the presidency passes to another Contracting Party. The Commission oversees the work of a Coordination Group, which meets quarterly to plan and coordinate the work of the ICPR. The Commission is supported by a small international secretariat with a permanent base in Koblenz, Germany. Three permanent Working Groups cover the areas of water quality, ecology, and emissions and a Special Project Groups address emerging issues of concern. Expert Groups deal with specific problem areas related to the tasks of the Working Groups and Project Groups. All groups consist of government experts from the ICPR member states. Ministerial conferences are held every two to three years to formulate the policy goals of the ICPR and to assess and evaluate the activities of the Commission.

The first years of the ICPR were dedicated to establishing a common understanding of pollution problems in the Rhine Basin and to creating a legal and institutional basis for cooperation, including development of joint monitoring programs. The first common measures to protect the river against organic pollution were taken in 1970 with the elaboration of the Convention to Reduce Chemical Pollution. Unlike the ICPDR in the Danube River Basin, which abstained from establishing transnational numeric water quality standards for the water bodies in the basin, the ICPR adopted a “Combined Approach” to water quality management. In its Water Framework Directive, the ICPR established basic technology-driven source controls which were to be implemented as a first step. The framework also: developed a list of priority substances for action at the EU level; prioritized the mitigation of substances on the basis of risk; and promoted the design of the most cost-effective set of measures to achieve load reductions of those substances taking into account both product and process sources. The ICPR also: coordinates all the environmental objectives in existing legislation; provides a new overall objective of good status for all waters; and requires action if measures taken to prevent or treat pollution are not sufficient to achieve these objectives.

While public participation is an important feature of decision making in the Rhine Basin, public participation in the ICPR is highly structured and limited. Public participation has been incorporated in recent conventions and regulations of many EU nations, including the riparian countries of the Rhine Basin. For example, the UN Economic Commission for Europe's (UNECE's) Convention on Access to Information, Public Participation in Decision-Making, and Access to Justice in Environmental Matters (the Aarhus Convention) is based on three pillars: the right to access to environmental information; public participation in the making of environmental decisions; and access to justice in environmental matters. Currently 34 states have ratified the Convention, while 46 states and the EU are signatories to it.

The ICPR publishes and disseminates reports, organizes conferences and invites NGOs and the public as observers to some of its meetings. NGOs have been invited to the Plenary Assembly and the meeting of the ministers of the ICPR as observers since 1998. To qualify as an observer, an NGO must meet certain criteria, such as involvement with Rhine issues. NOGOs must also be international in nature. The Coordination Group decides on inviting recognized NGOs and external experts for Plenary Assembly meetings. The ICPR also ensures different interests are represented equitably. Although the ICPR Coordination Group is closed to NGOs, representatives of these organizations can participate in the Working Groups as observers or as external experts, if invited. Only recently, have NOGs been allowed to contribute to all Working Group meetings.

The ICPR maintains a website with information about the organization and about its activities. Website visitors can access reports and submit requests for data and information on specific topics through the ICPR web portal. The various Work Groups and Expert Groups also maintain databases used in carrying out assigned technical tasks. However, the ICPR does not maintain a comprehensive data warehouse that is accessible to the public. The ICPR also does not use a single DSS to aid the Water Quality Working Group, or any other permanent or Expert Working Group, on water quality-related issues. The ICPR does use a computer-based decision support tool to determine the effects of control measures on flood risks. The GIS-tool named

“ICPR FloRiAn” (Flood Risk Analysis) enables the broad-scale assessment of the effectiveness of proposed flood risk management measures on the Rhine. The tool uses flood hazard maps and associated recurrence periods for an overall damage and risk assessment for four receptors: human health; environment; cultural heritage; and economic activity. For each receptor, a method is designed to calculate the impact of flooding and the effect of measures.

The ICPR has been credited with improving the biological status and water quality of the Rhine and many of its tributaries by improving wastewater treatment. For example, 96 percent of the population in the Rhine River Basin are now connected to a wastewater treatment facility ((Frijters & Jan Leentvaar 2003). These actions have enhanced the reach of migratory fish, restored riparian and wetland habitat, and reduced the negative impacts of Rhine River flood events. Frijters and Jan Leentvaar (2003) conducted an assessment of the performance of the ICPR and produced a set of conclusions and recommendations (Table 2-1).

Institutional Factors with Potential Relevance to LRGWQIDSS Design – Case Study 5

From an institutional perspective, the ICPR a most mature organizations created as a result of a transboundary water agreement. Its history and structure vary notably from that of other organizations studied as case studies for this dissertation. With a mandate limited to scientific research and the proposal of evidence-based solutions to riparian countries, ICPR’s role in decision-making is relegated to persuasion and facilitation in external forums. The ICPRs interaction with other organizations with similar and somewhat overlapping mandates sets it apart from other transboundary water commissions and affects its behavior. The last two conclusions of Frijters and Jan Leentvaar (2003) subtly address these two points and their statements can be interpreted as suggestions for institutional changes that would grant more independence and decision-making capability to the organization. The socioeconomic setting of the ICPR is also dissimilar to others. Several comparable themes are also represented in this case study: the involvement of top-level officials, albeit not strictly as part of the ICPR, and financial viability of studies and projects, albeit also not strictly as part of the ICPR. The ICPR itself does not put as much effort into public and local stakeholder participation as other transboundary institutions. This can be attributed lack of decision-making capacity and to the existence of alternative forums for public participation in decision making regarding water quality improvement in the Rhine River Basin.

Table 2-1. Conclusions and Recommendations for Improvement of the ICPR. Source: Frijters and Jan Leentvaar (2003).

Issue	Conclusion/Recommendation
Political involvement in technical matters	Too much political involvement can harm open discussion among experts and be injurious to flexibility in the search for common solutions. The organization should seek to insulate technical panels from political influence.
Poorly defined rules for conflict resolution	A clear description of the rules on how to act in case of a (potential) conflict or disagreement between members should be included in the treaty of the organization.
Lack of a coordination authority	A coordination authority supported by a technical secretariat is valuable for continuity of work in the Rhine River Basin.
Lack of Stakeholder involvement in planning and implementation	The secretariat and the members of the organization should formulate clear and attractive common targets and organize stakeholder involvement in planning and implementation of measures.
Lack of recognition and promotion of member country efforts	The sharing of successes by the commission and each member state/institute will stimulate mutual confidence and enhance public and political support.
Lack of institutional cooperation	Scientific assessment of facts in the Rhine River Basin supports sustainable transboundary cooperation. Cooperation among the research-oriented *CHR*, *ICPR*, and *CNR* should be stimulated.
Lack of basin-wide coordination	To comply with the European Water Framework Directive and to avoid duplicating work among the existing organizations, the ICPR should seek to promote a sustainable Rhine River Basin approach for the whole catchment area, implementing IWRM as the task of one river basin organization.

The recommendation by Frijters and Leentvaar (2003) that the ICPR "should formulate clear and attractive common targets and organize stakeholder involvement in planning and implementation of measures" can be interpreted as suggesting the ICPR has not placed sufficient emphasis on stakeholder involvement in decision making.

The ICPR differs from other transboundary commissions in its lack of support for public access to data and information. While the ICPR produces reports and provides information on its web site, it only provides data and other specific information through data requests, which must be submitted and approved through a formal process, a reflection of the ICPR's federated structure. While the ICPR uses ICPR FloRiAn to assess the effects of proposed control measures on flood risks, the organization does not use a single computer-based decision support tool to assess how new infrastructure could affect water quality. Instead, the ICPR relies on external models, analytical tools, expert advice from its Working Groups, and the resources of its riparian member countries.

CASE STUDY 6: THE MEKONG RIVER (SOUTHEAST ASIA)

The Mekong River flows for 4,350 kilometers from its headwaters in the Tibetan Plateau to its confluence with the South China Sea at the Cambodian Coast. Its drainage basin encompasses a total area of 795,000 km² and includes parts of Cambodia, China, the Lao Democratic Republic (Lao DPR), Myanmar, Thailand and Vietnam. (Figure 2-8). In the most populous portion of the drainage basin, the Mekong River catchment includes a region of Indochina that is home to approximately 60 million people. Over 100 different ethnic groups live within the boundaries of the Mekong River Basin.

Regional cooperation between Cambodia, Lao PDR, Thailand and Viet Nam began in 1957 with the creation of the Committee for Coordination of Investigations on the Lower Mekong Basin, also known as The Mekong Committee. The United Nations endorsed the committee to address the financing, management and maintenance of water resources in the Lower Mekong Basin. In 1977, Cambodia left the Mekong Committee during rule of the Khmer Rouge. This resulted in the establishment in 1978 of an Interim Mekong Committee comprised only of Lao PDR, Thailand and Viet Nam (MRC, 2011). In 1995, the governments of Cambodia, Lao DPR, Thailand and Viet Nam established the Mekong River Commission (MRC) through an Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin. The MRC signatories agreed to manage jointly the share water resources and to develop the river's economic potential. The People's Republic China and Myanmar, the upstream countries of the Mekong River Basin, are "dialogue partners" of the MRC, but are not signatories to the treaty.

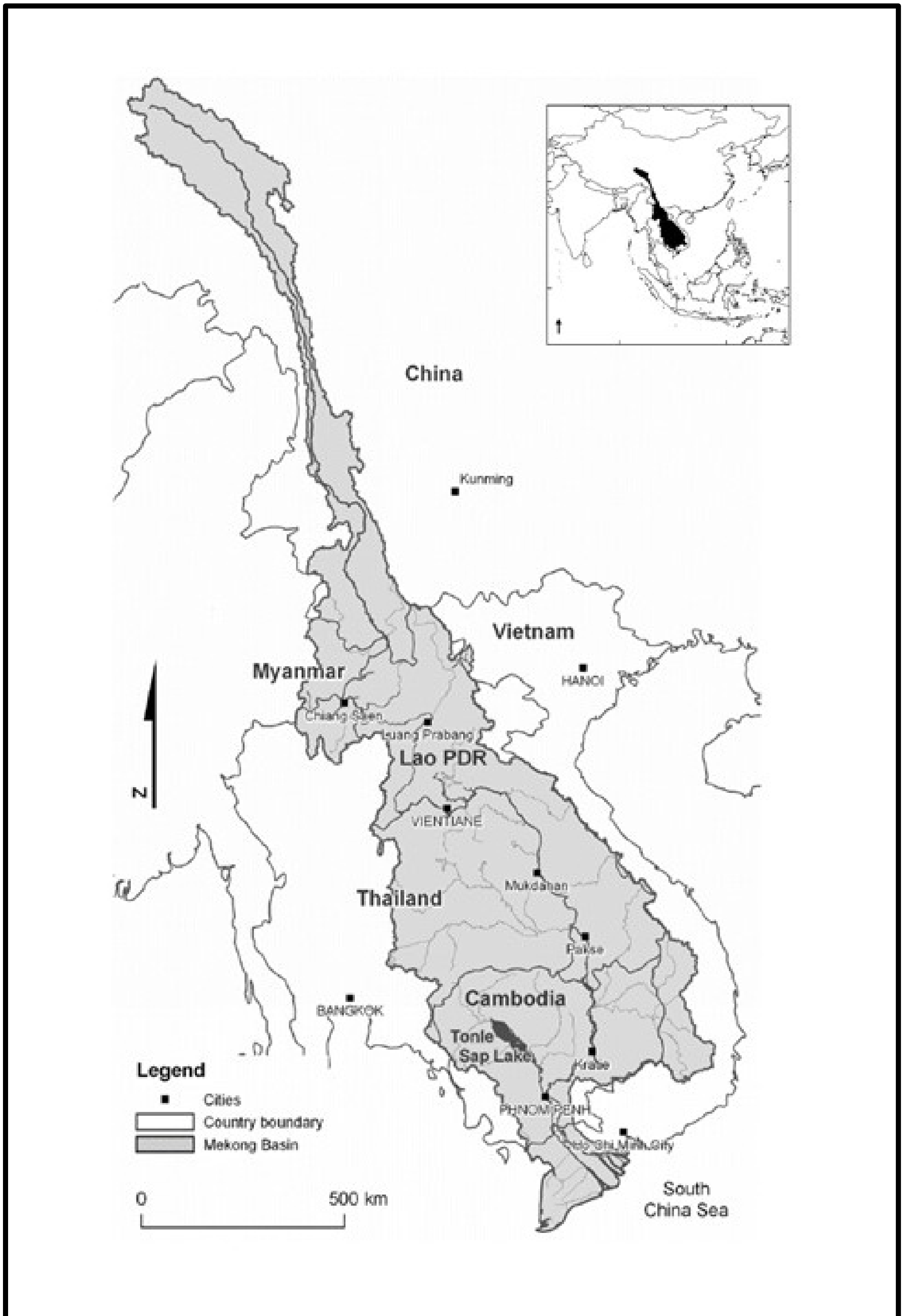

Figure 2-8. The Mekong River Basin. Source: Modified from Mehtonen, Keskinen & Varis, 2008.

The first activities of the MRC were to develop an IWRM strategy to shape a common transboundary understanding of the evolution of long-term planning, including a consultative process among the MRC countries. The MRC set up procedures for exchanging and sharing data and information, monitoring water use, notifying and consulting among members about diversions and water uses, and developing use rules to protect water quality. The MRC effectively applies the principles of IWRM, encouraging balanced and coordinated investments in the areas of irrigation and drought management, navigation, hydropower, flood management, fisheries, watershed management, tourism and environmental protection (MRC, 2011).

The MRC consists of a governing council composed of the water or environment ministers of the four member countries, who convene annually to review the current state of the basin and seek agreement on management and development policies for water resources of the Mekong. The MRC Joint Committee, comprised of senior government agency ("line" agency) officials of the four signatory countries, can put into action any decisions. The MRC Joint Committee is supported by the national line agencies of each riparian country. The MRC Secretariat is the operational arm of the organization, carrying out technical and administrative functions under the management of a Chief Executive Officer. The main functions of the MRC Secretariat are to provide technical advice on joint planning, coordination and cooperation. The MRC Secretariat also facilitates regional meetings and works closely with the four countries' coordinating bodies, the National Mekong Committees (NMCs), and other national agencies, including the governments of non-member states, such as the People's Republic of China and Myanmar (MRC, 2011).

The MRC is funded by contributions from the four member countries and several major foreign aid donors. The World Bank and the Asian Development Bank (ADB) are the international financial organizations most heavily involved with project funding. The MRC holds an annual Donor Consultative Group meeting to review project progress and present proposals for new projects. Out of the transboundary water resources institutions studied for the case studies included in this dissertation, the MRC has perhaps the strongest connection with donors. In 2008, over 90% of the MRC's funding came from external donors (Mehtonen, Keskinen & Varis, 2008). Donors to the MRC include the governments of The Netherlands, Sweden, Germany and Finland, Denmark, Belgium and France.

Within the stated goals of the MRC are several important environmental and ecological objectives, including:

- Monitoring of the basin's environment, focusing on water quality, ecological health and social development
- Increasing environmental and socio-economic knowledge in the Mekong River basin
- Improving dissemination and accessibility of environmental information within the basin and between the basin and elsewhere
- Ensuring that social, economic and ecological concerns are incorporated in basin-wide environmental policies and procedures in line with Article 3 of the 1995 Agreement
- Enhancing awareness and capacity of MRC and riparian government personnel to address transboundary and basin-wide environmental issues
- Seek to plan and implement development initiatives with a view to minimize negative environmental impacts in the Mekong River Basin

Despite these objectives, the Lower Mekong Basin waters continue to suffer from poor water quality, especially in heavily populated areas (MRC, 2011). Evidence of water quality degradation has also been recently reported near the Mekong Delta and in some upstream tributaries in the lower basin, with high bacteria, nutrient and dissolved solids problems linked to population growth and agricultural development (Chea, Grenouillet & Lek, 2016).

The decision-making process of the MRC is supported by a Basin Development Plan, which is the centerpiece of a joint, basin-wide planning process involving the four riparian countries of the lower basin. The Plan seeks to implement the development principles of IWRM and engage in participatory planning that involves an expanding range of stakeholders. The MRC has made data and information available to its member countries and to the general public for decades. In 2010, the organization developed the MRC Toolbox which contains a knowledge base with hydrologic and meteorological data (Hydro-met), water quality data, GIS layers, and completed reports. The toolbox is part of a broader Decision Support Framework (DSF), which was developed with funding from the World Bank. The DSF has important components designed to aid in decision making, including a Basin Modeling Package and various Impact Assessment Tools. The DSF System was developed as a transparent modeling and analysis system that could be used by the member countries and financing organizations to check the effectiveness and impact of proposals and strategies for water resources developments. The main purpose of the DSF is to assist planners in assessing the impacts of man-made interventions on people's livelihoods and the environment. A more comprehensive DSS is currently under development, with the hydrological component already in place. In addition to simulating major hydrological aspects of river basin behavior, which can in turn support and inform negotiations on water-sharing issues, the DSS will be capable of assessing water quality impacts (World Bank, 2017).

There have been institutional problems noted in the MRC. One such problem noted by researchers is the absence of upstream riparian countries as signatories to the Mekong Agreement (Mehtonen, Keskinen & Varis, 2008). An important basic principle of cooperation in transboundary water resources management is that it must involve all participants, which is not the case in the Mekong, as China and Myanmar are important upstream riparian countries that are not signatories. Departure from the full participation principle manifests itself in important ways, including inequitable water allocation and persistent pollution problems. Regional cooperation among MRC countries can be undermined by upstream interests (i.e., China's and Myanmar's). Researchers have reported the MRC does not place sufficient emphasis on so called "vertical" cooperation (Mehtonen, Keskinen & Varis, 2008). While horizontal cooperation among signatory governments usually functions rather well, vertical cooperation with lower governance levels is far more challenging. Due to the centralization in decision making, cooperation between the different governmental levels in the lower Mekong is difficult (Mehtonen, Keskinen, & Varis, 2008). Also, in the Mekong region, most riparian countries continue to struggle with stakeholder participation efforts, making only feeble attempts to achieve the important IWRM goal of local-level participation in planning and decision-making.

Institutional Factors with Potential Relevance to LRGWQIDSS Design – Case Study 6

Case Study 6 focuses on another multi-nation water agreement, the 1995 Mekong Agreement, which governs a transboundary river basin in many ways dissimilar to the Rio Grande/Río Bravo. However, the case study reinforces several institutional themes presented in the previous analyses of transboundary agreements. While the lack of success in reducing water quality problems is always a concerning factor, available analysis of the MRC attributes this outcome to a consensus-based preference for development over ecological and environmental concerns on the part of the riparian member countries and, to some extent, also on the part of the financial and donor organizations (Mehtonen, Keskinen & Varis, 2008). The same analyses, however, recognize the success in cooperative planning efforts with regard to development projects, which the MRC works hard to make financially viable.

The MRC's administrative capacity and strong relationship with international financial organizations and donor countries also has resulted in an impressive technical infrastructure for cooperative decision making, including the development of the MRC's DSF system, which has been credited with enhancing decision making in important policy and offering transparency in multilateral cooperation on technical projects. It is conceivable that the MRC's technical and administrative infrastructure, along with the working relationships and trust built over the years among MRC member countries, could yield better environmental results, including water quality improvement, if the focus is directed more towards sustainable development and increased local stakeholder involvement in decision making (Mehtonen, Keskinen & Varis, 2008).

As with the many of the other case studies presented the MRC's DSF system is, first and foremost, a highly accessible knowledge repository for decision making. The evolution of this system to include dedicated decision support tools follows a pattern of information provision before the development of dedicated decision support tools. This pattern is an important insight for the design and development of the LRGWQIDSS.

2.1.2.2 Summary of Institutional Factors with Potential Relevance to LRGWQIDSS Design Deduced from Case Studies of Transboundary Water Resources Management Agreements

For the purposes of this dissertation, the main rationale for analyzing case studies of transboundary water resources management agreements was to investigate institutional factors that have a bearing on the design of the LRGWQIDSS. The geographic and socioeconomic settings in the transboundary watersheds of the case studies analyzed for this purpose differ in many ways from that of the Lower Rio Grande/Río Bravo. However, the circumstances faced by decision makers in these case studies share some similarities with the participants in the LRGWQI. In many of the case study settings, bacteria contamination from inadequate sanitary sewer infrastructure was an important water quality issue in need of planning and management. Notably this was the case not only for transboundary waters shared by developing countries, but also for case studies involving more developed nations, such as those in the Danube and Rhine River Basins. In all cases, the transboundary basin commissions created under the transboundary agreements were mandated to develop plans to address issues affecting water resources management including water quality management. Hence, for decision making associated with infrastructure planning, decision support tools capable of simulating the effect on water quality of factors such as population growth, industrial development and wastewater treatment, are important, especially within spatial and economic contexts. Tools to estimate infrastructure needs and to help plan the location, size and treatment capacity of effective sanitary sewer infrastructure as well as tools to help estimate the cost of different infrastructure scenarios are useful to planners and decision makers developing transboundary water quality management plans like the one described in the LRGWQI TOR.

An important theme that surfaces in the case studies of the institutions created under transboundary basin agreements is the role of local stakeholder input in decision making. In the case of the DRPC, researchers credited local stakeholder participation for reducing disputes among the different parties and sectors involved and for increasing the efficiency and rapidity by which basin projects are implemented in the Danube River Basin. Of the established transboundary basin commissions with underdeveloped stakeholder participation forums, such as the ICPR, scholars lament the lack of a more robust local stakeholder participation process, labeling as insufficient the access by local Rhine River Basin stakeholders to other pan-European public participation forums. Accordingly, local stakeholder input in decision making, although narrowed by its description in the LRGWQI TOR, could be incorporated in some capacity into the LRGWQIDSS. The case studies document that in each basin commission, senior government officials from each country participate in decision making. Therefore, in addition to incorporating features that facilitate local stakeholder input in decision-making, the LRGWQIDSS should probably also be useful for engaging top-level government officials in decision making.

An operational aspect of transboundary commission functions, rooted in the international agreements that establish them, is the way in which environmental and ecological goals are established and measured in transboundary waters. In particular, assessment of water quality (i.e., water quality standards and criteria) plays an important role in decision making associated with wastewater infrastructure planning and water quality planning in general. Each case study documents different institutional approaches to transboundary water quality assessment, from the NBI's set of transboundary water quality indicators in the Nile and its tributaries, to the DRPC's intentional lack of specific transboundary water quality standards for water bodies of the Danube River Basin.

As previously mentioned, the LRGWQI TOR, takes an approach similar to that of the DRPC, opting to characterize water quality goals in broad narrative terms to avoid potential impasses stemming from disputes over which nation's water quality criteria will dominate. The LRGWQI approach leaves open the question of what numeric water quality targets to use during binational decision making associated with transboundary water quality planning and management in the Lower Rio Grande/Río Bravo. While not directly addressing this problem, a DSS capable of supporting multiple or, in the case of the LRGWQI, dual numeric water quality criteria would, at least, not hamper progress in assessing planning and management scenarios, albeit assessed using different criteria. Use of dual water quality criteria during transboundary decision making also helps to mitigate the perception of power asymmetry between the United States and Mexico, as was pointed out by Swain (2002), in the case of the Nile River Basin and as a general problem in transboundary waters by Jägerskog and Zeitoun (2009).

An interesting observation made by UNESCO researchers in their 2003 assessment of the ICPR was the commission's interaction with other organizations with similar, and somewhat overlapping, mandates. According to these researchers, other Pan-European organizations affect the behavior and politics of the ICPR, which in turn affects the commission's activities associated with water resources planning and management. Like the ICPR, the IBWC is also a mature transboundary water commission and shares similar mandates with other transnational organizations such as the BECC (now part of the NADB) and the USEPA's/SEMARNAT's Border 2020 Program, especially on issues associated with sanitation. Consequently, the IBWC's behavior and the activities associated with water quality planning are affected by these and possibly other organizations. It follows then, that decision support tools that take into account the regulations and processes, not just of the six agencies participating in the LRGWQI, but also of organizations such as the NADB, would be advantageous to decision makers involved in the LRGWQI. The fact that some of the organizations not directly participating in the LRGWQI are also potential financiers of sanitation projects in the Lower Rio Grande/Rio Bravo watershed only adds to the saliency of this point.

These studies illustrate the value of transboundary decision support tools. The case studies show that transboundary commission use of DSSs can be advantageous in water resources planning and management, including restoration and protection of water quality. In the case of the NBDSS, uses of the system appear to be limited, for now, to national applications by NBI riparian countries. In the case of the ICPR's FloRiAn and (though not yet classified as DSSs) also the MRC's DSF system and ZAMWIS have been applied in transboundary decision-making situations. With the exception of the ICRP's FloRiAn, all these decision support tools include a component that provides access to a multinational repository of transnational data. A robust technical infrastructure for cooperative decision making is often credited for the development of sound policies as well as providing transparency in multilateral cooperation on water resources management projects, which are made more financially viable through this process. Decision support tools that provide wide access to transnational data can also facilitate trust and enhance working relationships among riparian countries resulting in better environmental and development outcomes, including increased sanitation and water quality improvement.

2.2 Decisions, Decision Makers and Decision Support

In order to develop coherent theories about DSSs or to develop effective decision support tools, scholars and researchers must first understand the basic nature of the decision-making process. Merriam-Webster defines the term "decision" simply as "a determination arrived at after consideration." However, as Herbert Simon pointed out in his 1976 book *Administrative Behavior* (quoting Chester Barnard) "the decisions that an individual makes as a member of an organization are quite distinct from his personal decisions" (Simon, 1976, p.202). Similarly, the decision-making process associated with groups of individuals, whether within a single organization or as part of a consortium of organizations, differs from that of individuals. Although computer-based decision support tools exist to aid individual decision making, this dissertation focuses on DSSs that support the decision-making processes associated with a group or groups of individuals.

The concept of the DSS cannot be ascribed to a single researcher, as the notion of computer-based decision support developed simultaneously among a community of management science researchers. However, development of the modern concept of the DSS is often ascribed to the work of Gorry & Morton (1971), who built and expanded on, Herbert Simon's work on organizational decision-making in the 1950s. Simon (1960) distinguished three main organizational decision-making phases: (1) the gathering of "intelligence" to identify changes needed for problem solving or system improvement (also referred to as "agenda setting" by Rogers [2003] and others); (2) the development of strategies, plans, or options for solving the problem or identification of needed improvement during the intelligence gathering phase; and (3) the evaluation of alternatives and "choosing," which culminates in a solution choice. The innovation developed by Gorry and Morton (1971) was to distinguish between structured, semi-structured, and unstructured decision contexts, and then to define DSSs as computer-aided systems that help to deal with decision-making where, at least one phase (intelligence, design or choice) was semi-structured or unstructured (McIntosh et al., 2011).

2.2.1 DECISIONS AND DECISION MAKING

Whereas Simon and others approached organizational decision-making from a hiearchical, business admintration perspective, researchers in the DSS field, especially those involved in the development of effective computer-based decision support tools, emphasize the nature and role of the inputs used and the outputs generated by the group decision making process. Bonczek, et al. (1981) define decisions as "the output of a productive activity whose inputs include the intellectual efforts of an individual or group of individuals." The inputs and outputs mentioned in this definition are facilitated by elements such as data and information, expert opinion, computing hardware and software and other factors, situations, or tangible (or intangible) elements which contribute to the intellectual efforts made during the group decision-making process. Of these facilitating elements, pertinent data and information are perhaps the most widely recognized factors supporting decisions resulting in outputs considered beneficial by the individuals or groups of individuals tasked with decision-making.

Humans are information processors. In the present era, which has come to be known as the "information age," our ability to collect, share and process information has transformed the way decisions are made. Among other technical innovations, human-machine information processing systems have contributed dramatically to the number, type and complexity of human activities and enterprises. Computers not only make information available, they also have the ability to transform, store and display information for the benefit of decision-makers. Computers can process high volumes of complex information with speed and precision, which has greatly contributed to the efficiency and effectiveness of decision-making. This efficiency and effectiveness can be harnessed to facilitate human accomplishments, including the creation of numerical models of natural systems or models of artificial, human-made systems and even models of human thought processes and behaviors (Simon, 1976).

The broad problem is how to integrate human decision-making capabilities with the capabilities of human-machine information systems to produce outputs that are deemed "good decisions." The treatment of this problem depends not only on advances in computer technology, but also on the methodology of "information-decision systems" (Kami, 1958). Therefore, the primary focus of machine-based DSSs is in the interaction between decision-makers and computers. Relatively unstructured decision activities, such as those involved in strategic planning, can benefit disproportionately from computerized support systems because the decisions contemplated are rarely binary or even easily evident.

Researchers studying organizational structures often cite an individual's inability to process large amounts of information as the reason for the emergence of organizational coping mechnisms, such as division of labor and compartmentalization as key characteristics of organizational structures (Barnard, 1948, Simon, 1960). Similarly, a modular structural design appears to be necessary in decision support mechanisms in order to construct a system capable of processing large amounts of information of various types (Bonczek, et al., 1981). Modular systems possess the flexibility necessary to serve a variety of decision situations and to adapt to a number of contexts. Furthermore, modular decision support structures increase the lifespan of DSSs by making it easier to improve or upgrade certain portions of a system without having to replace the system entirely.

It is important to point out that information processing is only one component of decision-making and, therefore, only one function of decision support. In order to be useful as decision support tools, information processing systems need to be imbedded within a a more comprehensive information processing "procedure" system. Bonczek, et al. (1981), refer to an information processing system that is imbeded in an information processing procedure system as a DSS.

Designers of DSSs have the task of creating tools that transform raw information (quantitative or qualitative) into information that is useful to decision makers. Often this involves discovering mathematical descriptions and/or algorithms that accomplish this task. An algorithm is a step-by-step procedure for solving a problem or accomplishing some end (Merriam-Webster, 2019). Algorithms can also be described as formal information processing models or submodels that specify process patterns according to the inputs supplied and the type of outputs desired (Bonczek et al., 1981). The term "model" is used in this context to describe a consistent mechanism or strategy by which information is transformed to gain insight about observed phenomena.

The author has, so far, described the terms "data" and "information" as important elements which facilitate decision making. However, it is useful to distiguish between these two terms and, in doing so, explain the connection between them. One of the most widely used definitions of "data" is "a collection of facts which can be used as a basis for reasoning" (Mitra, 1990; p. 238), whereas the definition(s) of "information" most comonnly used in the decision support literature involve a characterization of information as processed or transformed data (Johnson et al., 1967, Davis, 1974). In other words, data can be used to convey information when it is assembled in a specific pattern or transformed in a way that makes it more comprehensible to the user. Data can be used as a basis for reasoning; when used for reasoning, they become information. How data are transformed into information and how information, in turn, is used in decision making are two topics that are at the center of decision support tool development.

Earlier in this section, the author mentioned that unstructured decision activities benefit disproportionately from computerized DSSs. The reason for this lies in the nature of unstrutured decision making. Whereas structured decision making refers to decision making that is routine and repetative, unstructured decision making deals with complex or illusive situations, the nature of which can be hard to comprehend (Simon, 1977). These situations are not commonplace, so there is no time-tested strategy available to address them. Unstructured decision-making situations may benefit from a customized treatment tailored to the specific situation.

Ebert and Mitchell (1975) described psychological mechanisms for human processing of information as part of the decision-making process. To the extent that information processing mechanisms or strategies can be precisely stated as an algorithm or set of algorithms, they can be incorporated into a machine-based routine (i.e., a computer program/application). Hence, part of the information processing needed for decision making can be automated, thereby making unstructured decision situations more structured (Bonczek et al., 1981). This is illustrated in Figure 2-9, which depicts decision-making situations as a linear spectrum between the "structuredness" and "unstructuredness" of decision making. The principal goal of DSSs can be viewed as an effort to push the boundary between structured and unstructured decision making.

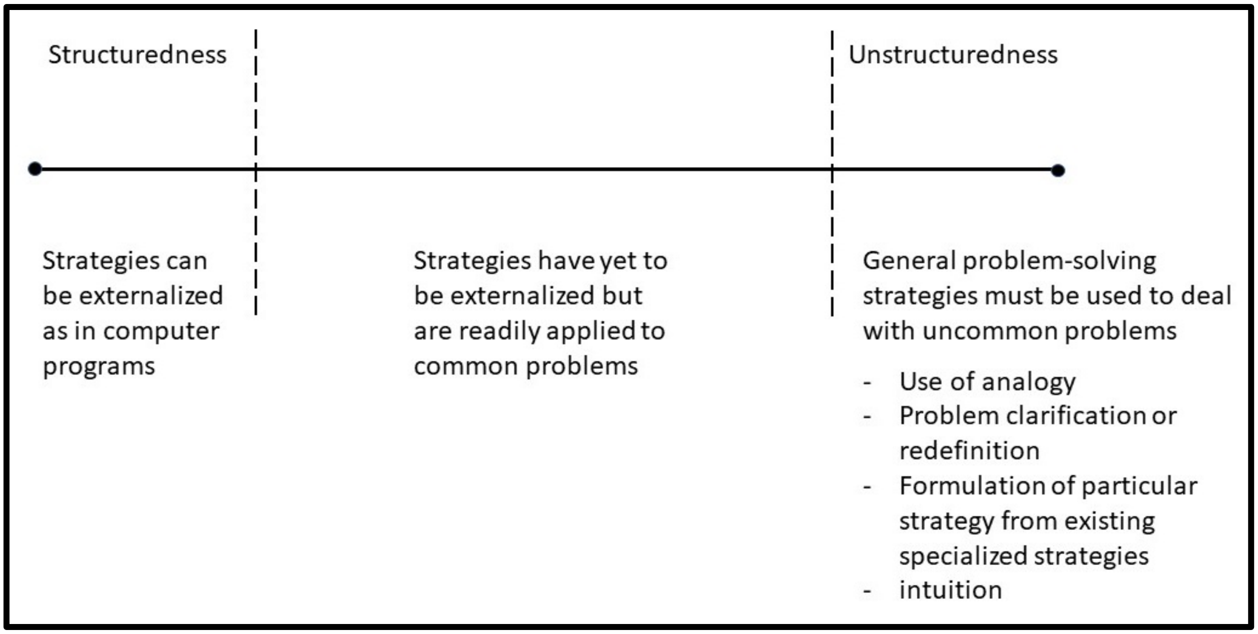

Figure 2-9. Decision-Making Spectrum. Source: modified from Bonczek et al., 1981.

2.2.1.1 The Role of Decision Support in Decision Making

Beyond the abstract concepts of structured and unstructured decision making, DSSs can be thought of as tools designed to relax the cognitive, temporal, spatial and/or economic limits often faced by decision makers. DSSs allow a decision episode to unfold in more productive ways, with greater agility, innovatively, reputably and with higher satisfaction on the part of decisional stakeholders (Holsapple, 2008). These concepts are illustrated in Figure 2-10.

According to Holsapple (2008), the decision sponsor, participants in decision making, the decision implementer, and the consumer of the decision outcome can be separate individuals or several of these roles can be played by a single individual. Use of a DSS in a decision situation has the effect of influencing the outcome of the decision-making process in at least one of the ways indicated by productivity, agility, innovation, reputation, satisfaction (PAIRS).

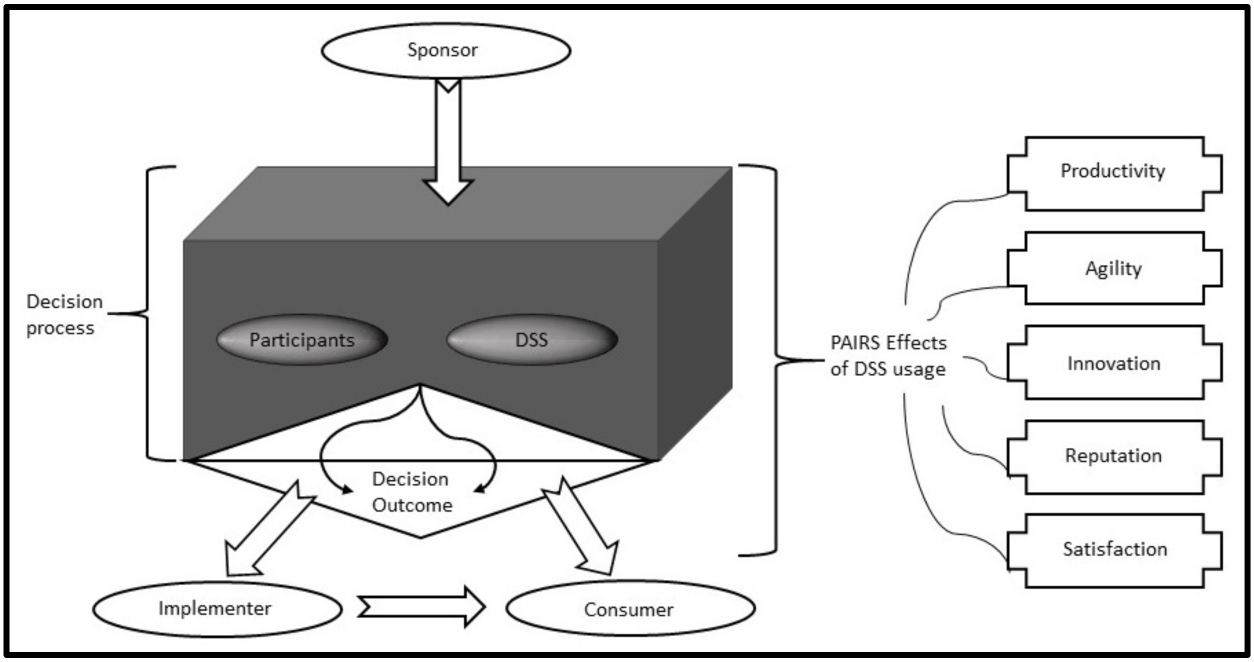

Figure 2-10. Role of DSSs in Decision Making. Source: Holsapple, 2008.

DECISION MAKERS AND STAKEHOLDERS

The term stakeholder is used often in the literature on DSSs, as well as in other research and non-research publications. Although used in a variety of contexts, the term's meaning can be consistent across different fields of study. With the exception of the gambling world, where the term stakeholder is used to describe a person who is entrusted with the stakes of bettors, the term stakeholder is used to describe an individual involved in or affected by a course of action (Meriam-Webster, 2019). The Global Water Partnership defines a stakeholder as "people and organisations who may impact or be impacted by the outcomes of a decision" (GPW, 2018). Applying these definitions to a decision situation, a stakeholder is an individual or group of individuals that experience(s) the effects of a particular decision. Hence, within the context of a decision process, stakeholders are the consumers of the decision outcome(s) produced from a decision process (Figure 2-10).

Decision makers or those who participate in the decision process may or may not be stakeholders. Decision makers may or may not experience the effects of their decisions. Depending of the level of accountability to stakeholders, decision makers may experience varying levels of, or no perceptible, consequences as a result of their decisions. Users of decision support tools, even if involved in the decision process, may lack decision-making authority. Sub-section 2.4.1 provides a more detailed discussion of stakeholders, decision makers and users of decision support tools.

2.2.1.2 History of Machine-based DSSs

According to Bonczek et al. (1981), the term "decision support" first began to appear in technical articles in the early 1970s. Following the concepts derived from the theoretical studies of organizational decision making that originated at the Carnegie Institute of Technology during the late 1950s and early 1960s, and the psychology and economics research done at the University of Chicago in the late 1960s and early 1970s. The discipline is considered an outgrowth of the management information system (MIS) field, which was itself derived from database management study.

Through its evolution, the DSS discipline underwent a broadening of scope, crossing over and incorporating other areas of study such as psychology, linguistics and computer science. The DSS field of study differs from the MIS field in the emphasis it places on three specific issues: (1) incorporating models into information software; (2) providing useful information to higher level decision-makers to support comparatively unstructured decision-making; and (3) providing the user powerful, yet simple-to-use tools for decision making (Bonczek et al., 1981). Another attribute that has contributed to the success of DSSs has been the ability to provide interactive and timely queries. That is, the system ought to provide the user a means to interrogate the system easily, intuitively and in a timely fashion. A query facility that permits nonroutine, nonstandard queries for data retrieval provides added value to the user and the ability of a DSS to perform *ad hoc* analysis of data is of value to a decision maker for providing information for decision making that would not otherwise be considered available.

Early computer-based DSSs were referred to by a number of acronyms that reflected their multi-termed names, including executive information systems (EIS), group DSSs (GDSSs), and organizational DSSs (ODSSs). The names and acronyms given to these early systems were, in effect, the names given to the software used to query and retrieve data from a diverse array of databases. Like most software of the time, decision support software ran on large main frame computers which were designed for single users. In the late 1980s, DSSs began to incorporate data analysis and modeling capabilities and the software started to become more interactive. However, few applications beyond managerial and business planning efforts were available at the time. The mid-1980s also saw the proliferation, first of intelligent work stations and later personal computers which advanced the sophistication of DSSs in general.

The development of the Gate Assignment Display System (GADS) by Texas Instruments in 1987 is one of the first recorded examples of a DSS application designed to improve the efficiency of a business process rather than organizational management or business planning. Designed for United Airlines, GADS is credited with significantly reducing travel delays by improving the management of ground operations at various airports (Turban et al., 2008). In the 1990s, advancements in computer hardware and software, including early forms of artificial intelligence, such as expert systems and neural networks, saw the broadening of the application of machine-based DSSs. Likewise, the advent and widespread public use of the internet in the late 1990s gave rise to web-based DSSs, which greatly increased the use of these systems throughout a variety of sectors and fields. By the turn of the millennium, DSS software was being developed for applications as diversified as agronomy, the military, oil and gas production, and medicine. Although there is currently no single focus in the DSS discipline, most of the cutting-edge research being conducted at this time has seen a shift away from developing better analytical, and visualization tools or more interactive and intuitive user interfaces and towards gaining a better understanding of the nature and needs of the DSS users themselves as exemplified by the work of Douglas Engelbart.

2.2.1.3 DSS Architecture and Design Frameworks

Early classifications of machine-based DSSs identified six basic types of systems based on their use in decision making: (1) retrieval of isolated data values; (2) performance of *ad hoc* analyses; (3) production of standard reports; (4) estimation of consequences of proposed decisions; (5) proposal of decisions; and (6) decision making (Bonczek et al., 1981). More recently, DSSs are generally expected to incorporate most, if not all, of these uses. As early as the 1980s, special emphasis began to be placed on logic, linguistics and artificial intelligence as areas of advancement in DSS research. Determining the data and information processing strategies that are appropriate for any given decision-making situation (i.e., logic) and properly communicating the meaning of the results of the information processing efforts to the user (i.e., linguistics) are still the subject of intense research. While basic functions associated with data base management continue to play a role, automation of logic and linguistics now forms the core of DSS research.

Bonczek et al. (1981) proposed a generic description of DSSs which included three principal components: a language system (LS); a knowledge system (KS); and a problem processing system (PPS). More recently (2008), Clyde Holsapple added a fourth component, which he termed a presentation system (PS). Figure 2-11 illustrates how these components are typically arranged and interact within a generic DSS.

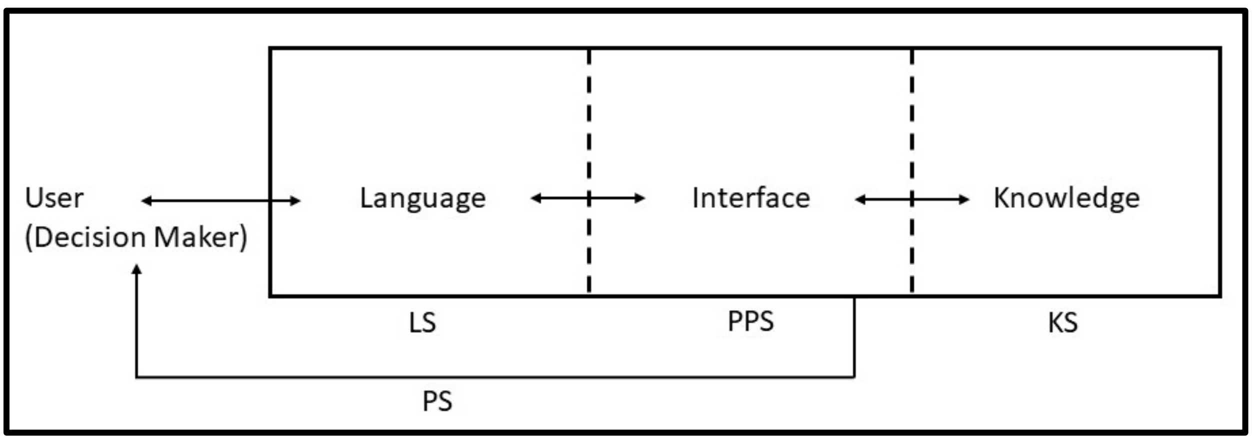

Figure 2-11. Generic Structure of a DSS. Source: Modified from Bonczek et al., 1981.

Within the context of a DSS, the LS is comprised of the total of all linguistic facilities available to the decision maker by the system, which may include data retrieval languages as well as computational languages. The user need not be cognizant of which of these two functions the DSS is performing as a result of a particular request or command. A system may react to a specific user request or command through a combination of these and other functions. The user is, however, limited by the statements, commands or expressions they are allowed to make while using the system. Thus, a language system provides the means by which decision makers are allowed to express themselves, but only in the ways provided by the DSS.

DSSs must contain, or at least provide access to, facts (i.e., data and information) relevant to the decision problem domain. These decision-facilitating elements are collectively referred to as the DSS's problem domain knowledge. A DSS's ability to produce problem domain knowledge, either from its own local databases or from remote databases, is referred to as its knowledge system or KS. The KS of a DSS must be able to organize problem domain knowledge in a systematic manner. This is typically done through a set of rules developed according to the manner in which the knowledge is represented or used in the system.

The interface between expressions of knowledge in the KS and expressions of problems in the LS is referred to as the problem-processing system or PPS. The PPS translates the relatively simple high-level language(s) of the LS into actionable requests. In addition to "understanding" the user's statements, the PPS must be able to provide relatively abstract, and often complex, representations of knowledge originating in the KS to the decision maker through the LS. The capabilities of a DSS's PPS are limited only by the imagination and the abilities of its designers and by the software and hardware used by the DSS itself. An effective PPS must, at a minimum, take into account the boundaries of the problem domain faced by the decision-maker.

Typical PPS capabilities can include information collection, data analysis, model formulation, modeling and even, problem recognition. In all cases the capabilities of the PPS rely on information supplied by the user (i.e., required inputs, requests, commands, etc.) and data and information (i.e., raw and processed data) stored locally or remotely. Figure 2-12 illustrates some of the potential capabilities of a PPS within the context of the decision support linkage schema and structure presented previously in Figure 2-11.

Finally, the PS of a DSS consists of all the messages the system can emit (Holsapple, 2008). In this context, the term "message" refers to a host of potential visual and/or linguistic elements available for presentation to the user.

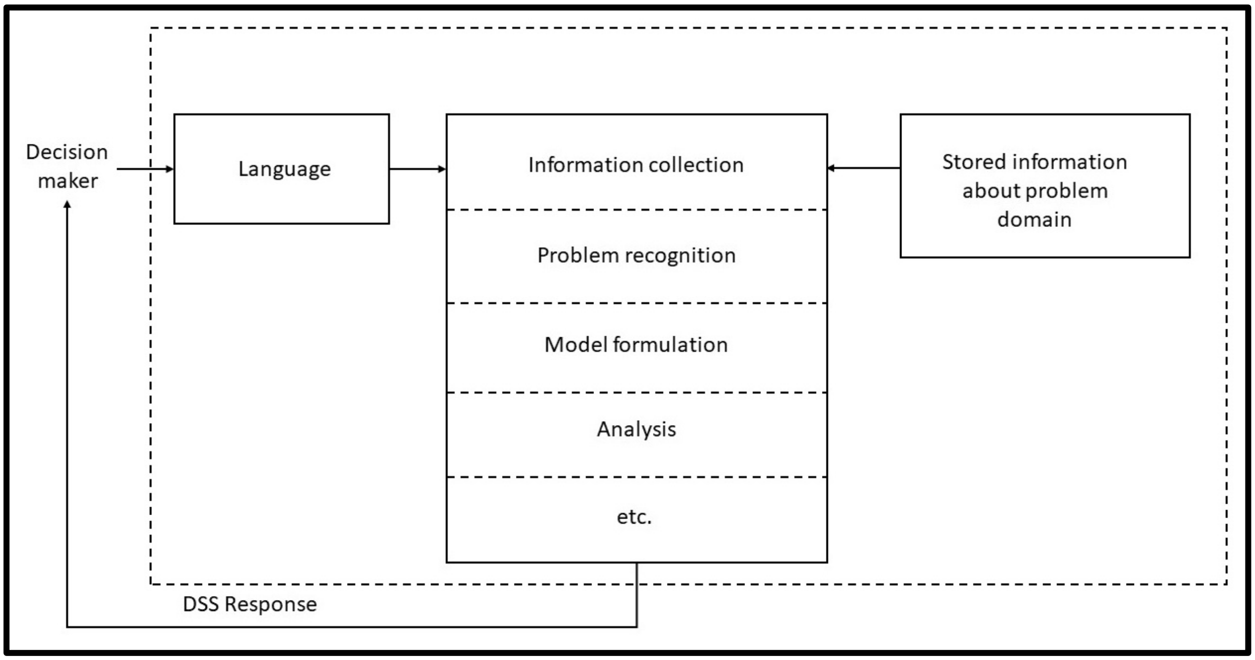

Figure 2-12. Generic DSS Schema Illustrating Typical PPS Capabilities. Source: Bonczek et al., 1981.

The PS is, therefore, closely associated with the LS of the system, in that it must be able to present knowledge-conveying elements in a manner that is pertinent and easily understood by the user.

Building on the research conducted in the late 20th century, Holsapple elaborated on different aspects and dimensions of the basic components of machine-based DSSs. Through his own research, he developed an early classification system for DSSs and proposed basic architectural frameworks for each of the DSS types included in his classification schema. Holsapple is careful to point out that the architecture of DSSs does not necessarily define what the system is, but instead functions as an ontology that gives a common language for design, discussion, and evaluation of DSSs regardless of their variation in style and function. Recognizing that a DSS may contain, or at least provide access to, multiple types of knowledge, Holsapple began by classifying three different types of knowledge provided by these systems: descriptive knowledge, procedural knowledge, and reasoning knowledge (Holsapple, 1995). These are briefly described as follows:

Descriptive knowledge – describes the state of the world of interest in a past state, present state, future state, expected state, speculative state or any other conceivable state. It refers to the world of interest, as conceived by the decision maker. It could be actual, potential, hypothetical, symbolic, fixed, dynamic, physical, intellectual, or emotive.

Procedural knowledge – characterizes how to do something; a stepwise specification of the process by which to accomplish a specific task or explore some procedural path or direction.

Reasoning Knowledge – specifies what conclusions are valid given a known situation. Reasoning knowledge specifies the logic that links a premise with a conclusion. The nature of this linkage can include causal, correlative, associative, definitional, advisory, or analytical.

Figure 2-13 shows the three types of knowledge described by Holsapple (1995). The vertical divisions within the KS indicate the three knowledge orientations that cut across knowledge types: domain, relational and self.

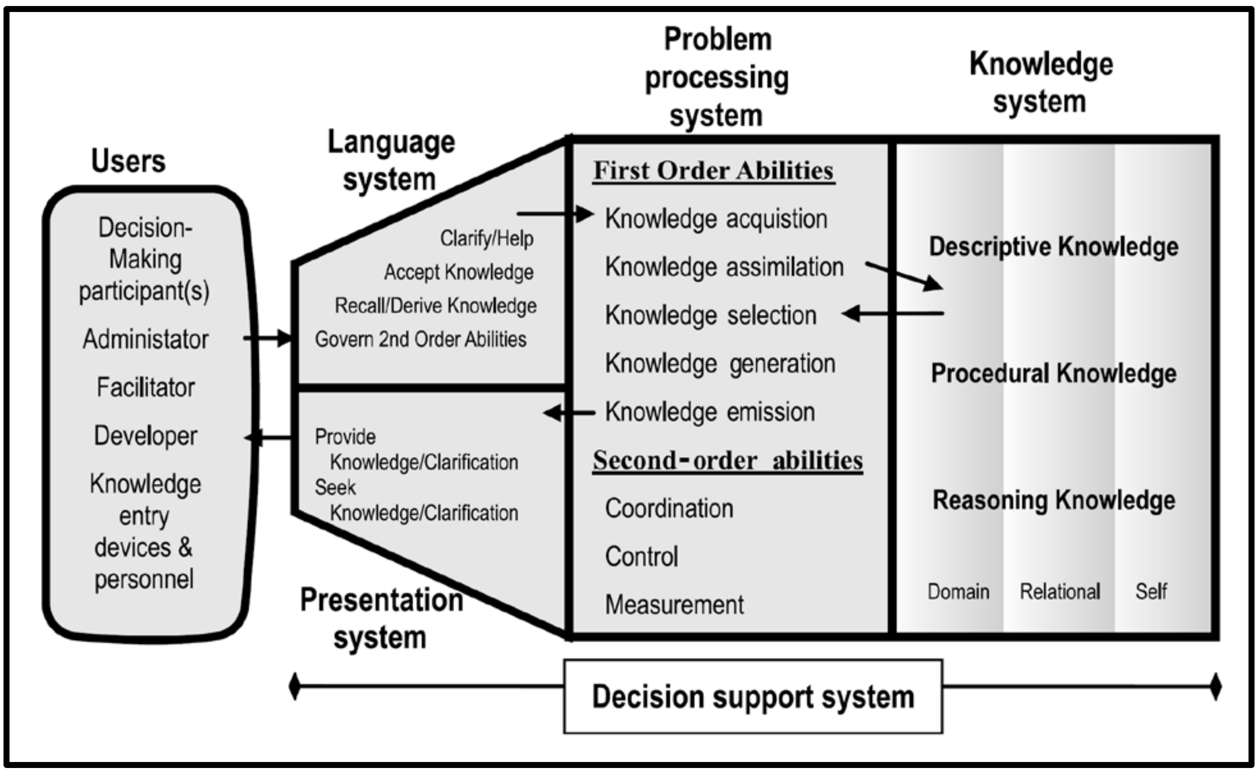

Figure 2-13. Basic Architecture for a DSS. Source: Holsapple, 2008.

According to Holsapple, knowledge oriented towards a domain is the descriptive, procedural and/or reasoning knowledge used by the PPS in dealing with the subject matter of the decision domain. Relational knowledge is the knowledge the DSS has about the system user, including preferences, capabilities, behaviors, etc., and knowledge it has about the LS and PS used to interact with the user. Self-knowledge is simply the knowledge the DSS has about its own capabilities and behaviors, including KS content, organization, and what is allowed into, and out of, the KS through the PPS.

In addition to the knowledge types and knowledge orientations in the KS, the DSS structure depicted in Figure 2-13 also illustrates two basic types of problem processing abilities within the PPS, first and second order abilities. Holsapple defines first order problem processing abilities as the primary front-line capabilities of the DSS that contribute to a decision outcome, which include knowledge acquisition, assimilation, selection, generation and emission. Second order abilities are concerned with oversight and governance of first order abilities and include coordination, control, and measurement functions. The control and measurement functions of a DSS are involved in the manipulation of the five first order PPS abilities. These functions may be specified by the user or may be built into the system. A DSS's PPS may also use a combination of user-specified and built-in control and measurement functions.

The coordination abilities of a DSS's PPS govern the arrangement of knowledge manipulation tasks and the knowledge flows that connect these tasks to create configurations and sequences that are in the interest of the decision process (Holsapple, 2008). Multi-participant DSSs require vastly more sophisticated coordination abilities to accommodate joint decision-making situations. These multi-user systems may also require a partitioning of the KS, LS and PS into private and public partitions to prevent the accidental release of confidential information. As with all other functions of the PPS, second order PPS abilities are governed by the LS of the system.

Variations in the basic architecture shown in Figure 2-13 are related to the typology of DSSs. Holsapple (2008) identified six categories of DSSs based on the knowledge management methods used by each type of system. The categories include: (1) text-oriented DSSs; (2) database-oriented DSSs; (3) spreadsheet-oriented DSSs; (4) solver-oriented DSSs; (5) rule-oriented DSSs; and (6) compound DSSs. The knowledge management techniques used by these systems dictates the character of the PPS included in each system. Each management technique may emphasize a particular ability or set of abilities within the PPS. Some of PPS abilities shown in Figure 2-13 may be completely absent in some DSS types. Knowledge management techniques used by DSSs influence the structure, organization and content of the KS of a DSS. Each technique for processing knowledge has access to the knowledge in a manner that is compatible with the processing technique. Thus, the knowledge processing method characterizes each class of DSS by restricting the PPS abilities to the processing allowed by the method's techniques and by limiting the content of the KS to representations that are compatible with the processing technique(s) used by the system. The following sub-sections provide a brief description of the six DSS categories proposed by Holsapple based on knowledge management methods.

TEXT-ORIENTED DSSS

As the name implies, text-oriented DSSs make use of (digital) written materials as repositories of knowledge. The KS of a text-oriented DSSs is composed of electronic versions of published and/or unpublished documents or written passages that are potentially useful to the user. This may include entire, or only portions of, books, periodicals, technical journals, reports, letters, memos, instructions manuals, transcriptions, or any other visual expression of language. The knowledge contained in these repositories can be descriptive (e.g., examples of similar decision situations), procedural (e.g., mathematical formulae), or reasoning (e.g., proven remedies for unwanted situations). The PPS of text-oriented DSSs is typically software that helps the user make requests, such as key word searches, or the manipulation of contents possible (e.g., language translations).

The LS of text-oriented systems facilitates the PPS's functions and often resembles established human languages. Text-oriented DSSs provide the user with problem domain knowledge in a manner many times more efficient than would otherwise be possible, even when the decision maker has access to the same problem domain knowledge outside of a DSS.

The PS of text-oriented DSSs can be simple in nature, as the content of the KS is typically limited to alpha-numeric or other language-expressing symbols. However, recent innovations in software development and DSS design are pushing the limits of PS and PPS abilities in text-oriented systems by incorporating text mining and content analysis.

HYPERTEXT-ORIENTED DSSS

Considered an extension of text-oriented DSSs, hypertext-oriented DSSs allow the flow of ideas through separate pieces of text. This is possible through the use of hyperlinks. Hypertext

DSSs first became popular as stand-alone applications used mainly by scientists in the mid-1990's, but their use became common place with the spread of the world wide web. Though not officially considered a DSS, a familiar example of a hypertext system is the on-line encyclopedia, Wikipedia. Using Wikipedia, a user can access additional or related information on a particular subject by clicking on hyperlinks dispersed throughout the text contained within each Wikipedia web page.

As with virtually any web-based document or application available today, the PPS of a hypertext-oriented DSSs allows the user to create or delete hyperlinks of interest, thereby creating a flow of knowledge that is tailored to the interests and thought rationale of the decision maker. Hypertext-oriented DSSs can offer links to non-text based knowledge components such as graphs, diagrams, photographs and videos. Hosapple et al. (2000) described the world wide web itself as a form of a DSS composed of a vast, distributed KS and a variety of untailored and also distributed PPS and PS.

DATABASE-ORIENTED DSSS

The relational database is a time-tested, and still common, method of knowledge management. Relational databases contain data and/or information arranged in a highly structured, tabular format. Database-oriented DSSs help the decision maker by tracking and selectively recalling knowledge pertinent to the decision domain. The knowledge provided by these systems is typically descriptive and is arranged in a systemized fashion, often tailored to the decision domain. In addition to, sometimes, very large amounts of data and information, the KS of database-oriented DSSs also contain detailed information about the type and volume of the data tables found in the system as well as details pertaining to the structure of each table (i.e., field names, types, linkage keys, etc.).

The PPS of database-oriented DSSs typically has two basic abilities, a database control function that can manipulate or transform existing tables and/or create new ones and an interactive query system capable of fulfilling standard types of user requests for data extraction and presentation. User requests must be made through a query language, which is part of the system's LS. The requested data/information is provided to the user through the PS of the system.

Database-oriented DSSs often possess custom-built processing systems that provide non-standard knowledge processing abilities which can be tailored to the decision domain or decision situation. Depending on the sophistication of the DSS, custom-built processors (application programs) can be made available to the user as part of the DSS's standard abilities or the DSS may offer the capability, to the user, of building a custom processing application using other tools available within the DSS.

Although the main focus of database-oriented DSSs is on the storage of relational data and the interactive search of existing and new data, database-oriented systems may also have the ability to analyze and/or transform data and information. This can be accomplished through simple calculations or through more complex mathematical procedures or models. Advanced versions of database-oriented DSSs can also draw from various sources of data/information contained in multiple operational systems. These systems are referred to as data warehouses and are characterized by their ability to permanently assimilate content which is time-stamped and linked to specific types of metadata (Immon, 2002).

SPREADSHEET-ORIENTED DSSS

Like data-base-oriented DSSs, spreadsheet-oriented support systems contain data/information arranged in a highly structured fashion. Although not generally focused on the relatability of the data contained with them, spreadsheet-oriented DSSs offer additional dimensions of data storage and processing not typically available in database-oriented systems.

Spreadsheet-oriented systems are composed of "flat" table files (i.e., spreadsheets). The spreadsheets are comprised of cells that resemble the records in tables or simple databases. But, unlike the records in a simple database, the cells of a spreadsheet are arranged in a two-dimensional grid; each cell having its own unique name, which is based on its location on the spreadsheet grid. Spreadsheet cells have a definition and a value; a cell's definition (either a constant or a formula) determines its value. The formulas within spreadsheet cells can reference other cells within the same spreadsheet or in other spreadsheets. In this sense, the KS of spreadsheet-oriented DSSs provide descriptive knowledge in the form of constant-associated values and procedural knowledge in the form of formulae that inform the system's PPS how to derive a cell's value. The formulae contained in spreadsheet cells can be simple mathematical functions or more complex mathematical operations involving statistical or deterministic procedures and/or models.

In addition to descriptive and procedural knowledge, many spreadsheet-oriented DSSs have the ability to present information to the user in a variety of ways that facilitate comprehension of decision domain knowledge and which stimulate the development of useful ideas. Most standard spreadsheet programs include powerful and user-friendly graphing and illustration packages capable of presenting information in a variety of useful ways. Spreadsheet oriented DSSs may contain PSs that automate the creation of visual representations of data and information that are tailored to a particular decision domain or decision situation.

Spreadsheet-oriented DSSs can also hold linguistic knowledge by facilitating user requests. A good example of this ability is the use of macros, which are algorithms constructed within the spreadsheet environment. Macros facilitate user requests by automating the sequence of key strokes necessary to make the request of the DSS. The macros can be made available to the user as a standard part of the LS or may be custom-built by the user through other features of the LS.

SOLVER-ORIENTED DSSS

Solver-oriented DSSs derive their name from the concept of the solver. The term "solver" can be defined as a procedure consisting of instructions that a computer can execute in order solve any member of a particular class of problems (Holsapple, 2008). The problems addressed by solvers include a wide variety of subjects, such as accounting (e.g., net present value, depreciation, etc.), economics (e.g., demand elasticity, marginal costs, etc.), engineering (e.g., concrete failure analysis, predictions of dissolved oxygen in surface water, etc.) and many other subjects in a variety of fields. Each solver is specific to each type of problem and the problems can include varying degrees of complication from simple formulae to complex mathematical procedures. Solver-oriented DSSs typically include more than one solver and so, by necessity, multiple-solver DSSs include a management system for the storage and use of the solvers contained within the system.

There are generally two types of solver-oriented DSSs, fixed and flexible. Fixed solver-oriented DSSs incorporate all solvers within the DSS into its PPS, making it difficult for the user to add, delete or modify any of the solvers available. Under a fixed solver-oriented system, a user is relegated to choosing and executing single solvers, or sets of solvers, from the fixed number of solvers available to the user in the PPS. The PPS can acquire, assimilate select, and emit descriptive knowledge in the KS as data sets, problem statements or reports. Depending on the function of each solver, the descriptive knowledge in the KS can be shared by several of the solvers available to the user (e.g., two solvers using the same data set or presentation templates as input and outputs). The LS of a solver-oriented DSS provides the user a means to express problem statements and requests, including which solver, or set of solvers, the PPS should use as well as the mode of presentation the PS should provide.

Under a flexible solver-oriented system, the PPS is designed to manage and/or manipulate solvers in response to a user's request. In this sense, the KS of these DSSs contains procedural knowledge not otherwise available in the fixed solver-oriented DSS. In addition to data residing in the KS, some solvers in flexible solver-oriented DSSs may require additional data to perform their functions, which can be provided either by the user or by other solvers that form the PPS of the system.

The solvers in a flexible solver-oriented system may be arranged in solver partitions known as modules. The user may choose to run a single module or a sequence of modules. Modules of a flexible solver-oriented DSS require data generated by another module, or several other modules within the DSS, to solve a particular problem. The user may or may not be aware of this requirement. As a result, the DSS may or may not alert the user of the need to run other modules, depending on the sophistication of the LS and PS of the DSS. In advanced flexible solver-oriented systems, the PPS may select the appropriate module or modules and the proper run sequence needed to fulfill a user request without requiring instructions from the user. Alternatively, the PPS of advanced flexible solver-oriented DSSs may allow the user to modify, combine, or delete existing solver modules, or create new modules for customized use. The capabilities of the PPS of flexible solver-oriented DSSs are reflected in the language available to the user in the system's LS, which may also allow the user to request customized presentation of solver results.

RULE-ORIENTED DSSS

Based on a knowledge management method involving the processing of rules and rule sequences, rule-oriented DSSs incorporate reasoning knowledge into their KSs. Given certain decision situations, which can be defined through objective qualifications, rule-oriented DSSs provide conclusions considered valid if the information provided by the user is also valid. The rules in a rule-oriented DSS take the familiar form of if-then statements, often supplemented by an accompanying explanatory statement. Thus, rule-oriented DSSs are straight-forward advice producing tools that use information about decision situations as input and produce advice to the user as output.

The KS of a rule-oriented DSS contains a set of rules associated with some reasoning about potential recommendations that a user might seek given a defined decision situation. The KS of these systems may also contain a description of the current state of affairs within the decision domain. The description of the current state of affairs in the KS may be inherent to the KS (i.e., built-in) or it may be supplied by the user, or it may be derived from another process within the PPS of the DSS. In any case, rule-oriented DSSs often require a base case from which to start.

In addition to advice or determinations, rule-oriented DDSs often also have the ability to provide reasons for the resulting advice or determination, basing the justification(s) for these on the input used by key rules in the rule sets that define the reasoning process. The PPS of a user-oriented DSS possess the ability to create, revise, or delete descriptions of the decision situations. When the PPS of a rule-oriented DSS establishes a premise (i.e., "if x is the case…"), it follows the action specified in the rule (i.e., "…then y is the conclusion"). Actions resulting from one rule may clarify the decision situation further and provide direction for further forward reasoning, allowing premises for other rules to be determined as true. The forward reasoning continues until some action is taken that produces the advice requested by the user or the PPS determines there is insufficient knowledge in the KS to yield a valid answer.

In the case of "expert systems," the PPS evaluates rules in a pertinent rule set, searching for those whose premise is true for the decision situation presented by the user. In simple expert systems, the problem processing flow may depend on very limited LS elements available to the user (e.g., inputs of "true" or "false"). In more advanced expert systems, the PPS may determine if a premise is true using various forms of knowledge, but the flow of reasoning is confined to a binary choice.

Expert systems evolved from the field of artificial intelligence and are often cited as one of the first techniques employed by researchers in that field (Holsapple, 2008). However, the binary nature of the forward reasoning approach used by expert systems is a serious limitation to decision making. The advent of "neural networks" in the early 1990s greatly improved the capabilities of rule-oriented DSSs. With neural networks, the flow of reasoning is in various directions, and hence the establishment of premise within the PPS, does not depend on a binary choice. Instead, neural networks are comprised of a system of interconnected nodes linked by simple rules and the system can create its own rules by using examples. Neural networks are considered to be at the cutting edge of DSS research and represent the future of rule-oriented decision support.

COMPOUND DSSS

With increasing complexity in decision making there often comes a need for multiple knowledge management methods. To satisfy this need, decision makers may opt to use separate tools that provide decision support using different knowledge management techniques or, if available and affordable, decision makers may use a DSS that incorporates multiple knowledge management techniques. DSSs that incorporate multiple knowledge management techniques are referred to as compound DSSs.

Use of multiple DSSs for complex decision making requires the decision maker to be familiar with the LS and PS of each system. Moreover, the results of requests made in one system may be needed by the PPS of another system that uses a different knowledge processing technique. This places the burden on the user of translating the results, or result elements, of one DSS into a format that is compatible with other DSSs used for decision making. This burden is lessened and, in some cases, eliminated through the use of compound DSSs.

Holsapple and Whinston (1996) identify three approaches to knowledge management integration across DSSs: conversion, clipboard and confederation. The conversion approach requires a method or tool capable of converting the output of one DSS into a form that can be processed by the PPS of another DSS. The conversion tool, usually computer code, can be available as a stand-alone program/application or it may be incorporated into the PPS of either the knowledge-emitting or knowledge-acquiring DSS. In either case, the conversion approach requires the overt, and sometimes cumbersome, transfer of output files from one DSS to another.

The clipboard approach is similar to the conversion approach in that there may still be a need for conversion of one output format to a separate input format. However, with the clipboard approach, the transfer of knowledge from one PPS to another is accomplished through a shared intermediary repository known as a clipboard. With the clipboard approach, needed conversions of output knowledge are accomplished seamlessly and the shared clipboard knowledge can be added to or discarded from a single clipboard, saving file storage space. As in the case of some single-technique DSSs with built-in conversion software, developers of DSSs that use the clipboard approach must consider, in advance, the formats used by the PPSs of other potentially knowledge-acquiring DSSs.

Confederated DSSs, while separate single-technique systems, share a common KS. The confederation approach eliminates the need for both import/export translation software and clipboard repositories. The KS of confederated DSSs contains representations of decision domain knowledge that can be processed by each system's PPS. Confederated DSSs are not common as single-technique DSSs that use conversion or clipboard integration approaches. This is partly due to the difficulty of constructing KSs capable of accommodating different knowledge management techniques. Faced with the challenge of constructing a KS capable of accommodating different knowledge management techniques, DSS developers may opt to design a compound DSS.

In compound DSSs, there is one LS and one PS, which makes the system easier to learn and less demanding on the user, as the processes involved in import and export of knowledge across PPSs is typically automated. Holsapple and Whinston (1996) identify two approaches to knowledge management integration within a compound DSS, nesting and synergy. With the nesting approach, one or more knowledge management methods may be nested within the capabilities of a more global knowledge management method. For example, a database-oriented technique may be nested within a primarily solver-oriented DSS or a spreadsheet-oriented technique and a rule-oriented technique may be nested within an a DSS possessing an overall solver-oriented knowledge management method.

A compound DSS can eliminate the need to switch back and forth from PPSs contained in separate, single-technique DSSs. This is done by providing one PPS that has the ability of using multiple knowledge management techniques, all of which are accessible to the user through a unified LS and PS. When a compound DSS is synergistically integrated, its KS may be composed of a number of different elements of varying types (e.g., spreadsheets, database tables, solver modules, graphing modules, documents, images, rules, etc.). The PPS of these systems may be “intelligent” enough to ascertain the proper knowledge management method or set (and sequence) of methods to use to fulfill a request received through the LS from the user. It may also have the ability to interpret requests well enough to choose the elements of the PS most useful to the user, or at least offer the set of choices of PS elements that are most likely to present knowledge to the user in the most useful way.

Figure 2-14 shows an example of a compound DSS with synergistic integration. In this example the first order abilities of the PPS include five different knowledge management techniques, as well as post-processing capabilities associated with the system’s PS.

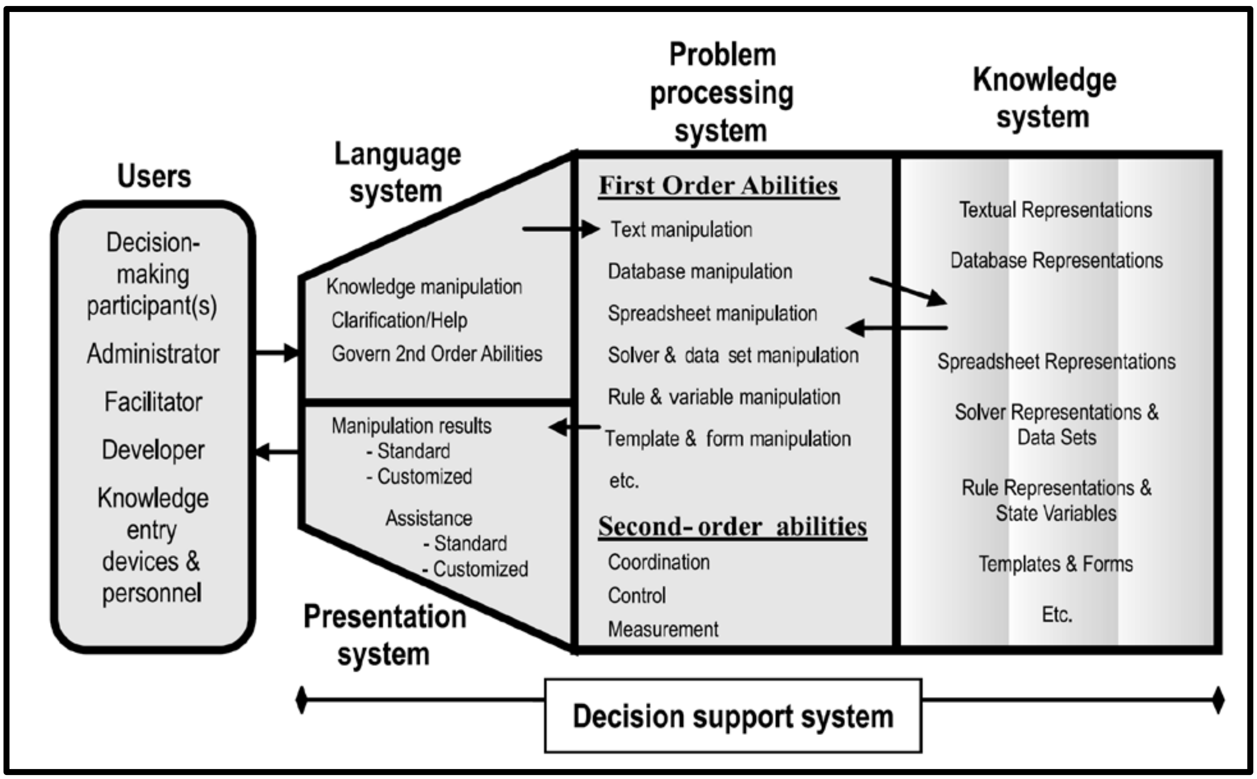

Figure 2-14. Example of a Compound DSS with Synergistic Integration. Source: Holsapple, 2008.

The KS of the DSS depicted in Figure 2-14 contains elements or objects that represent all three types of knowledge previously discussed (i.e., descriptive, procedural, and reasoning). The objects are manipulated by the system’s PPS which has the ability to employ any of the five knowledge management techniques in whatever sequence needed to fulfill the user’s request. Depending on the user’s request, the PPS may use a single knowledge management technique, or multiple knowledge management techniques without the user necessarily being aware what technique the PPS is using to arrive at its response(s). This is referred to as a "black box" approach in which significant effort is expended by developers to automate DSSs for the convenience of the user.

The desire on the part of DSS designers to create DSSs that not only provide the benefits outlined in the PAIRS acronym, but are also, flexible, easy to use, and inexpensive, is understandable and should always be part of the overall goals of DSS design. However, in striving to fulfill these goals, it is possible to overreach for one or more of these goals, creating a situation in which overemphasizing one of these qualities diminishes another to an unacceptable degree. For example, an effort to automate (or over-automate) the PPS and associated LS of a DSS may increase the ease-of-use of the system, but it may also decrease the DSS's flexibility or it's acceptability. Criticism of the black box approach centers around this the problem (Todd & Benbasat, 1987; Limayen, Banergee, & Ma, 2006). To ensure the proper balance in design elements, DSS developers should adhere to established best practices in DSS design. Best practices in DSS design are discussed in more detail in Sub-section 2.2.1.9 of this dissertation.

2.2.1.4 DSS Focus and Specialization

As advances in DSS research continue to identify common attributes of effective decision support systems, so too have researchers identified qualities that are desirable in DSSs used in specific types of decision domains or decision situations. In the last decade (2010-2019), references to a number of focus-based DSS categories have become commonplace in the technical literature, along with the acronyms used to designate their specializations. The following sub-sections provide a brief description of some commonly referenced focus-based DSS categories.

MULTI-PARTICIPANT/GROUP DSSS (MDSSS / GDSSS)

As the name implies, MDSSs, also referred to as GDSSs, are machine-based systems designed specifically for joint use by multiple decision-making entities. The number of participants in the decision-making group can be very large (e.g., participants using web-based systems) or very small (e.g., a group of four or five agency representatives). The makeup of the groups can also vary with respect to participant background, interests and role in the decision-making process. Specialization is necessary within the GDSS category to accommodate these and other variables, but most GDSSs share certain hallmarks that distinguish them from DSSs designed for single users. These include a PPS with strong coordination capabilities, for handling and/or guiding participant interactions, and also advanced first order capabilities, for acquiring knowledge from, and emitting knowledge to, participants. A second GDSS hallmark is a KS capable of assimilating, categorizing and storing this knowledge and serving as a group memory (Holsapple, 2008).

Certain types of GDSSs also concentrate on cooperative aspects of group decision making by supporting participant negotiations. These GDSSs are characterized by PPSs with second order capabilities designed to support problem-processing associated with participant groups that are typically organized into complex structures of authority, influence, and/or representation, which require specialized forms of communication and knowledge-sharing. Recent advances in GDSS software are producing systems that enable the partial automation of group facilitation tasks, thus increasing the ability of facilitators to monitor and control the meeting process (Alda et al., 2011). Future advances in the development of GDSSs could produce systems that provide indicators that suggest when additional information is needed to advance the decision-making process along or that make recommendations on mechanisms to help the group move towards agreement (Alda, Zarate, & Soubie, 2011).

ENVIRONMENTAL DSSs (EDSS)

DSSs developed for use in environmental decision domains are referred to in the decision support literature as EDSSs. Some early definitions of EDSSs specify that these systems integrate models, or databases, or other decision aids, and package them in a way that decision makers can use (Rizzoli & Young, 1997). This implies that EDSSs can be structured in a number of different ways, including solver-oriented DSS architectures, data-base oriented DSS architectures, or as compound DSSs that blend these and/or other knowledge processing techniques into a single integrated DSS structure.

The proliferation of EDSSs in the past thirty years has resulted in the incorporation of a multitude of features and functions designed not only to increase the efficacy and efficiency of these systems, but also to broaden the range of decision domains in which they can be used.

Cortés et al. (2000) describe EDSSs as intelligent information system[s] that ameliorate the time in which decisions can be made as well as the consistency and the quality of decisions, expressed in characteristic quantities of the field of application. Elmahdi and McFarlane (2009) describe an EDSS as an intelligent analysis and information system that pulls together, in a structured a but easy-to-understand platform (i.e. DSS), the different key aspects of the problem and system: hydrological, hydraulic, environmental, socio-economic, finance-economic, institutional and political-strategic. Implicit in this definition is that EDSSs should combine database management, engineering, modeling, and group facilitation tools in a platform that can be used in a participatory decision-making framework.

Decision support system developers argue that EDSSs can and do play an important role in helping to reduce the risks of environmental degradation resulting from human activities (Cortés et al., 2000). However, despite the perceived value of EDSSs in informing environmental and natural resource management, these tools often fail to be adopted by intended end users (McIntosh et al., 2011). McIntosh et al. (2011) reviewed the existing documentation associated with twenty EDSSs described in the DSS literature and reported that the extent to which the systems had been used operationally by the intended users was variable and not always clear. The researchers noted that no clear relationship was evident between the extent/success of use and the actual characteristics of the EDSSs reviewed. The lack of a correlation pattern between tool characteristics and tool use might indicate that the use of developed EDSSs is linked more to the tool development process than to the end product or to the targeted use itself. Their paper went on to describe a set of recommendations for best practices in EDSS development. Best practices in DSS development are discussed in more detail in Sub-section 2.2.1.9 of this dissertation.

SPATIAL DSSS (SDSS)

SDSSs are a class of DSSs designed to aid decision makers whose decision domain includes a geographic or spatial component. Applications of SDSSs can be found in a wide variety of decision situations, including (but by no means limited to) construction, transportation, urban planning, emergency/disaster response, agriculture, natural resource exploration, environmental protection, etc. Decision situations involving environmental problems often have a geographic or spatial component. Therefore, while only some SDSSs can also be categorized as EDSSs, the vast majority of EDSSs are also SDSSs.

The capabilities of SDSSs can vary from simple systems that are limited to providing static maps of different aspects of a decision domain to fully interactive web-based systems with sophisticated LSs, PPSs, KSs and PSs capable of: (1) acquiring and storing large volumes of knowledge from a large number of sources; (2) providing high levels of knowledge processing to a varied community of users; and (3) offering customized access to processed knowledge in nuanced and novel ways.

Since the coining of the term spatial decision support system, the platforms over which most of these systems have been developed has been primarily geographic information systems or GIS (Yeh, 2000; Keenan, 2003). GIS are essentially database management programs that include a geospatial interface, which allows analysis and visualization of georeferenced data. Since their appearance in the late 1980's, the capabilities and accessibility of GIS has been improving. The direct contribution of GIS to decision making has been in the ability of these systems to store, manipulate and analyze data based on the data's spatial location. In this sense, much of the architecture of SDSSs is based on the database-oriented DSS model.

Keenan (2003) has argued that, from an academic point of view, most GIS already meet the requirements of a DSS, as these systems contain an interface (i.e., LS and PS), a database (i.e., a KS) and some data manipulation and modeling components (i.e., a PPS), albeit mostly limited to spatial applications. Hence, the techniques needed for a SDSS are already within most currently available GIS programs. This view relegates SDSSs to being applications of GIS software that use a subset of the techniques available in these systems to support decision making. GIS also incorporate a pseudo-modular approach to problem solving by allowing the visualization, analysis and manipulation of different geospatial layers within the same area or view, thereby supporting different types of decision making or helping to navigate through different aspects of the decision domain. A simple example, offered by Keenan (2003), is illustrative of this capability: a developer or financial institution may be interested in knowing if a parcel of land is within a 100-year floodplain to decide whether to invest or build on that land; these decision makers would likely be interested in superimposing the 100-year floodplain layer over the map layer that shows the location of the proposed development. An emergency response or disaster planning official may be interested in superimposing the same floodplain layer over a map or satellite image showing existing dwellings and/or a layer of streets and highways to evaluate evacuation routes.

Among the impediments for the use of SDSSs is the expense involved. Commercially available GIS software can be expensive. The price of customizing commercially-available GIS software raises the expense of using these tools for decision support. The cost of maintaining commercially available software (e.g., upgrading for use in new operating systems releases) locks the users into a cycle of additional expense, which in many cases is difficult to assess at the start of a project.

Another potential impediment to the use of commercially available software for decision-support is the proprietary aspect of the products used; a factor which may contribute to the "black box" problem discussed in previous sub-sections. The source code for commercial software is almost never made available to users, or anyone else outside of a software company for that matter, for fear of the company losing competitiveness. This not only creates a dependency on the software company for modifications and upgrades, it also obscures the algorithms and other DSS knowledge processing methods from the decision makers. This lack of transparency has the potential of sowing distrust among the users/decision makers and could contribute to a loss of reputability, and ultimately acceptability, of outputs and associated potential outcomes. As part of their standard operating policies, some government agencies require the use of non-proprietary software for analyses conducted, by permitted entities, in support of permitting decisions.

The use of open-source GIS software, such as QGIS, and associated non-proprietary software libraries, can serve to mitigate the financial and transparency concerns linked to the use of proprietary software for the development of SDSSs. Some open source software products are also associated with a robust community of users that often offer advice, and even support, for the use of these products. To be sure, the use of open source software for SDSS development does not come without risks. For example, some open source software products can contain malicious software or spyware. Also, the level of support may not be adequate for long-term software maintenance. Users of open source software are advised to conduct extensive research on the products they are considering for use in SDSS development and to stay current with the information made available by the pertinent user communities. Nevertheless, the use of open source software is a growing trend in the development of DSSs and especially in the development of SDSSs, despite the associated risks.

MULTI-CRITERIA DSSS (MCDSS)

An emerging area of high interest in DSS research is multi-criteria decision analysis (MCDA). Multi-criteria decision making refers to decision making in the face of multiple, often confounding or conflicting, decision criteria. The problems faced by decision makers, under circumstances in which multiple criteria are used to evaluate potential decision outcomes, share the following characteristics: (1) potential decision outcomes are evaluated using multiple criteria [attributes or objectives]; (2) the decision evaluation criteria, at the very least, interfere with one another [but, more often confound one another or conflict with one another]; (3) the criteria used to evaluate potential decision outcomes have different units of measurement or may not be reconcilable in other ways; and (4) measurement of some or all decision criteria is illusive (Baizyldayeva et al., 2013).

Two major types of multi-criteria decision making are identified in the MCDA literature: multi-attribute decision making and multi-objective decision making. The former concentrates on discrete or finite decision spaces (i.e., decision domains) and the later concentrates on continuous decision domains. There are a number of mathematical methods that can be used to optimize solutions to both types of multi-criteria decision problems and several of these methods have been incorporated into specialized DSS software designed for specific multi-criteria decision situations. These include methods such as the analytic hierarchy process (AHP), the multi-attribute adaptive utility (MAAU) method, the multi-variate value (MAV) method, fuzzy goal programing (FGP) and Compromise Programming, just to name a few. Razmak and Aouni (2014) conducted a review of 75 papers documenting the use of MCDA in DSSs in various fields and sectors and found that, in general, applications of MCDSSs was most frequent in addressing environmental problems. They also found that the most commonly used method of analysis were AHP (24%) and MAAU (20%). The following paragraphs provide a brief description of these two methods.

The goal of all MCDA methods is to structure decision problems by systematically representing and quantifying the objective and subjective elements of the problem in a way that allows these elements to be simultaneously related to each other and to the overall decision goals. The first step in the AHP method is to decompose a decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. Having established this hierarchy, the decision makers evaluate the sub-problem elements, comparing them in pairs over multiple comparison rounds. If objective information is available (e.g., cost-benefit relationships), it can be used to compare sub-problem elements. Otherwise decision makers must develop a consensus judgment about the relative meaning and importance of each element using their informed opinions and/or using expert advice. The next step in AHP is the conversion of these evaluations into numerical values representing weights or priorities. Decision alternatives and associated scenarios are scored based on a mathematical aggregation of element weights. This allows the decision makers to make an objective or semi-objective comparison of often incommensurable problem elements in a consistent manner.

The MAAU method is based on the well-established economics principle of utility. The method uses the attributes of the decision options available to the decision makers to calculate the overall utility of those options to the decision maker(s) or stakeholders, under a specified or unspecified amount of uncertainty. In this sense, the MAAU method is less flexible than AHP, as it leaves little room for the quantification of decision attributes for which rational utility cannot be easily assigned. However, the computational aspect of the MAAU method is considered by proponents of quantitative MCDA methods to be more robust than AHP.

The underlying presumption of the MAAU method is that a person's preference can be represented by a numeric function. Under conditions of absolute certainty, economics theory postulates that consumer preferences can be expressed in terms of an ordinal utility function. Under conditions of uncertainty, the bundling of the goods/benefits and costs/risks becomes more complex and the calculation of utility becomes more complicated. To estimate utility for the later cases, economists use cardinal utility functions or scales, which can serve to order preferences by creating utility indices for the value of goods bundles. Assuming the number of possible bundles is finite, and that absolute satisfaction exists, utility indices differ only with respect to scale and origin. A diminishing marginal utility then is a function of fixed constants assigned to the affine transformation that relates the indices.

At the center of the MAAU method is the construction of utility functions associated with the goods bundles, which incorporate both preferences and uncertainty. The simplest form of the process is a two-step procedure by which the goods bundles are ordered least preferred to most preferred, assigning utility 0 to the former and utility 1 to the latter, and assigning, to each bundle in between, a fractional utility equal to the probability of an equivalent lottery (Keeney and Raifa, 1993). The difficulty with this approach lies in the difficulty in assessing utility in terms of value to the decision maker when combining potential benefit and probability.

As with SDSSs, many of MCDA-DSS programs are proprietary and suffer from the same impediments for use (i.e., high cost and "black box" problems). An additional impediment to MCDA-DSSs is the lack of flexibility inherent in the commercial programs currently available in the software market. These impediments notwithstanding, the incorporation of MCDA into DSS development offers practitioners the ability to integrate policy preferences with technical evaluations of future conditions. In the case of EDSSs, MCDA methods can be used to assist decision makers in making difficult tradeoffs between stakeholder interests and the environment. It should be noted that the term "MCDA methods" need not be confined to the various quantitative methods available for decision analysis. Any DSS which addresses multiple decision criteria can be thought of as a type of multiple-criteria DSS. MCDSSs can be helpful tools in situations of significant uncertainty and data scarcity.

2.2.1.5 The Role of Models

If decision makers could see into the future to assess, *a priori*, the outcome of their decisions, there would be little need for DSSs or for the decision domain knowledge these systems are designed to provide. Unfortunately, or perhaps fortunately, human beings are not (yet) capable of observing future conditions. But, decision makers *can* gain some insight into possible future conditions through the use of predictive models.

Models are "description[s] or analog[ies] used to help visualize something (such as an atom [or future water levels in an estuary]) that cannot be directly observed" (Merriam-Webster, 2019). As such, models are representations of reality based on prior observation. In addition to prediction, models can be used for explanation (e.g., identifying the factors that cause river levees to break), retrodiction (e.g., modeling the creation of our moon through planetoidal impact), and emergence explanation (e.g., game theoretical accounts of cooperative human behavior [Eason et al., 2007]).

While there are many kinds of models, including physical models (e.g., building mockups), conceptual models (e.g., process models or workflow diagrams) and numerical models (e.g., statistical regressions, deterministic environmental models), DSSs tend to include primarily process models and/or numerical models. EDSSs, in particular, tend to include mostly numerical models, either of the deterministic or probabilistic types. For the purpose of this discussion, the author will use the term "model" to refer exclusively to numerical models that produce outputs by transforming the information input into them. Within this context, models can be conceptualized using a tripartite structure consisting of input conditions, mechanism, and output conditions (Grim et al., 2013).

Having created a model of a particular process or decision situation, the decision maker can use the model to assess future conditions by altering model inputs and examining the associated model outputs. The specific advantages of incorporating models into DSSs includes: (1) a decrease in analysis time required for manipulating data; (2) greater accuracy of analyses than is otherwise possible using individual calculations; (3) standardization of forecasting logic leading to more universal acceptance of results; (4) a decrease in the amount of time needed for overall planning activities; and (5) production of more nuanced analyses based on factual information (Bonczek et al., 1981).

A DSSs ability to formulate and employ models that are useful in decision making is not only reflected in the sophistication of the language available to the user for directing modeling functions and retrieving model output (i.e., the user-model interface and the user-data interface), but also in the internal language the DSS uses to ensure proper access, by the model, to pertinent data (i.e., the model-data interface). Figure 2-15 illustrates these generic interfaces.

The decision maker may use the user-data interface (see b in Figure 2-15) to provide data, or other information, needed by the model or to retrieve data generated by the model, either as a standard data output generated by the DSS or, if available through the LS, as a customized data output in a user-specified format (i.e., reports, graphs, tables, etc.).

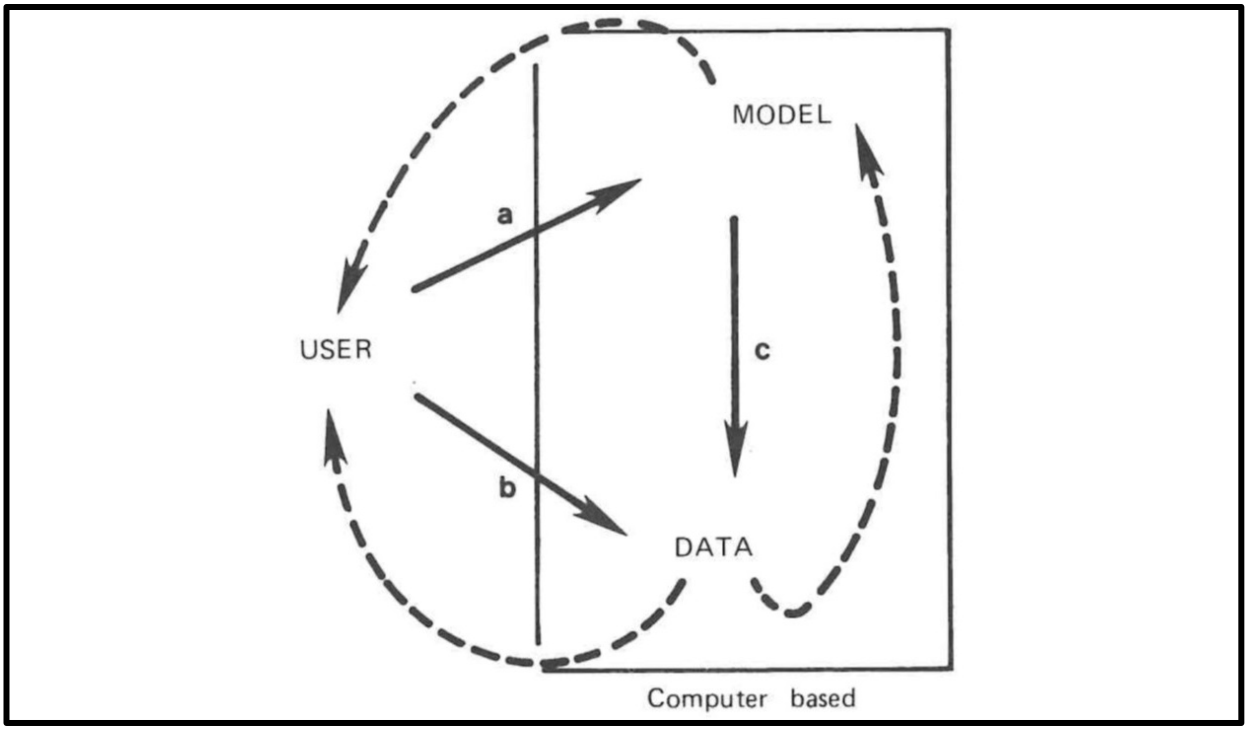

Figure 2-15. Basic Modeling Interfaces in a Generic DSS. Source: Bonczec et al., 1981.

Through the user-model interface (a in Figure 2-15), the decision maker can request the model functions or sub-models (i.e., modules) they desire, and which are made available through the LS. Depending on the system, the user may have the option of requesting some model functions without invoking others. The information produced by executing one model or module may be immediately available for use by another model in the system. The user may be required to specify the sequence of model or module execution or the system may choose the model execution sequence based on the user's request. The model-data interface (c in Figure 2-15) requires accessibility to one or more databases and/or to a linkage between models or modules.

The degree to which a DSS provides modeling capabilities can vary from one system to another. At one extreme, the user of the system may perform a large share of the model design. At the other extreme, model building may be automated to the point of being limited only by the language available to the user (e.g., type of output desired, kinds of input the model should have, etc.). Systems with highly developed model formulation capabilities may possess well developed information collection capabilities. For example, if a user provides ambiguous or erroneous information through the LS, the system will reject the information, perhaps also providing an explanation of why the information is being rejected and suggesting an alternative.

It is important to remember that models are only one potential component of a DSS and that with the rising sophistication and automation of model-centric DSSs comes a commensurate decrease in the flexibility of these systems. As early as the 1970s, researchers noted that many of the models used in decision support frequently fell into disuse. According to Sprague and Watson (1979), this is not typically due to the lack of the models' mathematical validity or ease-of-use, but instead tends to be due to an insufficient amount of attention given, by the model designers, to data sources and, more importantly, to the utilization of model outputs by the model users. In answer to this problem, researchers began advocating a more participatory approach to model development for decision making and a higher focus on the overall decision-making process rather than on the models themselves. It is currently considered standard practice for DSS design to emphasize stakeholder involvement in the design, implementation and execution of models used in DSSs (McIntosh et al., 2011).

Another early recommendation for the enhancement of DSS model design is the use of modular DSS modeling systems. Modular systems were briefly discussed in Sub-section 2.2.1.3 within the context of generic DSS architecture types. Within the narrower context of model design and usage in DSSs, a modular design is advantageous because it facilitates model extension and/or modification, thereby increasing the flexibility, usefulness and durability of model-based DSSs. Bonczek et al. (1981) defined modules as models that are capable of being used in some configuration with other modules to form a larger or more comprehensive model. Modules can be thought of as "building blocks" for a model. However, a model may or may not be used as a module. The use of modular frameworks for decision support design is discussed in more detail in Sub-section 2.1.1.3.

No model is a perfect representations of reality or "models are always wrong but sometimes useful" (an aphorism commonly attributed to the statistician George Box). In a meta-analysis of technical papers on modeling, Grim et al. (2013), explored how model simulations fail and described the factors that contribute to model failure. Grim and his co-authors conducted their analysis by exploring failures occurring during each part of the tripartite modeling structure described earlier in this section (i.e., input conditions, mechanism, and output conditions). They found that, for predictive models, the realization of failure usually comes at the point of "correspondence;" that is, when the model is tested against a known reality, and that the failures were rooted primarily in the uncertainty inherent in each component of the tripartite modeling structure.

Uncertainty in input data, either measured, derived from previous work or assumed, can lead to uncertainties in model configuration (i.e., wrong model set up). Uncertainties in the data used to calibrate a model can lead to the use of inadequate values of calibration variables. Similarly, uncertainty in the representation of the processes or situations being modeled can lead to errors in the model mechanism, either because the process is not well understood or because the abstractions used to simulate reality are too simplistic, or because the model is focused on facets of the processes or situations that are not relevant to the decision domain. Uncertainty in the representation of output conditions leads to errors in correspondence with reality, present and/or future, either because model outputs cannot be interpreted correctly, yielding misleading outcomes, or because the outputs are the result of uncertainty/error propagation from the first two tripartite modeling parts, input conditions and/or the model mechanism.

Voinov et. al. (2016) used the term "epistemic uncertainty" to collectively describe the sources of uncertainty outlined above. The term generally refers to uncertainty due to a lack of knowledge of the "true system" being modeled, which can manifest itself in various forms previously discussed. Bijlsma et al. (2011) further identified three distinct categories of epistemic uncertainty: substantive, strategic and institutional.

2.2.1.6 Participatory Modeling

The role of modeling in GDSSs has been the subject of extensive research since the 1980s (e.g., Liang, 1988; Davey and Olson, 1998; Chen et al., 2018). More recently, there is a growing trend among model-centric DSS developers to place as much emphasis on the human dimensions of the modeling process as on the technical aspects of the models themselves (Voinov et al., 2016). Experts in the DSS field have developed a consensus regarding the value of stakeholder involvement, not only in group decision making itself, but also in the development and usage of decision support tools, and especially in the models used for group decision support (van Eeten et al., 2002; Jones et al., 2009, Voinvov and Bousquet, 2010). The term "participatory modeling" or PM is used to describe a form of model development and usage that incorporates the implicit and explicit knowledge of the stakeholders associated with a decision situation. In the PM process, multiple participants co-describe the problem at the center of a decision situation, co-develop a model of that situation, and use the model collaboratively to simulate the outcome of proposed solution(s), including planning scenarios, structural controls, policy interventions, etc. PM produces models that have a higher degree of 'ownership' by the participants involved in model development. In addition to producing better decisions, the decisions produced though PM are more likely to be implemented. The PM process itself is thought to reduce obstacles to the acceptance of the changes brought about as a result of the policies or interventions recommended through the PM modeling effort.

Voinov et al. (2016) conducted a review of over 200 technical articles that refer to stakeholder involvement in environmental modeling. The authors identified a consensus among researchers regarding levels of participation or engagement in PM, the most passive of which was simply to inform stakeholders of the modeling efforts being conducted, which does not involve what the authors termed "true" stakeholder engagement. The next level of participation, which the authors termed "extractive use," limited stakeholder involvement to providing data and information used to develop and calibrate environmental models. Higher levels of participation involved the collaboration of stakeholders in various activities associated with the modeling efforts. The most intense participation cited by the authors occurred when local stakeholders actually initiated the PM process and were engaged in all aspects and stages of the PM process, including problem identification, model design, parameter selection, data collection, data validation, model application etc., up to, and including, decision formulation based on model outputs. By most accounts this last, and highest, level of PM engendered high degrees of ownership of all aspects of the modeling effort. Voinov et al. (2016) also identified seven general domains or components that present opportunities for stakeholders to engage in the PM process, these are presented in Figure 2-16.

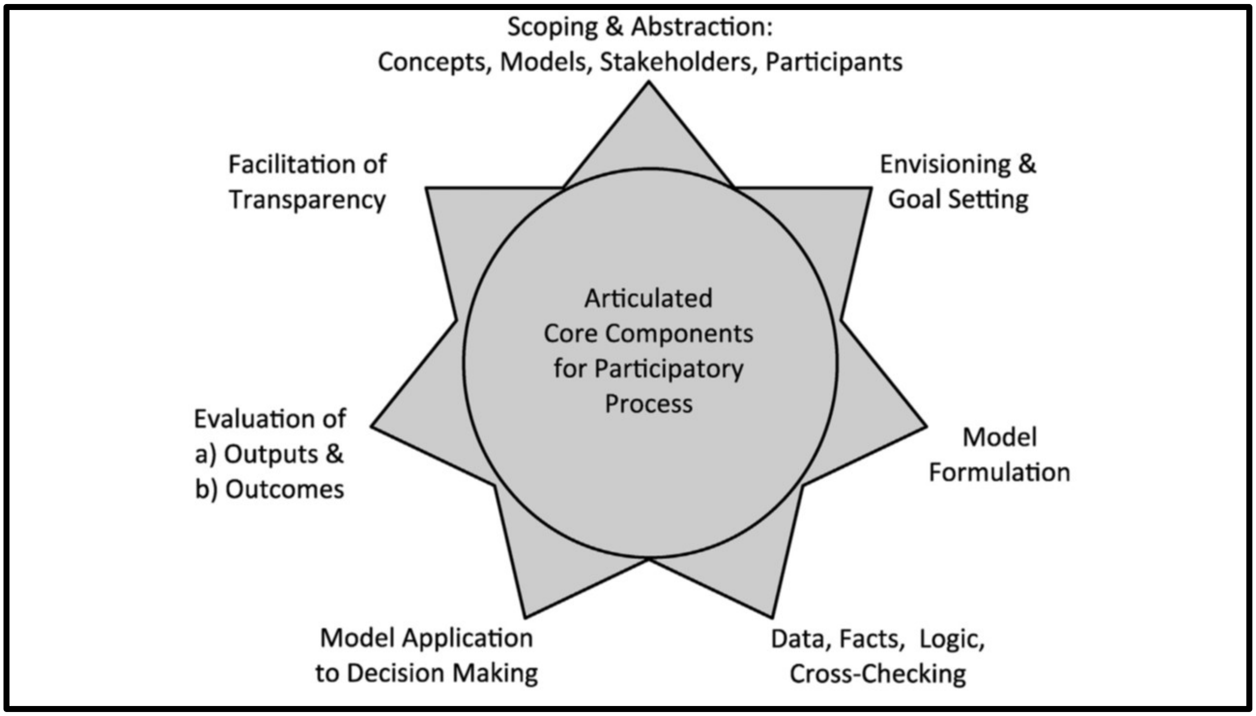

Figure 2-16. Components of the PM Process. Source: Voinov et al., 2016.

The two components of the modeling process in which stakeholders most commonly participate are supplying data for model development and calibration and evaluation of model results. The second of these two components (evaluation of model results) sometimes includes aspects of PM that go beyond objective assessment of model outputs, especially when dealing with a heterogeneous group of participants (e.g., stakeholders of different ethnic backgrounds or nationalities). In these situations, the credibility and acceptability of modeling results may be affected, both by the verifiable accuracy of model results and also by social values, national identity or, even international relations, all factors that intrinsically affect trust in the PM process and in its outcomes. When intrinsic levels of trust are low, there is much greater need to build up two-way, shared communications slowly and sensitively; this is most likely to happen through trusted intermediaries (Voinov et al., 2016). This notion was tested in the development of the LRGWQIDSS and is discussed in more detail in Chapter 4 of this dissertation.

It should be noted that model outputs and the outcomes associated with model results are separate and distinct facets of the modeling process and the evaluation criteria for each differs in substance. While model outputs are typically evaluated using technical measures (e.g., fecal bacteria or dissolved oxygen concentrations in surface water, etc.), modeling outcomes are often evaluated based on long-term, broader scale results (e.g., water treatment costs, aquatic habitat loss, etc.). In most cases, the evaluation criteria for the former (model outputs) is closely related to the later (simulated outcomes). However, while the evaluation of model outputs typically assesses the accuracy of model results, the evaluation of simulated outcomes assesses the adequacy or desirability of the situations or scenarios represented by the model outputs.

While both of these types of evaluations benefit from stakeholder participation, it is important to consider the internal and external factors that constrain the decision domain. According to Voinov et al. (2016), in addition to technical considerations, evaluation criteria need to be used in a way that is politically feasible, both locally and at other political levels. For example, a locally developed conservation plan may need government agency approval before it can be implemented. Hence, a comprehensive understanding of the internal and external factors that constrain the decision domain can be a useful part of any DSS-associated modeling effort.

Participation in group modeling efforts associated with decision support can never be all inclusive, and so there is inevitably a balance between “breadth” to engender inclusivity, and “depth” to include experience and expertise. Finding such a balance can be challenging and laborious and there is currently no guaranteed procedure for ensuring adequate stakeholder engagement in PM.

Efforts to identify modeling participants with an understanding of the internal and external constraints affecting the decision domain may have the effect of reducing the epistemic uncertainty associated with DSS modeling (Sahin et al., 2014). Bijlsma et al. (2011) identified three categories of epistemic uncertainty associated with PM: substantive, strategic and institutional. Substantive uncertainty refers to uncertainty associated with the “substance” of policy problems; for example, fecal bacteria contamination in surface water or aquatic habitat loss. Strategic uncertainty refers to the uncertainty associated with how actors act or react to specific situations; for example, land owners’ reaction to a new land use policy or the reaction of public utilities to new planning procedures. Institutional uncertainty refers to uncertainty associated with formal competencies, procedures and conventions; for example, the feasibility of implementation of new immigration policies or binational water quality planning efforts.

In addition to including key participants in the modeling process, there are several technical and nontechnical approaches to reducing uncertainty in PM, including methods that employ statistical theory (e.g., O'Hagan, 2012; Rinderknecht, et al., 2012), possibility theory (e.g., Page et al., 2012) and qualitative methods (Uusitalo, et al. 2015). And, while these and other methods have focused on reducing, or at least characterizing, substantive and strategic epistemic uncertainty, few examples exist of methods designed to characterize and/or reduce institutional uncertainty in PM. However, recent research has suggested the use of institutional analysis as a means of reducing uncertainty in environmental decision making (Cowie & Borrett, 2005; Maier et al., 2008; Primmer et al., 2016). The use of institutional analysis in the design of EDSSs is discussed in more detail in Section 2.4.

2.2.1.7 Visual Analytics

As decision making becomes less centralized and more inclusive, the use of innovative communication and visualization tools becomes as important as the development of advanced data acquisition and processing tools normally associated with modeling. Data is central to decision making and transforming data into useful information is an important part of decision support. Whereas a scarcity of data can limit the choices of decision makers or compel them to take risks, an overabundance of data can sometimes overwhelm decision makers, confounding their ability to process and make sense of large volumes of abstract facts and figures. In recognition of this problem, Information Visualization became an important topic of research among database scientists in the 1980s and 1990s (Card et al., 1999). While the emphasis of Information Visualization is on methods to present data in a more understandable manner, more current research focuses on simplifying and clarifying the actual transformation of data.

Visual Analytics (VA) can be defined as the interactive visualization of automated analysis techniques to facilitate effective understanding, reasoning, and decision making on the basis of very large or complex data sets (Keim et al., 2008). VA integrates information visualization with fundamental disciplines related to data management and analysis, spatio-temporal data, and human perception and cognition, all within an appropriate infrastructure and evaluation framework (Figure 2-17).

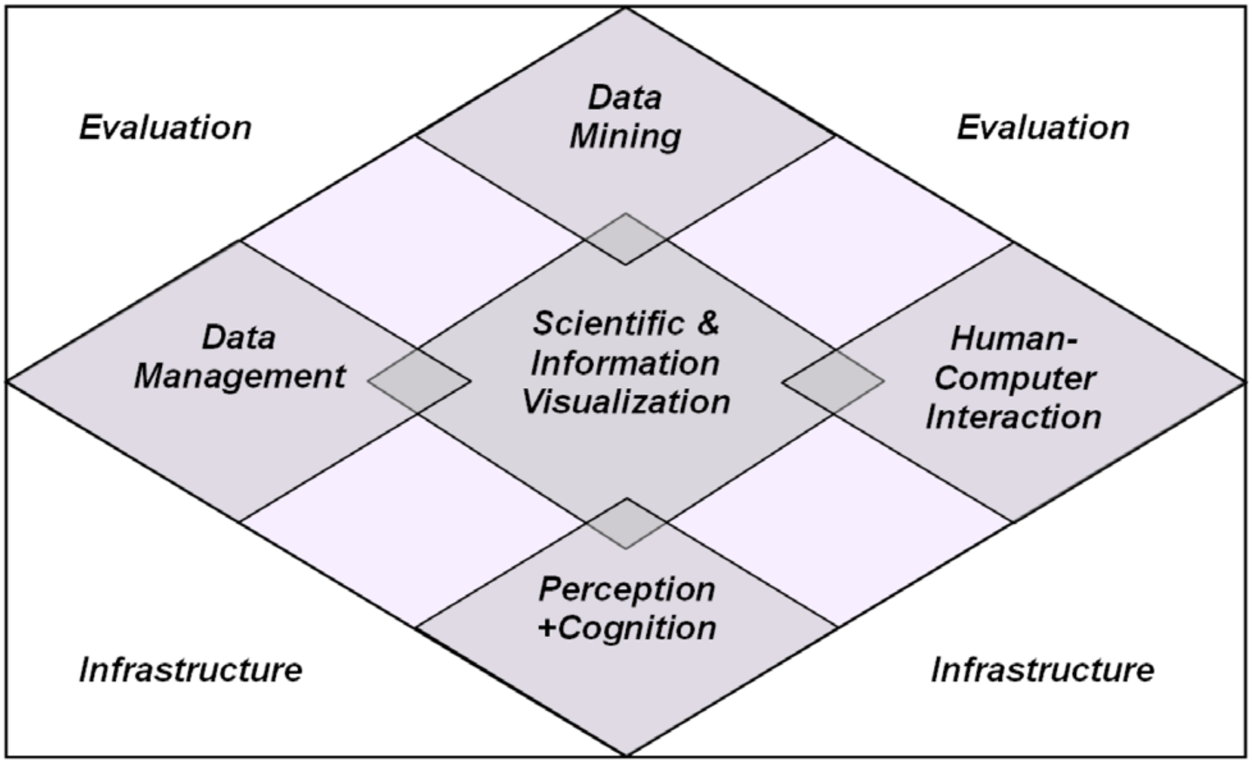

Figure 2-17. The Visual Analytics Framework. Source: Keim et al., 2008.

In addition to visualization methods for contextualizing and clarifying data VA adds a dimension of transparency to the decision-making process. The level of trust participants have in the methods, processes, and outputs of a multi-actor decision-making forum can influence its success. The more transparent the data analyses and data transformations used as part of the decision-making process, the higher the levels of trust that are achieved among the participants (Voinov et al., 2016). VA can create what Voinov et al., (2016) termed "boundary objects" which are items on which opposing or conflicting interests can agree without compromising their core stands of key positions. VA can therefore be a conduit to achieving consensus among decision makers and stakeholders.

VA has become an integral component of digital EDSSs, which are commonly used to support natural resource management efforts. At the center of these efforts is the development of EDSSs that combine traditional scientific and engineering methods with geovisual analytical features that provide a means for the decision makers to perceive and understand the transformation of data into useful information. Of particular interest to researchers is the professed ability of EDSSs with geovisual analytical features to enhance the co-management of natural resources (Romañach et al., 2014, Grainger et al., 2016, Schütz et al., 2017).

2.2.1.8 Co-management

Co-management is defined as a "situation in which two or more social actors negotiate, define and guarantee amongst themselves a fair sharing of the management functions, entitlements and responsibilities for a given territory, area or set of natural resources" (Borrini-Feyerabend et al., 2007, p.1). This form of natural resource management has been recognized by academics, analysts and natural resource management agencies as an alternative to traditional centralized, top-down natural resource management approaches, as shared governance is thought to enhance the efficiency and long-term sustainability of natural resource planning and management efforts (Berkes et al., 1991). Predating the promulgation of IWRM by almost a decade, the concept of co-management was instrumental in the development of the 3-E Principle of IWRM, which advocates inclusivity in decision making at multiple levels. Co-management approaches, such as those associated with implementation of IWRM, have also been instituted in planning and management efforts involving transboundary water resources.

Water resources co-management arrangements are often codified in legal agreements, with different degrees of power sharing, for joint decision making by the state, other forms of government, and/or communities, including transboundary settings. However, research has shown that successful co-management of natural resources is a not a fixed-state solution, but rather a continuous problem-solving process, involving extensive deliberation, negotiation and, most importantly, joint learning within decision making networks (Carlsson & Berkes, 2005). The role of joint learning is paramount in successful co-management situations (Armitage et al., 2008; Berkes, 2009). Some case studies documenting IWRM-based efforts in transboundary water bodies highlight the importance of decision support tools with advanced geo-visual analytics for collaborative decision making and co-management.

2.2.1.9 Best Practices in DSS Design

Decision making is a complex process under most circumstances, but decision making within the context of natural resources management is often complicated by situations which require consensus building among a group of diverse stakeholders with differing views and, often, with opposing interests. Consequently, researchers involved in the development of DSSs for natural resources management have developed a set of best practices obtained through several decades of experience building GDSSs, SDSSs and EDSSs.

An overriding theme when discussing best practices for the development of any type of DSS, but especially EDSSs, is to ensure user participation throughout the development process. For example, a DSS fails if it does not fulfill the needs of the end user, but successful DSS development is judged by whether the users adopt the DSS for decision making and user adoption has been shown to be influenced by user participation in the development process (McIntosh et al.,2011). It follows then, that the focus of DSS and EDSS development efforts should not only be on understanding how to create more functional and useful systems for decision-making, but also on building a sense of ownership on the part of the user community. This necessarily involves a design process that ensures an active role for the user in the design of the DSS as well as a good understanding of: (1) the scope of the problems that are to be addressed; (2) the needs and behaviors of the users working in their respective organizations; (3) the roles of users in those organizations; and (4) the roles the organizations have in the overall decision domain.

BEST PRACTICES IN ENVIRONMENTAL MODELING

Environmental modeling is a well-established area of research and practice. As early as 1925, engineers working for the US Public Health Service were developing numerical fate and transport models for common surface water pollutants, such as biochemical oxygen demand in urban sewage (Streeter & Phelps, 1925). In the 1970s and 1980s a set of guidance documents developed by the USEPA sought to standardize the development of environmental fate and transport models (USEPA 1978, USEPA 1985). In the late 1990s and early 2000s environmental modeling practitioners published journal articles on best practices for environmental modeling (e.g., Risbey et al., 1996; Van der Sluijs et al., 2005; Jakeman et al., 2006). While these efforts concentrated on building better models, the current trend expands the focus of model development to include factors that increase the acceptability of environmental models as tools for planning, management, and policy development.

One of the biggest concerns associated with model development has been the issue of uncertainty. For model developers, the quantification of uncertainty in environmental models is a technical exercise used primarily to qualify model results. The study of the types and sources of uncertainty in environmental models is a complex subject beyond the scope of this dissertation. However, a great deal of model uncertainty is related to scarcity or incompleteness of the data needed for model input, calibration and verification. Data collection to fill data gaps may either be impossible or impractical because of resource and/or time constraints, so modelers must resort to using assumptions and best professional judgement in lieu of hard data.

Uncertainty in model output translates to uncertainty in predicted management outcomes. Therefore, the subject of model uncertainty touches on many aspects of decision support, including transparency, communication and accessibility, all of which influence user perception and trust of models used as tools in decision support. Risbey et al. (1996) advocate a policy of actively exposing all "dirty laundry," reasoning that, by completely exposing a model's shortcomings, modelers not only display an attitude of complete transparency, which builds trust in the modeling process, but may also engender a sense of ownership in the model, as the user community sees that the feedback they provide the modelers helps improve the model. Van der Sluijs et al. (2005) propose complementing mainstream technical methods of uncertainty analysis with qualitative approaches, such as investigations of alternative problem framings and the relative assessment of alternatives under consistent uncertainty. These techniques promote further reflection and collective learning, which may help mitigate controversy and help to uncover inadequacies in existing institutional arrangements.

Of course, it also makes sense to reduce uncertainty as much as possible prior to, and during, model development. Jakeman et al. (2006) advocate establishing some sort of quality assurance procedure that documents important modeling elements, such as the source of the data used for model input and calibration, as well as the rates, constants, state variables and calibration procedures used in model development. Beginning in 2005, the USEPA began requiring all environmental models developed for the purpose of guiding wastewater permitting decisions or other official agency actions, such as TMDLs, be preceded by the development of a quality assurance project plan (QAPP). QAPPs not only detail the important modeling elements previously mentioned, but also provide detailed quality assurance information associated with the data used in the model. QAPPs also specify the quantitative and or qualitative performance criteria for the model. The USEPA also requires separate QAPPs for any data collection efforts used for official purposes, including model development for the support of permitting decisions or TMDLs.

Decision makers invariably possess knowledge that is useful to modelers and other decision makers. Decision makers may have different perspectives on the same problem and may perceive and interpret model output in different ways. These points all highlight the importance of communication between: (1) the modeler and the broader planning/management community; (2) between modelers and other researchers involved in providing decision support for that community; and (3) among the members of that community within the context of decision support. This communication between participants in a decision forum is most effective when it is reciprocal; that is, when all parties are motivated by the knowledge gained from their interactions.

Model development for decision support should also be iterative. It is unrealistic to expect to discover, process and understand all the knowledge needed to construct a model useful for decision support without a process of trial-and-error. Especially once the preliminary structure of an environmental model is established, the use of conceptual demonstrations and prototypes can be helpful in guiding further model development. Hence, flexibility and adaptability are important in the design of environmental models for decision support. Conversely, a lack of clear modeling objectives can lead to frustration and wasted effort on the part of both decision makers and modelers. Sometimes modeling objectives change, as decision makers gain a more thorough understanding of the decision domain. This can result in what modelers and project managers refer to as 'scope creep.' To avoid scope creep a modeler can seek to facilitate a collective understanding of the objectives of the modeling effort among all participants.

In addition to scope creep, there are other modeling pitfalls familiar to most experienced modelers, including ignoring data limitations, overpromising, overelaboration, oversimplification, failing to select the right model for the right purpose, overlooking or dismissing existing knowledge, failing to accurately assess modeling resources and/or time constraints, and unintentional (or intentional) obfuscation. To mitigate these and other modeling hazards, Jakeman et al. (2006) developed a set of 10 iterative steps for the development and evaluation of environmental models, including:

1. Defining the purpose of the model (definition of the problem and possible solution)
2. Specifying the modeling context (specification of scope and resources)
3. Conceptualizing the system (specification of data and other prior knowledge)
4. Selecting of model families and features
5. Choosing how model structure and model parameter values are to be found
6. Choosing estimation performance technique and criteria
7. Identifying model structure and parameters
8. Conditionally verifying the model including diagnostic checking
9. Quantifying uncertainty
10. Evaluating the model or testing it (with other models, with simpler algorithms, with comparisons with alternatives)

Jakeman et al. (2006) provide further advice on how to best carry out these steps and avoid costly missteps. The following is a condensed summary of the advice offered by Jakeman et. al. (2006). For the sake of brevity steps 4, 5 and 7 have been combined into a single category labeled "model selection." Also, some of the terminology has been modified to better fit the LRGWQI context.

General Advice for the Development and Evaluation of Environmental Models

1. Defining the purpose of the model:

a) Beyond a quantitative assessment of the physical system, make efforts to gain a good qualitative understanding of the non-physical system(s).
b) Elicit existing knowledge. This not only makes the subsequent model more accurate, but it will focus discussion on topics relevant to model development and will spur engagement, engendering trust from decision makers.
c) Identify what is known, but more importantly, identify what is not known, what is assumed and what decision makers say they would like to know; this begins a data gap analysis.
d) Encourage discussion among decision makers. Identify areas where there is agreement and areas where there is no agreement.
e) Make a concerted effort to understand the decision situation(s) and the decision domain.

2. Specifying the modeling context (Identifying the Scope and Resources):

a) Identify who will be the users of the model.
b) Identify what questions the model must answer.
c) Identify what model output is required to answer the questions.
d) Identify the forcing variables (drivers).
e) Identify the accuracy needed (e.g., level of aggregation of output).
f) Identify the spatial and temporal scopes, scales and resolution needed and under what conditions.
g) Identify the time frame for model completion.
h) Identify the resources available (human, financial, temporal).
i) Identify how flexible the model must be (this task is very difficult; it requires qualitative input; it affects resources and time constraints; it cannot always be determined at the start of a project).

3. Conceptualization of the System (Physical, Social and Economic):

a) Closely linked to Problem Definition but is more detailed.
b) The effort placed in this step can save time and effort in subsequent steps.
c) Define system boundaries and acceptable degree of aggregation of input (very difficult but essential; requires significant trial-and-error).
d) Refine data gap analysis begun in step 1 (What input data are available? Are the data in the appropriate spatial and temporal intervals?).
e) Assess the possibility of additional data collection.
f) Identify the modeling assumptions that must be made.
g) Identify simplifications and their acceptability to decision makers.
h) Refine forcing variables and outputs identified in Step 2.

4. Model Selection:

a) Recognize that a deterministic model or stochastic model is not always needed.
b) Recognize that model structure has a big influence on the data needed for input and calibration and vice-versa (i.e., the available data often limits the choice of models).

c) Always build on existing knowledge, but do not abstain from questioning.

d) Complexity should be commensurate with needs (a good overarching principle is "simpler is better").

e) Trial-and-error is a proven vehicle for success, but time and resources can limit the viability of this approach.

f) Make maximum use of the knowledge gained from Steps 1-3.

g) Keep acceptable levels of uncertainty in mind when aggregating or disaggregating inputs.

h) Freely elicit advice and opinion from users and other experts.

i) Choice of models should not be influenced by the preferences of the developer, or compatibility with previous practice, or peer pressure, or fashion within technical communities. However, recognize that user/decision maker preferences, availability of software tools, agency policies, and shortage of time and resources are valid considerations in model choice.

<u>5. Choosing estimation performance technique and criteria:</u>

a) Performance technique and criteria should be commensurate with the expectations of the user (but, recognize that user expectations of accuracy and acceptable levels of uncertainty are not always clear at the outset).

b) Technical considerations should, at a minimum, include assessment of prediction performance, robustness to outliers, bias, statistical efficiency, and power.

c) Recognize that rounding errors, numerical instability and ill-conditioning of data will affect performance measures.

d) Beware of parametric estimation algorithms, as they are output correctors that can mask problems with the model.

e) Recognize that overparameterization can be problematic (i.e., can lead to overfitting to noise, ill-conditioning and misinterpretation of output).

f) As with environmental models themselves, simpler model performance measurement methods are always preferred over complex ones.

g) There should be a contingency plan for what to do when the model does not meet the performance criteria.

6. Conditionally [calibrating and] verifying the model:

a) The answer to the following questions should be conveyed openly and honestly to decision makers: How well does the model fit the observed data temporally, spatially and both temporally and spatially simultaneously? Does the model meet the performance criteria? If not, why not? How far from the performance criteria is the model output? Where/when does the model perform well and not so well?
b) If possible, use more than one verification data set.
c) Understand that for some purposes, particularly increased understanding of the system and data, the modeling exercise may be useful even if the final model is poor in many respects. An inaccurate model may still shed light on how an environmental system works.
d) Assess whether the results of the model make sense to you, to the user/decision maker, to other technical experts.
e) Resist correcting model output; do not ignore potential problems with the model or input data.
f) Check and recheck assumptions, input data, preprocessing of input data and postprocessing of output.

6. Quantifying Uncertainty:

a) Determine the level of uncertainty analysis expected by the user. Present choices for uncertainty analysis.
b) Error bars and confidence intervals make good visual tools but the modeler should be confident (and honest) about confidence ranges.
c) Sometimes sensitivity analyses are as important as error analyses. At the very least sensitivity analyses can focus attention on the most relevant aspects of model uncertainty.
d) Recognize the nested and compounding nature of uncertainty in environmental models (e.g., theoretical error, measurement error, aggregation/disaggregation

error, rounding error, error associated with assumptions and simplifications, etc.). Explain, to the user, the relevant components of uncertainty propagation associated with the environmental model.

e) Acknowledge that the full degree of uncertainty can never be represented as a single statistical value.

7. Evaluating the model:

a) Model evaluation should not be dominated by traditional measures of model accuracy, but rather by whether the objectives of the model were accomplished.
b) Model validation should be a collective exercise among modelers and users. However, there should be a quantitative aspect to the exercise (i.e., spatial/temporal performance evaluation with data not used to construct the model).
c) Model calibration and validation need not be completely consistent with all available knowledge.
d) As with all modeling steps, but especially with model evaluation, transparency is of utmost importance.
e) Unfavorable evaluations must necessarily be followed by assessment of input and calibration data, testing of assumptions, searches for processing or coding errors and, if necessary, reconceptualization of the model domain.
f) Attention should be paid to “soft” performance criteria (e.g., speed, flexibility, etc.).

Jakeman et al. (2006) also make several recommendations for operational performance of modeling tasks. Modelers strike a balance between the resolution of model output, including accuracy, and the often resource-intensive computational efforts need for such output, reasoning that the level of user acceptance of uncertainty is dependent as much on decision outcomes as it is on cost-benefit relationships; decision makers may be willing to live with a certain degree of error, as long as it is consistent across a rank order of alternatives or modeling scenarios. Jakeman et al. (2006) discuss minimum standards for model acceptability and the importance of pre- and post-model documentation. They advocate conducting as thorough analysis and testing of the models as time and resources will allow. They promote the production of a priori quality assurance documents that clearly state the quality objectives of the model, describe the rationale for model choice, provide justification for the methods used to assess model performance, and provide information about the source and quality of input and calibration data.

Best Practices in EDSS Development

Following sound professional advice and best practices for the development of environmental models can help overcome the challenges faced by environmental modelers. However, the task of embedding analytical tools, such as environmental models, into broader decision support applications presents its own set of challenges. Because user participation can improve the development of both environmental models and DSSs, as previously discussed, many of the best practices discussed in the previous section are also applicable to the successful design and implementation of EDSSs.

The influence of organizational factors on the design, adoption, and use of decision and information support tools was studied by Diez and McIntosh (2009), who found that the most relevant implementation factors appeared to be user participation, computer experience, perceived effectiveness, system quality, management support, and user support/training. Subsequently, McIntosh et al. (2011) elaborated on the best practices in EDSS design and development. The authors of McIntosh et al. (2011), a group of 27 experienced EDSS researchers and developers from academia, government, and business, analyzed 19 EDSS applications, assessing the systems' strengths and weaknesses. Applying their collective experience and judgement, the group developed a set of 25 best practice recommendations for designing, developing and implementing EDSSs. The recommendations focused on four areas of design challenges related to: 1) user engagement; 2) system adoption; 3) cost and technology issues; and 4) evaluation. The following is a summary of the advice offered by McIntosh et. al. (2011) to help EDSS developers overcome these challenges in a methodical manner.

General Advice for Design, Development, Implementation and Evaluation of EDSSs

1. Addressing Engagement Challenges:

a) Create a robust forum for end user participation in system development. Ensure user feedback can be supplied easily, equitably, and free of admonishment.

b) Investigate the bounds of decision making. Beyond problem identification, define the decision domain surrounding the problem.

c) Identify outcomes, incorporating considerations for values, attitudes and behaviors.

d) Identify the end users and their roles and relationships. Understand that users, decision makers and stakeholders may not always be the same individuals and that EDSS development and implementation may involve different participants. There may also be different types of users with different roles in decision making.

e) Consider use of the EDSS at different organizational levels. Ensure participation in EDSS development at all pertinent organizational levels identified.

f) Dedicate resources for a requirements analysis and/or a usability survey.

g) Work with the users to define clearly what constitutes success.

h) Provide opportunities for users to discuss and challenge analytical assumptions and methods.

i) Be as transparent as possible about how inputs are used and how outputs are generated.

j) Discuss resource constraints and timelines with the users/decision makers.

k) Provide feedback and confirmation of user input. Discuss the viability and cost of design features and system modifications suggested from user input.

l) Ensure that the expectations of funding organizations are in harmony with those of the end user. Due to the iterative nature of EDSS development, the scope and timing of grant or contract deliverables are difficult to detail at the outset of a EDSS development project. Competing commitments can sometimes interfere with the developer’s efforts to engage the users.

m) Use prototypes and system demonstrations early and often.

2. Addressing Adoption Challenges:

a) Ensure that EDSS development is user driven. Guide, but do not direct system development. Successful engagement with end users lays the foundation for adoption.

b) Ensure user interfaces are commensurate with the roles and tasks of the users. Use vocabulary, navigation controls and look-and-feel attributes that are familiar to the user.

c) Follow the principles of Human-Computer-Interaction (Schneiderman, 1998). Strive for consistency, minimize opportunities for input error, avoid user mental overload, etc.

d) EDSSs must be easy to use. Complexity should be reduced as much as possible and the systems should not require the user to acquire new skills or expertise to operate.

e) Ensure the knowledge contained in the system can be easily updated.

f) Provide good documentation (i.e., detailed user's manuals) and electronic help capabilities. Ensure the user does not rely on the developers for technical support.

g) EDSSs should be flexible enough to be used, at least, in the specific ways that fit with the users and their organization and or to be modified without an inordinate amount of effort. Try to accommodate multiple uses. Anticipate changes in scope.

h) Develop representatives or "champions" embedded within targeted organizations. This ensures responsiveness and improves the probability of initial adoption.

i) Create a plan for continuity of system support, including a strategy for transitioning from development to support.

j) Strive for broader organizational adoption. Build capacity through training and long-term support. Develop a means to accept and incorporate suggestions for continual improvement. This will not only improve the system but will help gain wider adoption.

k) Provide frequent demonstrations and use prototypes during development. In addition to enhancing end user engagement, these practices improve the probability of adoption. The testing of system capabilities should begin as soon as possible.

l) Do not oversell the system. Be open and honest about the system's weaknesses and shortfalls.

m) Uncertainty must be addressed prior to completion of the system because it affects adoption. The output from EDSS tools must be trusted before efforts are made to better present it to the user.

3. Addressing Business Costs and Technology Challenges:

a) Perform a thorough assessment of resources and time constraints (i.e., a business plan); include costs of training and long-term support and maintenance. Developers often underestimate project costs and fail to plan for unforeseen delays, both of which can threaten adoption and longevity of the final EDSS.

b) Develop and maintain scoping documents and produce progress reports. Record the input received and development decisions made.

c) Endeavor to use familiar operating platforms. Assess the advantages and disadvantages of using open source versus proprietary software. Proprietary software can be expensive but is often well documented and tends to be more reliable for long-term support and training. Open source software can be an inexpensive alternative, free of licensing commitments; open source consortia can also provide, at least, passive support.

d) Develop analytical tools incrementally. Use an iterative approach allowing refinement of functionality only when needed. Avoid high risk or unproven methods and technologies. Make extensive use of user feedback.

e) Minimize costs by avoiding scope creep and reducing the need for user training. Agree on clear objectives and functionalities at the outset and ensure these are met; provide detailed user's manuals and embedded help tools.

f) Incorporate modularity in the system design. Flexibility is highly linked to longevity.

g) Cultivate organizational commitment to long term support, both financial and logistical.

4. Addressing Evaluation Challenges:

a) Establish the context for evaluation. Users, decision makers, project funders, and stakeholders often have different notions of success. Ensure the proper measurement of pertinent outcomes.
b) Assess the analytical capabilities of the system. Evaluate not just the accuracy of analysis, but also the level of user satisfaction with the system outputs. Ensure the accuracy of system data and system knowledge.
c) Assess the application of the EDSS, including the role of the system in the decision-making process and the degree to which the system was, and is still, used.
d) Assess the non-analytical contributions of the system. Did the system help frame the problem(s) in a useful manner? Did the EDSS advance learning?
e) Be mindful of causality. Attribution of success is not an easy task. Good questions to ask are: Could this outcome have occurred in the absence of the EDSS? How did the EDSS contribute to this outcome?

2.3 Institutional Analysis

Section 2.2 of this dissertation addressed the value of user participation in the design of EDSSs (see 2.2.1.9 Best Practices in DSS Design). Section 2.2 also described the role users/stakeholders can play in the development of decision-support tools such as environmental models. Sub-section 2.1.2 (Review of Transboundary Water Resources Management Agreements) reported that a lack of meaningful stakeholder participation is a common criticism not just of some river basin commissions established under transboundary water resources management agreements but also of the processes used to develop EDSSs for use by these commissions. Common sense alone suggests that effective and efficient water resources management, including water quality planning and management, can benefit from participation of those who are responsible for taking actions, implementing measures and influencing behaviors that affect the quantity and quality of water resources. Correspondingly, a great deal of research has gone into the dynamics of stakeholder participation in decision making associated with water resources management, including the development of decision support tools for this purpose (e.g., Jones et al., 2009; Sahin et al., 2014; Voinov et al., 2016). While this research has centered around methods to identify, engage and involve relevant stakeholders in the design and development of EDSS tools, some EDSS and environmental model development efforts have focused on understanding how the internal and external organizational constraints affecting the decision domain ultimately affect the use and longevity of EDSSs (Elmahdi & McFarlane, 2012; Kuhn et al., 2016).

Case studies illustrate that if institutional problems associated with water quality management are not addressed, progress on technical and management issues that commonly plague water quality planning and management efforts may not occur (Grigg, 2005). Development of tools designed to support decision making associated with these efforts would benefit from an assessment of the institutional arrangements currently in place to manage and protect water quality and of the interactions of the institutional actors involved in carrying out these tasks. However, institutional analysis is not commonly mentioned among the methods used to enhance the development of effective decision support tools.

Planning and management associated with transboundary water resources such as those of the Rio Grande/Río Bravo involves a set of challenges unique to transboundary situations. Beyond issues of political boundaries and legal jurisdictions, economic, cultural and normative issues affect the interaction of actors involved in transboundary water resources management, including water quality management. An analysis of the institutional arrangements currently in place to manage and protect water quality in the Lower Rio Grande/Río Bravo and of the interactions of the institutions and institutional actors involved in these endeavors not only informs efforts to develop a comprehensive plan to effectively and sustainably protect water quality in this portion of the river but also informs the design of tools created to support decision making in such settings. In keeping with the observations of Voinov et al., (2016), understanding the interactions of the institutions and institutional actors involved in water quality planning in the Lower Rio Grande/Río Bravo reduces the epistemic uncertainty associated with the development of these tools. The following sub-sections describe a systematic investigation of the formal and informal institutional arrangements currently in place to manage and protect water quality in the Lower Rio Grande/Río Bravo, including a qualitative study of the interactions between institutional actors currently involved in these efforts.

2.3.1 INSTITUTIONS, INSTITUTIONALISM AND INSTITUTIONAL ANALYSIS

Merriam-Webster currently defines an institution as "a significant practice, relationship, or organization in a society or culture" or, as a second definition, "an established organization or corporation (such as a bank or university) especially of a public character." Significantly, the term "organization" appears in both of these generic dictionary definitions of the term institution. The fact is that defining the term "institution" has been controversial in virtually all disciplines that have aspired to study what the term represents, including history, political science, sociology, economics, psychology, business and other fields of study. One of the most quoted definitions of the term "institution" was proposed by the Nobel Prize-winning economist Douglass North who succinctly defined institutions as the formal and informal rules that organize social, political and economic relations (North**,** 1990). North further describes formal institutions as the codified constraints on human behavior and informal institutions as uncodified constraints on such behaviors, including mores, conventions, taboos, customs, traditions, and codes of conduct.

Notably absent in North's descriptions is the term "organization." Nevertheless, insofar as organizations invariably formulate, promulgate and enforce certain sets of formal and informal rules, these entities can arguably be included in North's broad definition(s) of institutions. Alternatively, political scientist, Oran Young, a contemporary of Douglass North, defines institutions as "social practices consisting of easily recognized roles coupled with clusters of rules or conventions governing relations among the occupants of these roles." (Young, 1989, 32).

Young's conception of institutions distinguishes, sometimes ambivalently, between institutions and organizations, the latter of which he describes as "material entities possessing physical locations (or seats), offices, personnel, equipment, and budgets." To exemplify this distinction, the market would be considered the institution, while individual companies would be considered organizations. Similarly, under Young's definition(s) marriage is an institution, while the family would be the organizational manifestation of that institution. This distinction is not always upheld in the political science literature and the terms "institution" and "organization" are frequently used interchangeably, even within Young's own writings. In any case, for all contemporary definitions of the term "institution," regardless of discipline, formal and informal constraints on human behavior (i.e., rules, conventions, mores, etc.) and the individuals to which these apply feature prominently in the various conceptual interpretations of an institution. Accordingly, the study of institutional influences on natural resources management, including water quality planning and management, should focus on these two definitional components.

A variety of analytical methods have been used to study the role of institutions in the management of surface water resources (e.g., Lubell, et al., 2002; King, 2006; Rahaman, 2009; Imperial, 2012; Burright, 2012). A number of these analytical methods have been used to investigate institutional arrangements and the behavior of institutional actors and their effects in transboundary water bodies (e.g., Frisvold & Caswell, 2000; Schlager & Heikkila, 2009; VanNijnatten et al., 2016). Similar institutional analysis methods, both quantitative and qualitative, have been applied more narrowly to study water quality management in transboundary water bodies (e.g., Bennet, 2000, Bernardo & Gerlak, 2012; Frisvold 2012). These studies provide a rich source of background information for the type of research conducted for this dissertation. In collaboration with David Eaton, Ph.D. and graduate students participating in the LRGWQIDSS, the author conducted the qualitative research detailed in Sub-section 1.0.11.1 of this dissertation to investigate the institutional factors that influence decision-making associated with water quality planning and management of the Lower Rio Grande/Río Bravo. The goal of the research was to use the inferences and insights gathered from this research to guide the design and development of the LRGWQIDSS. The following sub-sections detail how the findings from the research were used in the design of the LRGWQIDSS.

2.3.1.1 Institutionalism and Institutional Analysis Methods

Contemporary institutional analysis is rooted in the institutionalist movement of the 1970s and 1980s. Prior to these decades, the analysis of institutions was conducted primarily under formal legal and administrative approaches and was subsumed under theoretical frameworks associated with public administration (i.e., public administrative theory in the US and administrative science in European countries). Influenced heavily by Common Law and Roman Law, respectively these approaches to the study of institutions have collectively been referred to as 'old institutionalism' (Thoenig, 2003). In the decades following the social upheavals of the 1960s, in the US and other western countries, scholarly interpretation of perceived institutional failures coincided with the nascent field of policy analysis, which brought the study of institutions back into the research agendas of several social science disciplines. The result has been described as the "new institutionalism" movement (March & Olsen, 1984), which generated a variety of new theoretical approaches to the study of institutions. Classification of the various new institutionalism schools into specific disciplines is confounded by the disciplinary admixture and ambiguity of the different approaches. For example, both rational choice institutionalism and historical institutionalism have been described as being rooted in the field of economics.

An exhaustive discussion of institutional analysis methods is beyond the scope of this dissertation. However, it is instructive to present an overview of institutional analysis methods used to study institutional arrangements associated with water resources management. These can be categorized into methods developed within rational choice institutionalism, historical institutionalism, and normative institutionalism schools.

RATIONAL CHOICE INSTITUTIONALISM METHODS

Institutional analysis methods classified under the rational choice institutionalism school are informed by rational choice economic theory, which assumes that utility maximizing individuals are the central actors in a given socioeconomic process. Under this view, institutions emerge, and are perpetuated, because they fulfil functions that maintain or advance the self-interests of the actors affected by these institutions. The methods used to analyze institutions under a rational choice framework make use of theoretical concepts such as transaction costs, principal-agent and game theory.

Transaction Costs Analysis

Originally introduced in 1937 by economist Ronald Coase, the concept of transaction costs and their role in organizational economics was expanded into the study of institutional dynamics in the 1980s by authors such as Oliver Williamson and Douglass North. Underpinning the conceptual framework of transaction cost theory is the notion that factors such as measurement costs, enforcement costs, the costs incurred by ideological attitudes and perceptions and the size of the "markets" (or in the case of natural resources, the size of the resource itself), shape the institutional arrangements that emerge and prevail. Under rational choice economic theory, the institutional equilibrium reached is a product of the minimization of the costs associated with these factors. Hence, an analysis of these costs yields valuable insight into the behavior and interaction of institutional actors.

Used primarily to analyze the feasibility of implementation and/or to predict the effectiveness of proposed policies, transaction cost analysis has also been used to investigate the costs and benefits of existing, or potential changes in, institutional arrangements governing water resources management. Thompson (1999) examined the institutional transaction costs of two water quality control policies to gage the feasibility of their implementation. Similarly, Rees & Stephenson (2014) analyzed the transaction costs of instituting a nonpoint source water quality credits program in the Chesapeake Bay watershed. In theory, transaction cost analysis could be used to understand the motivations and interactions of institutional actors under existing institutional arrangements associated with water resources management in the Lower Rio Grande/Río Bravo. Transaction costs, though a factor in institutional dynamics, is only one of many motivations driving institutional actions, institutional change, and interactions among institutional actors (Lubell, et al., 2002). Consequently, to help guide the development of tools designed to support decision making in water resource management, transaction cost analysis should be coupled with other institutional analysis methods in order to provide the insight needed to understand decision making and thereby aid DSS design.

Principal-Agent Analysis

The principal-agent theoretical framework emerged in the 1970s out of the exploration of the principal-agent problem, also known as the agency dilemma, which occurs when an entity (the "agent") is in the position of making decisions, taking actions on behalf of, or that impact, another entity (the "principal"). In these situations a difference in motivation between agent and principal can lead to agents acting in their own self-interests, which may be contrary to those of the principal. This inherent conflict of interest arises when activities useful to the principal are costly to the agent and observing the activities of the agent is costly to the principal. These opposing interests coupled with information asymmetry between principal and agent lead to an intrinsic moral hazard rooted in rational choice economic theory. The conceptual framework of principal-agent theory has been extended to the study of institutions. Under this framework, power dynamics is emphasized over the dynamics of collective action (Martimort, 1996; Moe, 2005).

Within the context of water resources management, institutional analysis based on principal-agent theory has been employed as a means to analyze or evaluate water-related policies. For example, Hartje (2008) used a principal agent framework to analyze the institutionalization of IWRM as a prevailing policy within the World Bank. Similarly, Seppälä (2002) analyzed barriers to stakeholder participation in water and sanitation policy development in complex institutional environments using a principal-agent conceptual approach. While principal-agent analytical frameworks can provide valuable insight into the motivations and constraints that influence the actions of institutional players, the framework is typically focused narrowly on interactions defined by contractual or intra-organizational structures and is not easily applied to the analysis of inter-institutional interactions or informal institutional arrangements. This narrow focus can limit its usefulness in providing insight into multi-organizational decision making, which in turn limits its usefulness in LRGWQIDSS design.

Game Theoretical Analysis

Game theory emerged in the 1930s as researchers applied mathematical models to the study of strategic interactions between rational decision makers. As such, game theory is rooted in the wider theory of rational choice. Originally conceived as the mathematical representation of zero-sum interactions (i.e., games) between two individuals, game theory was expanded in the 1940s to include cooperative games between several players. The theory has been used extensively in the fields of economics and political science and has also been applied to the study of organizations, contracting, and general decision making. Beginning in the 1990s, game theory began to be applied to the study of institutions; initially as extensions of the application of game theoretical concepts to organizational theory and decision making within organizations and later to include the study of collective strategic behavior in general. In the 2000's, the concepts of cooperative game theory, which deal with the structure, strategies and payoffs of coalitions of individuals, were used to develop empirical analytical methods applicable to the study of institutions (e.g., Greif, 1992; Walliser, 2006; Binmore, 2010; Ambrosino, 2013).

Since cooperative game theory explores decision-making among multiple players in strategic situations, which depends not only on an individual's behavior but also on the expected behavior of others, it enables the examination of institutional elements exogenous to each of the interacting individuals and these elements' influence on the behavior of individuals in interactive situations. In principle, game theoretical analysis can capture features of the decision-making environment such as asymmetric information situations, hidden actions, uncertainty, and the importance of knowledge. Having evaluated and accommodated assumptions regarding human cognitive and computational abilities, as well as economic, social, and coercive considerations, researchers can use game theory to model the behavior of institutional actors as players in a given decision situation. Less common, but also established, is the use of game theory to model the collective behavior of groups of individuals, such as organizations or sovereign governments. For example, Chambers & Jensen (2002) used a two-stage game framework to evaluate the effectiveness of untied aid, from a donor country, in reducing transboundary air emissions from the emitting country. More pertinent to the LRGWQI, Frisvold and Caswell (2000) used a game theoretical framework to analyze institutional arrangements associated with water resources management along the US-Mexico border. Firsvold (2012) expanded this research to include environmental management along the US-Mexico Border.

Practitioners of game theory approaches to institutional analysis make the case that considerations of moral, and even cultural, motivations can and have been included in these analyses and that the framework is well suited for large and small subject populations (e.g., Greif, 1992 and Binmore, 2012). However, critics of the game theory approach point to the infrequent validation of game theory-based models, citing a general lack of concurrence with observed reality. Much of the discordance is thought to be the result of inadequate representation in the models of the complexity of multiagent interactions, which is thought to be rooted in a lack of understanding of endogenous motivating factors often “assumed away” in game theory models (Moss, 2001). It follows from this criticism of game theory models that a detailed understanding of the motivating factors, both exogenous and endogenous, would improve the structure, and therefore the accuracy, of the models. To the extent that the motivations of decision makers can be identified using qualitative methods, qualitative institutional analysis may help increase the accuracy of game theoretical modeling of institutional actors.

Agent Based Modeling

A practical quantitative application that combines aspects of game theory with elements of other subfields, such as computational sociology, systems theory and computer programing, is agent-based modeling (ABM). ABMs are computational models used to simulate the actions and interactions of autonomous agents in decision making situations. They can be used to model individual behavior or the behavior of collective entities such as groups of individuals or organizations. ABM uses Monte Carlo methods to introduce randomness into complex systems composed of multiple autonomous agents and uses evolutionary numerical algorithms to simulate the behavior of multi-agent systems using the principle of emergence.

The process of emergence can be described as the development of higher-level system properties from the interactions of lower-level subsystems. In the case of ABM, macro-scale state changes in complex multi-agent systems are thought to emerge from micro-scale agent behaviors. ABM models the behaviors of individual agents through the application of simple decision rules, then simulates the aggregation of these behaviors into complex system-level behaviors using numerical algorithms that incorporate randomness into the analysis. The decision rules used to model the behavior of individual agents, in ABM, assume bounded rationality. That is, individuals are presumed to be acting in what they perceive is their own best interests with allowances for factors such as social learning and adaptation.

ABM can create models of complex multi-agent systems that seek to explain current behavior or predict behavior in the face of exogenous change, including changes in the physical or social environment (e.g., resource depletion, increased natural risks, human migration, etc.) or changes in policy/governance (e.g., changes in public transportation, power generation and distribution, land management, etc.). ABM has been used to analyze institutions that govern the management of natural systems. For example, Abebe et. al. (2016) used a coupled agent-based - hydrological model to conduct an institutional analysis of the rules, norms and strategies used for flood mitigation. ABM is also used to test the outcomes of proposed policy alternatives using models based on simple decision rules applied to individual agents. So, the predictive capacity of ABM can hinge on a modeler's ability to construct realistic decision rules for individual agents in the model. Whereas the ABM input and simulation processes are based on empirical methods that allow for the specification of multiple agents at various scales, as well as the interaction topology and decision environment, the methods for identifying the decision-making heuristics, learning rules and adaptive processes are less well defined and commonly rely on qualitative methods similar to those of other non-empirical policy analysis methods.

HISTORICAL INSTITUTIONALISM METHODS

Whereas institutional analysis approaches rooted in the tenets of rational choice theory assume individual and collective strategic behavior based on the preservation and advancement of self-interests, both historical and normative institutionalism approaches focus on the moral and cultural factors that bound human rationality and influence the behavior of individual actors and their interactions with others. Under these alternative investigative lenses, institutions "provide moral or cognitive templates for interpretation and action" (Hall & Taylor, 1996: 939). The distinguishing characteristic of historical institutionalism is its use of history as an explanatory variable.

Historical institutionalism emphasizes the influence of historical factors such as path dependency, which presents a barrier to institutional change by upholding the historical status quo, and punctuated equilibrium, which explains the observed patterns of institutional stasis interrupted by abrupt change. From a historical institutionalism perspective, institutions are products of the cultural and political history of a community or society. Understanding the cultural and political elements that lead to the formation and preservation of institutions can help identify institutional elements and predict institutional change. Historically based analysis has been used to investigate and evaluate institutional arrangements associated with water resource management. For example, Harris, Kooy & Jones (2011) used a historical institutionalism framework to analyze the political economy of governance structures managing water and sanitation service delivery. Historical Institutionalism frameworks have also been used to analyze the political evolution of river basin organizations around the world (Huitema & Meijerink, 2017). Soliev, Wegerich & Kazbekov, (2015) used a historical institutionalism framework to analyze shared water development in the Ferhana Valley of the Syr Darya Basin and Drombowsky (2008) used a historical institutionalism approach to analyze the effectiveness of a water quality management regime in the (transboundary) Elbe River Basin (2008).

Relying mainly on qualitative methods and using guidance derived from its literature base, historical institutional analysis seeks to illuminate the behavior of institutional actors and their interactions by characterizing the contextual environment around which institutions emerge and by investigating their political and cultural evolution. Unlike rational choice-based methods, historical political economy analysis and historical institutional analysis methods in general lack a consistent, systematic analytical methodology. Instead, elements of historical institutional analysis are often subsumed under more structured methods and theoretical approaches, such as those associated with institutional rational choice theory, which combines elements of rational choice institutionalism, historical institutionalism and normative institutionalism.

NORMATIVE INSTITUTIONALISM METHODS

As its name implies, normative institutionalism emphasizes the role of norms and values as prime motivating factors behind institutional formation and resilience. Like historical institutionalism, normative institutionalism focuses on the bounds placed on human rationality by non-instrumental factors. In the case of normative institutionalism, rationality is bounded by the so called "logic of appropriateness," which posits that the norms and rules of institutions shape the actions of the individuals operating within them. Rooted in the subfield of organization theory, normative institutionalism is a sociological interpretation of institutional arrangements. The approach views institutional formation as legacy of collective social experience and conceptualizes institutional change as an expression of social learning (Peters, 1999). James March, an organizational behaviorist, characterizes the logic of appropriateness as being "matched to situations by means of rules organized into identities" (March, 1994: 57-58). Thus, in the view of normative institutionalism, norms and rules form part of the identities of institutional actors. The behaviors of the actors are based on the recognized situation they encounter and its relation to their perceived identity in the situation. The analysis, by the actor, of the rules that generally govern behavior for a particular situation govern the decisions made and/or actions taken by the actor in that situation.

Normative institutionalism frameworks have been used to analyze transboundary water resources management institutions. For example, Kliot, Schmueli and Shamir (2001) used a normative institutionalism analytical framework to examine the evolution, structure and characteristics of the management systems of 12 transboundary river basins, including the Mekong, Indus, Ganges–Brahmaputra, the Nile, Jordan, Danube, Elbe, Rio Grande and Colorado, Rio de la Plata, Senegal and Niger. Like historical institutionalism frameworks, normative institutionalism approaches to institutional analysis also rely heavily on qualitative analytical methods and lack a consistent, systematic analytical methodology. As previously mentioned, elements of normative institutional analysis have been incorporated into more structured methods such as the institutional analysis development (IAD) framework, which is based on institutional rational choice theory.

THE IAD FRAMEWORK

In recent years, a growing number of scholars and researchers have focused their efforts on viewing institutional analysis through the lens of institutional rational choice (IRC) theory, especially researchers studying institutions that govern or affect natural resource management. Many of these researchers have adopted the IAD framework, developed by Elinor Ostrom and her colleagues at the University of Indiana, to analyze institutions that govern water resources management (Cowie & Borrett, 2005; Schlager and Heikkila, 2009; Burright, 2012; Imperial, 2012). In fact, Integrated Water Resources Management (IWRM), the standard by which the Global Water Partnership and the United Nations base their rating of best water resources management policies and practices, incorporates many of the key principals of IRC and the IAD framework (Hassing et al., 2009). Many of the concepts associated with IAD were published in conference and workshop proceedings as early as the mid-1990s and also appeared in scattered form in a number of political science and public policy publications (Ostrom, Feeney & Picht, 1993; Crawford & Ostrom, 1995). However, IAD's debut as a detailed framework for institutional analysis did not occur until 2007 when Elinor Ostrom published a detailed description of the framework in the public policy compilation publication titled *Theories of the Policy Process*, edited by Paul Sabatier (Ostrom, 2007).

The IAD framework is deeply rooted in the concepts of IRC theory, which posits that the most effective and efficient institutional arrangements to sustainably manage common pool resources, such as surface water resources, are not found in governmental regulation or in the free market, but in the agreements that emerge from the interactions of the users of the resource themselves. This hypothesis implies that one-size-fits-all governance formulas for managing common pool resources are inherently less efficient than those that emerge "locally" from the community of resource users. Common pool resources management institutions that originate within the user community are tailored to the unique circumstances associated with the resources they govern, including cultural, environmental and socioeconomic factors. To function sustainably, these institutions must also have the ability to adapt to changes in these factors. Ostrom studied common pool resources management institutions to try to identify the universal elements that any theory relevant to the same kind of phenomena would need to include.

In developing the IRC theory, Ostrom built on elements of rational choice, historical and normative institutionalism frameworks, as previously discussed in this sub-section. Under the IRC conceptual framework, actors are described as boundedly rational individuals, self-interested and acting to achieve their highest benefit, but constrained in this pursuit by social conventions and norms that form part of their identities and, thereby, also influence their decision-making patterns. Actors are also bounded by a lack of access to complete information and by the transaction costs associated with acquiring such information. Some actors may have access to more information than others, leading to the type of information asymmetries that characterize principal-agent interactions. Under these circumstances, some actors must make decisions about a range of alternatives based on one level of knowledge while others are advantaged by greater access to information. If the interaction between actors is repeated, as is the case in most common pool resource situations, learning becomes an equalizing factor, which partially neutralizes the effects of initial information asymmetries; a feature of repeated cooperative games. IRC theory includes other aspects of game theory, such as the role of reciprocity and coalition building.

Ostrom and her colleagues used the conceptual foundations of IRC to construct a systematic approach for analyzing institutions established to govern any number of collective action arrangements, including natural resource management. The IAD framework defines institutions as a set of prescriptions and constraints (i.e., rules) that members of a community use to organize a set of repetitive and structured interactions. The arrangements can be formal, informal or, more often a combination of both The associated rules can be characterized as rules-in-form, as is the case in formal codified arrangements, or rules-in-use, as is the case in actual operational situations. By focusing on rules, norms, and strategies, the IAD framework identifies the factors that structure human interactions and decision-making. IAD also explicitly calls attention to the specific contextual factors that influence resource decisions at multiple levels (Ostrom, 2007).

The Action Arena

The IAD framework guides researchers in the identification and evaluation of institutional factors that affect the interaction of stakeholders and influence decision-making in collective action situations by first identifying and describing the specific “action arena” associated with a situation (sometimes a conflict, other times a cooperative forum) in which social choices are made. Action arenas are composed of an action situation and the actors themselves (Figure 2-18).

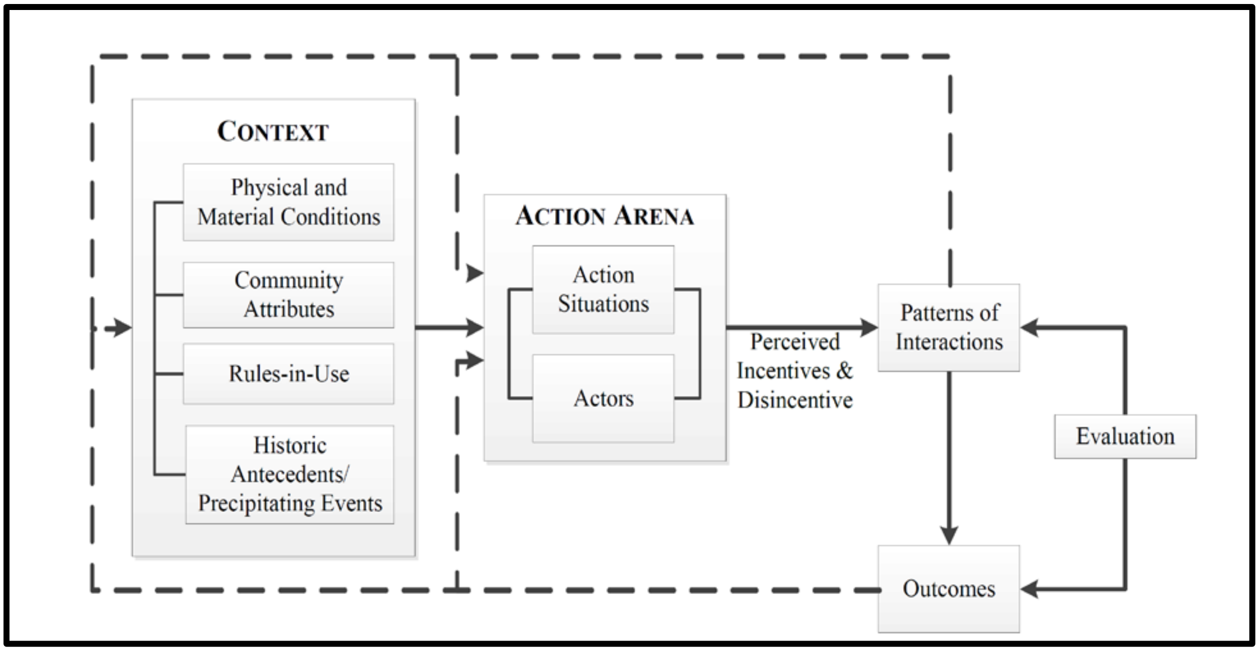

Figure 2-18. The IAD Framework for Institutional Analysis. Source: Burright, 2012 (Adapted from Ostrom 2007).

According to the IAD framework, action situations, also referred to as "decision spaces" (Burright, 201, p. 30), are characterized by the following clusters of internal variables:

1) The set of *participants* (i.e., *stakeholders* or their representatives); they could be individual actors or groups of actors; they could be in conflict or in coalitions or both;
2) The *positions*; reflect the nature of the interests of the participants (e.g., agency representatives, irrigation district managers, city mayors, etc.) as well as the participant's role in the decision space;
3) The set of *actions* and their linkages to perceived outcomes (e.g., wastewater treatment levels, agricultural practices, etc.);
4) The *Outcomes* (or potential outcomes) and the linkages between these and the decisions/actions of the participants;
5) The *level of control* over choice; typically varies among participants; dependent on established practice;
6) The *information* available; about the resource; about the costs and benefits of actions (the participants' own actions and that of other participants); about the linkage between cumulative actions and cumulative outcomes.

These clusters of internal variables, referred to subsequently in this sub-section as "elements" of the decision space, influence an action situation (i.e., decision space) to produce potential outcomes (Figure 2-19).

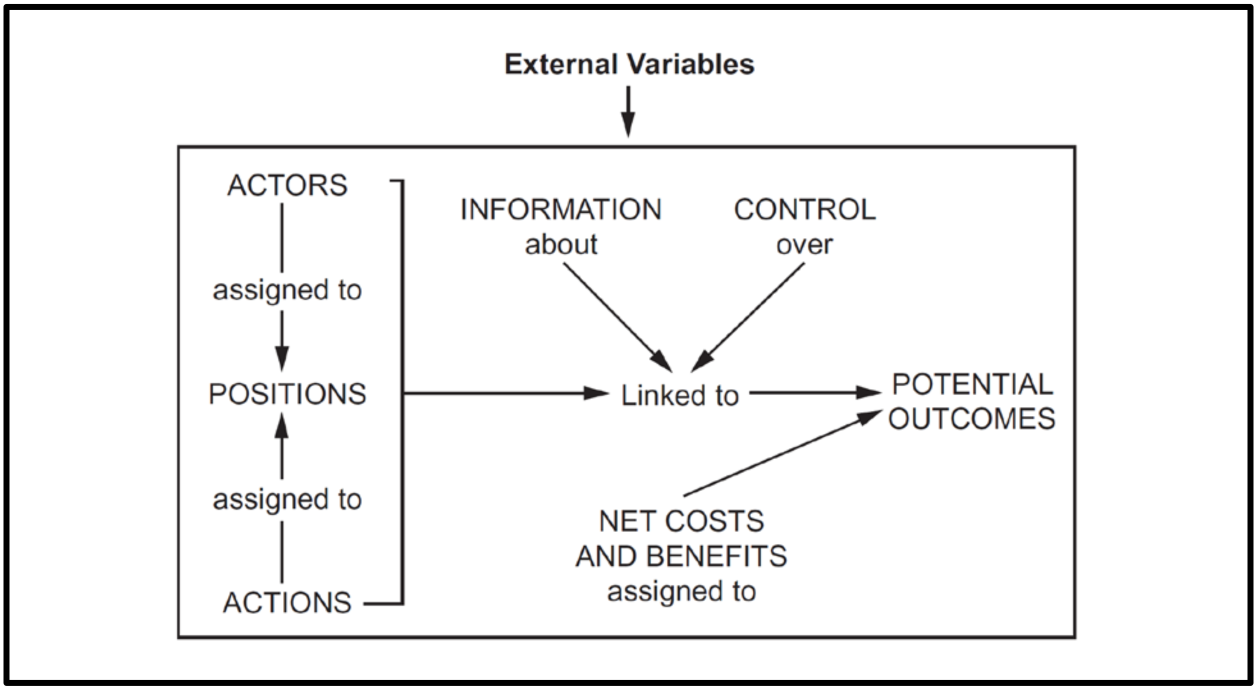

Figure 2-19. The Internal Structure of an Action Situation. Source: Ostrom, 2011.

Elements of the decision space are themselves influenced by a set of external variables. A more detailed explanation of these exogenous variables, as conceived by the IAD framework, is presented in the following sub-section.

In addition to identifying the action situation/decision space, the IAD framework further defines the action arena by characterizing the actors themselves. Actors can be individuals or groups of individuals that have a regularized way of making decisions, such as a firm or a government agency. Actors can be characterized by the following variables:

1) The *resources* that an actor brings to a situation (e.g., time, financial resources, etc.);
2) The valuation, actors assign to states of the world (i.e. *cost-benefit* bounded by internalized *norms*);
3) The way actors "acquire, process, retain and use" contingencies and *information*; and

4) The process actors use for selection of particular courses of action (i.e., decision-making and action-taking *strategies*).

According to the IAD framework, the contextual factors that influence action arenas can be classified into three main categories: (1) the physical and material conditions [later re-characterized by Ostrom as the biophysical world] within which the group of actors interact; (2) the attributes of the community[ies] or group[s] involved in the action arena; and (3) the rules (i.e, rules-in-use) that incentivize and constrain actors in the action arena (Ostrom, 2007). More recently Burright (2012) incorporated historic antecedents and precipitating events as an additional component of the context under which action arenas exist (Figure 2-18). Contextual factors affecting action arenas include geographic, social, economic and cultural elements that frame the action arena and help to characterize it from a perspective of institutional design, implementation and performance.

Qualitative methods can be used to investigate the elements depicted in Figure 2-18. The patterns of interaction can be traced to the incentives/disincentives, as perceived by the actors (i.e., perceived costs and benefits), as well as the rules-in-use, available information, and the sense of control experienced by the actors. Repeated interactions offer opportunities for learning, as actors ascertain how their decisions and actions affect outcomes, as they perceived them. The measures of effectiveness and efficiency in IAD focus not only on the institutional outcomes, but also on the patterns of interactions among the actors, which according to IRC theory, largely govern the outcomes.

Rules and Rule Types

Within the context of IAD, Ostrom defines rules as "shared understandings among those involved that refer to enforced prescriptions about what actions (or states of the world) are required, prohibited, or permitted" (Ostrom, 2007; page 36). Reflecting on human rule making in general, Ostrom recognized the process of formal rule making at different levels of human organization, from legal codes and agency rules to the bylaws of local voluntary associations; Ostrom categorized these formal rules as rules-in-form. Ostrom also described the frequency of informal human rule making using examples such the division of labor and collaboration procedures developed by colleagues participating in a work team. Ostrom (2007) accepts the tendency of humans to sometimes flout formal and informal rules as a common occurrence in human societies.

With these complicating factors in mind, Ostrom and her colleagues acknowledged the difficulty in examining the "working rules" under which action arenas operate. Ostrom lamented the endless cataloging of rules unrelated to any method of classification useful for theoretical explanations (Ostrom, 2007). Consequently, she and her colleagues set out to develop a rule classification system that was consistent with IRC theory and could be useful to analyze institutional arrangements. They tackled this challenge by classifying rules according to their impact on the elements of the decision space. According to the IAD framework "the set of working rules that affects these [decision space] variables should constitute the minimal but necessary set of rules needed to offer an explanation of actions and results used by participants to order their relationships within an action arena" (Ostrom 2007, p. 37). Table 2-2 lists the rule types described in the IAD framework along with a brief description of each rule type and an explanation of how its use informs institutional analysis.

The IAD rule types presented in Table 2-2 are generalized abstractions of the specific rules-in-use manifested as the "working rules" in specific action situations. Ostrom makes a point of stating that "the set of working rules is a configuration in the sense that the effect of a change in one rule may depend upon the other rules-in-use" (Ostrom, 2011, p. 20). In the IAD framework, the working rules of an action situation/decision space are depicted as exogenous variables that affect the elements of the decision space (i.e., they affect the internal variables of the action situation). Each rule type directly affects specific elements of the decision space and, through the internal linkages of the decision space, indirectly affects all others (Figure 2-10). To investigate these rule types, the IAD method focuses on a series of questions intended to help the analyst uncover the rules-in-use that structure the decision space.

Table 2-2. IAD Framework Rule Types*

Rule Type	Description	Use in Institutional Analysis
Boundary Rules (Entry and Exit Rules)	Determine which individuals/entities are allowed to participate in the action arena and in what position	Evaluation of fiscal equivalency, equity, conformance to general morality, and adaptability
Position Rules	Specify a set of positions with corresponding resources, opportunities and responsibilities and how individuals/entities are assigned to these positions	Evaluation of fiscal equivalency, equity, efficiency, accountability, conformance to general morality, and adaptability
Scope Rules	Delimit the potential outcomes that can be affected by actions (typically, but not always, specified in terms of measurable units)	Evaluation of efficiency and adaptability
Choice Rules	Determine the shape of the decision tree that links actions to outcomes	Evaluation of efficiency and adaptability
Aggregation Rules	Determine how interactions between participants within the action situation accumulate to final outcomes (voting schemes, etc.); they affect the level of control a participant in a position exercises in the selection of an action	Evaluation of fiscal equivalency, equity, efficiency, accountability, conformance to general morality, and adaptability
Information Rules	Affect what information is available to actors about which actions are available and the link between actions and outcomes	Evaluation of fiscal equivalency, equity, efficiency, accountability, conformance to general morality, and adaptability
Payoff Rules	Affect the benefits and costs that will be assigned to combinations of actions and outcomes, and they establish the incentives and deterrents for action	Evaluation of fiscal equivalency, equity, efficiency, conformance to general morality, and adaptability

* Modified from Ostrom, 2011

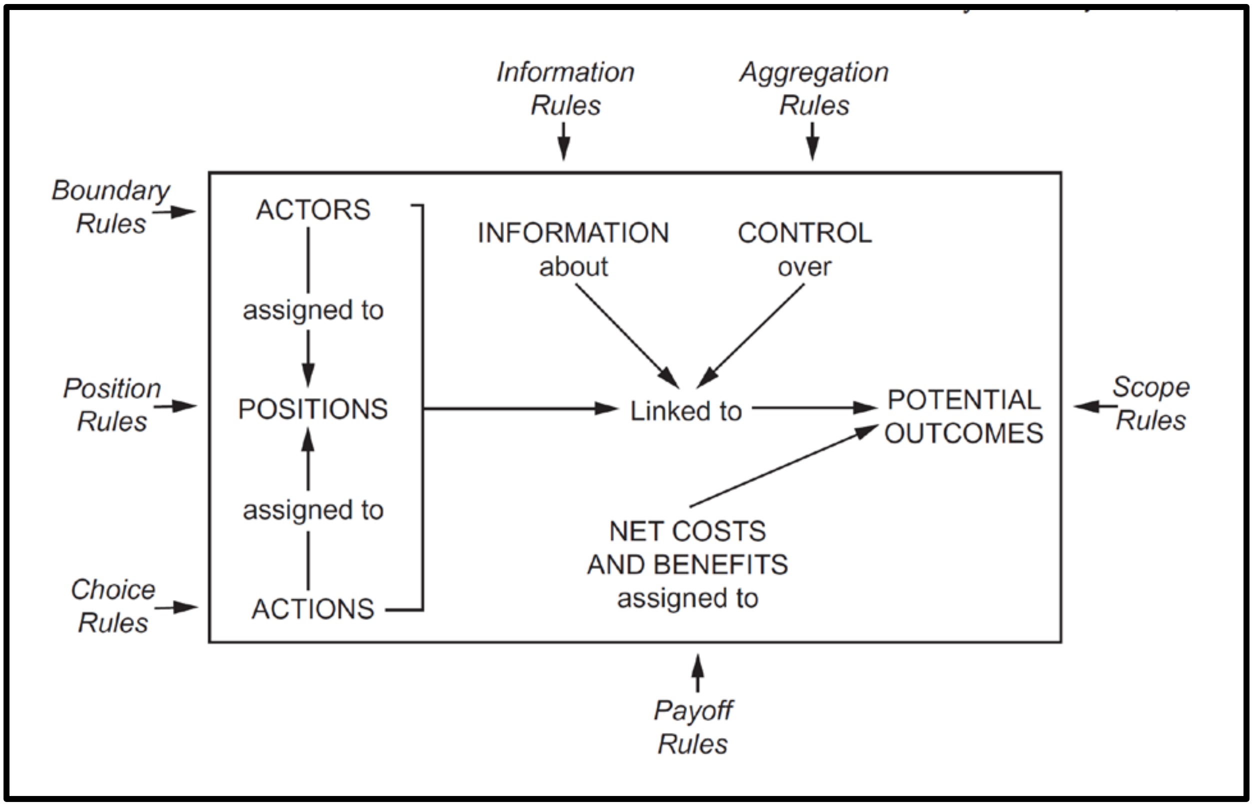

Figure 2-20. Rules as Exogenous Variables Directly Affecting the Elements of an Action Situation / Decision Space. **Source: Ostrom, 2011.**

Multi-Level Analysis

One of the defining features of the IAD framework is its conceptualization of rules as components of hierarchical institutional structures. Viewed through the lens of IRC theory, "all rules are nested in another set of rules that define how the first set of rules can be changed" (Ostrom, 2007, p. 44), which implies that rules, even those codified at their highest (constitutional) level, do not exist as solitary, unconnected instruments of order, but rather they are invariably nested within hierarchical institutional levels (Figure 2-21).

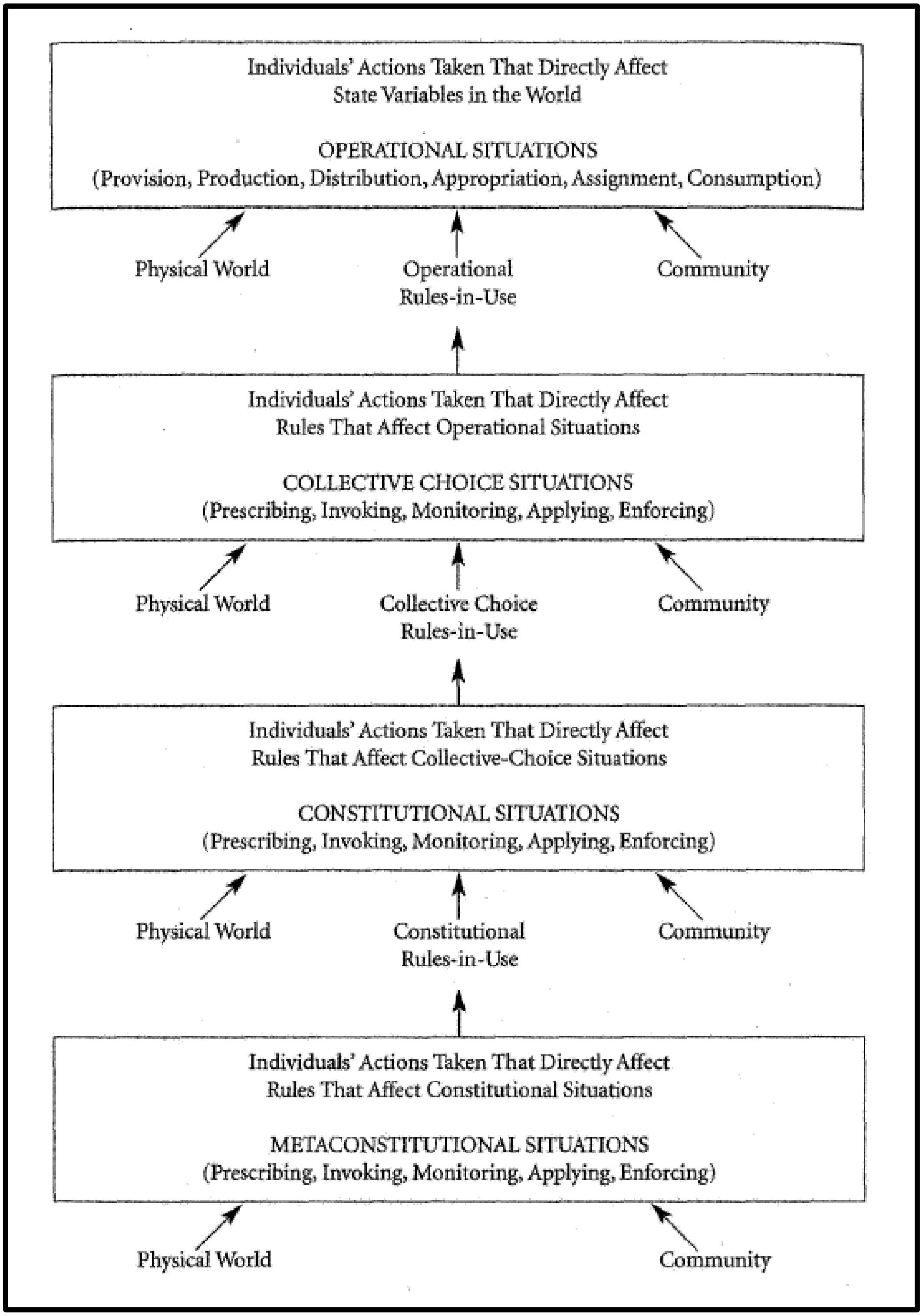

Figure 2-21. Levels of Analysis Within IAD. Source: Ostrom, 2007.

The IAD framework identifies four levels of analysis consistent with the hierarchical rule levels depicted in Figure 2-21. Although the labels placed by Ostrom and her colleagues on different levels of analysis correspond roughly with the hierarchical levels normally associated with rules-in-form (e.g., constitutional, operational, etc.), the rules investigated at the different levels of analysis are typically a mixture of rules-in-form and rules-in-use. In fact, Ostrom observes that the rules investigated at the metaconstitutional level, which are not frequently analyzed, consist almost exclusively of social norms and conventions from which constitutional "rules" are derived. The idea behind analyzing rules hierarchically is to supply a template for analysis of the working rules, of a decision space, at multiple levels.

Because of the influence of rules on the decision space, the IAD framework extends the concept of the hierarchical institutional structure to the action arena, portraying action arenas as connected through the tiered configuration of the working rules that influence them. For example, Ostrom states that "Policymaking (or governance) regarding the rules that will be used to regulate operational-level choices is usually carried out in one or more collective-choice arenas." (Ostrom 2007, p. 46). Figure 2-22 illustrates these connections and also shows how outcomes of an action arena can, in turn, affect rule changes at multiple levels.

Multilevel institutional analysis is a time and resource intensive effort. Moreover, the complexity of such efforts often leaves lingering doubts as to the thoroughness of the final analysis. High level constitutional and collective-action arenas, in particular, are difficult to analyze, as the outcomes associated with these arenas are typically not obvious or immediately apparent and require analysis in, and of, themselves. On the other hand, focusing the analysis on operational situations may obscure the influence of higher-level institutional constraints and barriers on lower-level action arenas. When applying the IAD framework to analyze action arenas and their relationship to each other, a first step is to analyze how individual decisions/actions are made at the operational level and build an understanding of the connected decision space(s) by working in an "upward" hierarchical direction across the different levels of analysis portrayed in Figures 2-21 and 2-22 (Cowie & Borrett, 2005).

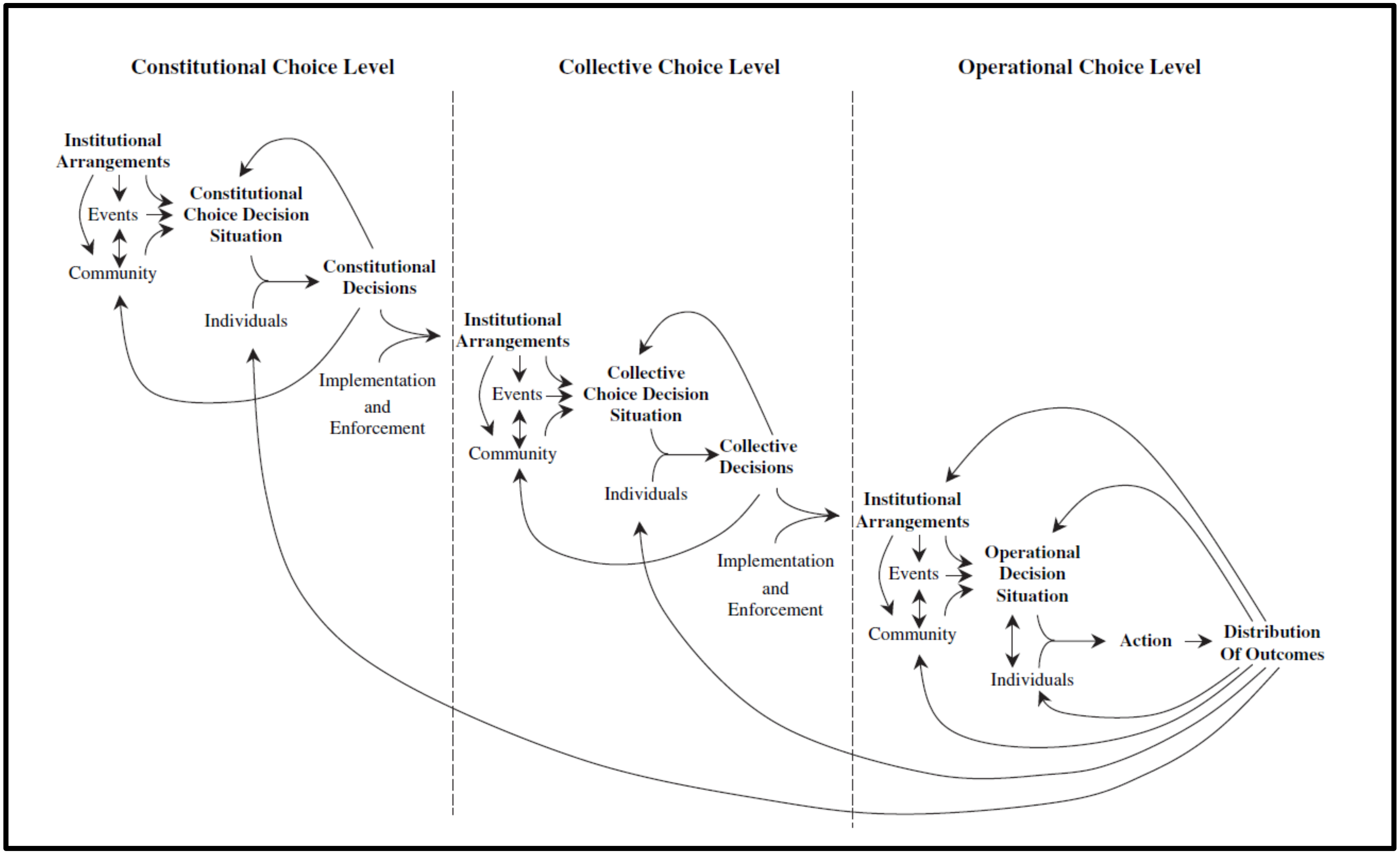

Figure 2-22. Levels of Analysis Within IAD. Source: Cowie & Borrett, 2005 (adapted from Sabatier, 1991).

Individual decisions/actions which affect the physical world, are typically made at the operational level and are controlled by institutional arrangements and decisions made at the collective choice level. Constitutional choice decisions, in turn, constrain those made at the collective choice level. The research approach adopted by the author follows this pattern: first analyzing how decisions/actions are made at the operational level, and then examining how decision making at this (operational) level is enabled and/or constrained by rules established in higher level action arenas (e.g., collective choice action arenas).

Application to Transboundary Water Resources

In theory, institutional arrangements crafted to manage transboundary water resources possess the same basic characteristics as other institutional arrangements intended to manage water resources. Hence, the institutional "grammar" of IAD (e.g., action arenas, decision space, actors, rules as exogenous variables, etc.) is also applicable in transboundary situations. Indeed, several researchers have applied the IAD framework to analyze transboundary water resources management institutions.

Examples of these applications include the work performed by Schlager and Heikkila (2009) on interstate water compacts in the United States[5]; Malmros (2014) on the Mara River Basin Initiative; Hartely (2015) on the governance of water supplies in Hong Kong and the southern Chinese province of Guangdong; Huitema and Meijerink (2017) on institutional design choices, coalitions and the associated consequences of the politics of river basin organizations; and Garrick et al. (2018) on institutional adaptation to manage drought risks in transboundary water bodies. Of these examples, only the work by Albin Malmros (2014) includes an assessment of institutional arrangements to manage transboundary water quality. Nevertheless, through these efforts a methodology has emerged for the analysis of institutional arrangements and actors involved in transboundary water resources management that can be applied to the LRGWQI.

[5]Although the research by Schlager and Heikkila (2009) on interstate water compacts in the United States does not relate directly to water bodies shared by sovereign countries, many of the water resources management issues faced by water bodies shared by regional and provincial entities are the same as those faced by international transboundary water bodies.

Institutional Analysis and Institutional Change

Applications of the IAD framework have included institutional analyses to study the emergence of new institutions, to identify strengths and weaknesses of existing institutional arrangements, to predict institutional change, and to identify cause-and-effect relationships between institutional structures and natural resources management outcomes. In her seminal publication "Governing the Commons," Ostrom (1990) describes the importance of recognizing the difference between the emergence of new institutions and the transformation/evolution of existing institutions. While both instances involve changes in rules, new institutions face lower levels of community resistance than does the modification of existing institutions. Existing institutions and the rules they embody create socioeconomic incentives for actors to maintain the status quo, a phenomenon known as "path dependency." Rules at the higher levels of rule-making (i.e., constitutional and meta-constitutional levels) are usually more difficult and costlier to modify, as they tend to have deeper connections to cultural norms and wider socioeconomic impacts (Ostrom, 2007). Nevertheless, higher level rulemaking exerts a suppressing influence on the modification of rules made at lower levels of rulemaking due to the nested nature of rules and action arenas. As a result of path dependency, institutional transformation, at all levels, typically occurs in an "incremental, sequential, and self-transforming" manner in a process that involves revisiting and revising rules in an iterative manner (Ostrom, 1990, p. 139).

A question relevant to this dissertation is whether the analysis to identify institutional factors relevant to the development of the LRGWQIDSS should be conducted as an analysis of existing institutional arrangements or as an analysis of potential institutional change. Keeping in mind that the goal of the LRGWQI is improvement of water quality in the Lower Rio Grande/Río Bravo, an argument can be made that, since the LRGWQI seeks a different institutional outcome from that of the status quo, an analysis to identify institutional factors relevant to the development of the LRGWQIDSS could be considered an analysis of institutional change. Certainly, one of the capabilities envisioned for a decision support system such as the LRGWQIDSS is to simulate the (water quality) outcomes of changes in a variety of factors, including changes in one or more of the rule types shown in Table 2-2 and Figures 1-22 and 2-22 (e.g., information rules at the operational level).

On the other hand, the research goals of this dissertation do not include the evaluation of the actual outcomes of any rule or policy changes resulting from the LRGWQI, including any institutional changes facilitated by the LRGWQIDSS. The decision support process seeks to evaluate of the benefits that can be derived from developing transboundary decision support tools (e.g., efficiency, effectiveness, frequency of use, longevity, etc.), from analysis of existing institutional arrangements. In other words, the goals of this dissertation are to demonstrate how institutional analysis can aid the development of better transboundary decision support tools in general, not how such analysis can predict, evaluate or guide specific institutional changes.

In the opinion of the author, both of these viewpoints are valid. Ostrom defines institutional change as "a change in any rules affecting the set of participants, the set of strategies available to participants, the control they have over outcomes, the information they have, or the payoffs" (Ostrom, 1990, p. 140). So, if development of the LRGWQIDSS is considered a change in the information rules of any of the action arenas analyzed, then the effort constitutes an analysis of institutional change conducted using the IAD framework. Alternatively, since analysis of the change in information rules is not a stated goal of this research and, conversely, the analysis of exiting institutional arrangements to enhance the development of the LRGWQIDSS *is* a stated goal of the research, the analysis can also be considered an analysis of existing institutional arrangements using the IAD framework.

2.3.2 Stakeholders, Decision Makers and DSS Users

In Sub-section 2.2.1.1, the author characterized stakeholders as "consumers of the decision outcome(s) produced from a decision process." The author also argues in Subsection 2.2.1.1 that the roles of the decision maker, stakeholder, and user of a decision support tool do not always coincide and are frequently played by different individuals. This fact is an important consideration when applying the IAD framework to the research detailed in this dissertation. As discussed in Sub-section 2.2.1.6 (Participatory Modeling) and Subsection 2.2.1.9 (Best Practices in DSS Design), the involvement of stakeholders in the development of EDSSs is a practice that is commonly advocated among environmental modelers and EDSS developers. However, even after years of concerted efforts to involve stakeholders, EDSS developers struggle to produce effective and, most importantly, persistently-used EDSSs (McIntosh et al., 2011).

Practitioners in the field of EDSS design have employed numerous techniques for ensuring the widest level of stakeholder participation possible in the development of EDSSs, including various methods of stakeholder analysis. Stakeholder analysis refers to a set of systematic procedures designed to achieve effective and inclusive stakeholder participation. The Global Water Partnership considers stakeholder analysis to be part of the modeling and decision-support tool development process because it is a key part of these and other technical efforts associated with IWRM (GWP, 2018). Methods for conducting stakeholder analysis vary widely. However, many stakeholder analysis methods follow a procedure involving stakeholder categorization using one of many stakeholder classification schemes; typical attributes used to categorize stakeholders include, power, influence, interest, needs, support and attitude (Kimmich, et al. 2012). Typically, this information is subsequently used in “stakeholder mapping,” in which a didactic matrix is constructed with the intent of helping the analyst navigate complex participatory forums. Knowledge acquisition in these efforts is generally conducted using qualitative methods. Examples of stakeholder analysis conducted in transboundary water resources management forums include the cases documented by Ganoulis, et. al., (2008); Hernandez (2011); and Van Ingen et al., (2010).

More recently, institutional analysis has been used as a tool to conduct stakeholder analysis in transboundary settings (e.g., Schreiner et al., 2015) and some researchers have even applied the IAD framework to conduct stakeholder analyses in transboundary settings (e.g., McFadden, et al., 2010; Wang et al., 2017[6]). However, the purpose of these efforts has been to improve stakeholder participation in decision making in general, not to produce better environmental models or more effective EDSSs. Fueled in part by the proliferation of institutional analysis in IWRM and other natural resource management fields, researchers have begun integrating institutional analysis into environmental modeling and EDSS design, primarily as a way to refine, expand, and in some cases focus stakeholder involvement in these efforts (e.g., Grigg, 2005; Cowie and Borrett, 2005; Abebe et al., 2016). The authors of at least one of these research efforts (Cowie and Borrett, 2005) attributes the success of applying the IAD framework to the analysis of stakeholder participation to the focus this (IAD) framework places on the rule types and rules that govern the pertinent action arenas, a conclusion that the author of this dissertation proposes to test with his research.

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6 Although the research conducted by Wang et al., (2015) centers around water governance technically within the sovereign borders of the Chinese state, Hong Kong is one of China’s few Special Administrative Regions (SARs), having been a British Dependent Territory until July 1997. Governance of the Hong Kong SAR, as well as its physical and organizational infrastructure, differs markedly from that of other mainland Chinese regions, which do not enjoy similar levels of autonomy. Hong Kong receives 80% of its water from the Dongjiang River in China’s Guangdong province. The relationship between Hong Kong SAR stakeholders and Guangdong Province stakeholders of the Dongjiang River is essentially that of transboundary stakeholders.

In essence, the main hypothesis of this dissertation is that institutional analysis, and in particular institutional analysis conducted using the IAD framework, results in a superior stakeholder analysis, which is itself essential for the development of useful and enduring transboundary DSSs.

2.4.2 Institutional Analysis and the LRGWQIDSS

This sub-section (2.4.2) describes the institutional analysis conducted to support the development of the LRGWQIDSS. The sub-section is divided into four smaller sub-sections that describe the setting, methods, results, and conclusions of the analysis.

2.4.2.1 Preface

Several previous sub-sections of this chapter have described the role of stakeholder participation in the development of more relevant, more useful and more durable EDSSs. The subject of stakeholder involvement was an issue that was discussed among the representatives of the six agencies that negotiated the LRGWQI TOR. While the final language in the TOR document states that "each of the binational partner agencies involved in water quality will determine the appropriate stakeholder involvement," (LRGWQI TOR, p. 4) the TOR document also states that "Due to the complexity and the numerous stakeholders involved, both sections of the Commission will establish the necessary framework to allow for the joint evaluation of proposed cooperative measures that could benefit both nations" (page 1 of LRGWQI TOR).

These statements taken together were meant to convey the following operating "policy" for LRGWQI participants (in this author's words): each individual partner agency participating in the LRGWQI was free to interact with whomever it perceived to be its stakeholders, but any interaction of the LRGWQI committees, as entities established under the LRGWQI TOR, was to be regulated by the IBWC. The USIBWC/CILA understanding was that Mexican individuals or representatives of Mexican organizations, or communities, could not reasonably be expected to qualify as stakeholders of US agencies and vice versa. Since development of the LRGWQIDSS was a US-funded effort (i.e., funds were awarded to the TCEQ by USFWS and USEPA for the development of the LRGWQIDSS), the US partner agencies (USIBWC, USEPA and TCEQ) were free to interact with US stakeholders, without prior approval from IBWC, as long as project data collected in Mexico was not shared with US stakeholders. However, approval by IBWC was needed before any LRGWQI-related interaction between US partner agencies and Mexican stakeholders took place. This operational policy presented a barrier to LRGWQIDSS developers for accessing stakeholders to seek their input in the development of the LRGWQIDSS, as all three Mexican partner agencies (CILA, CONAGUA and CEAT) opposed the sharing of any data collected as part of the LRGWQI with US or Mexican stakeholders prior to the promulgation of the Declaratoria de Clasificación for the Lower Río Bravo. Also, Mexican partner agencies opposed any direct LRGWQI-related interaction between US partner agencies and Mexican stakeholders in general.

This barrier was partially overcome by the participation, in the qualitative data collection efforts associated with this research, of UT's LBJ School of Public Affairs, as CEAT agreed to distribute, collect and forward completed stakeholder surveys that were developed by the UT LBJ School as part of the knowledge acquisition efforts associated with LRGWQI. Also, the IBWC and the LRGWQI Mexican partners allowed the UT LBJ School to contract with a local Mexican university (Universidad Autónoma de Tamaulipas) to conduct key informant interviews and focus group sessions of Mexican stakeholders, also in support of LRGWQI knowledge acquisition efforts. This effort was funded by the BECC through a grant from the USEPA.

The constraints placed on information sharing and binational stakeholder involvement limited the choices available to the LRGWQIDSS developers for acquiring stakeholder input during the development of the software. Given these constraints, the author proposed developing a web-accessible decision-support tool with accessibility limited by password-protected user accounts. Although this choice would have prevented open access to project information, which was a restriction under the LRGWQI TOR operating policy enforced by the IBWC, several important operational questions had to be addressed under this initial proposal, such as: what organization(s) would host the web-based tool? What criteria would be used to grant web access to the tool? What organization(s) would be responsible for maintaining the tool? These and other questions proved difficult to address and, with the exception of the TCEQ, the other LRGWQI participants (i.e., IBWC, CILA, EPA, CONAGUA [through IMTA] and CEAT) considered other tasks and discussion issues associated with the LRGWQI to be more urgent, such as watershed characterization, identification of data gaps and data collection, all of which are technical tasks specified in the Annex to the LRGWQI TOR. The creation of a web-based tool, though advantageous in many ways, including wider stakeholder participation in its development, increased the cost of development by an amount that was outside the funds budgeted for this task by the TCEQ. In view of these obstacles and in the interest of time, the author, in consultation with the LRGWQIDSS development team, developed a second proposal, which included the development of a software tool installable through a downloadable, self-extracting executable.

2.4.2.2 Action Arenas and the LRGWQIDSS

As described in Sub-section 2.4.1.1, action arenas are at the center of the IAD framework. As such, they constitute the unit of analysis in the institutional analysis effort undertaken for the research described in this dissertation.

IDENTIFICATION OF ACTION ARENAS

To identify the action arenas relevant to LRGWQIDSS development, the author followed the procedure advocated by Cowie and Borrett (2005), in which the decision spaces where individual decisions/actions are made at the operational level are identified and analyzed first to build an understanding of other decision space(s) connected to them at higher hierarchical levels of analysis. The first step in doing this is to identify the analytical context under which decision spaces exist (Burright, 2012). Because the reason for collaboration on the LRGWQI was ostensibly a binational impetus to improve water quality in the Lower Rio Grande/Rio Bravo and, in particular, to reduce levels of fecal bacteria and dissolved solids in this portion of the river, the author placed the analytical focus on the conditions that affect these water quality impairments and, on the decision/actions that influence current water quality conditions. Another reason for proceeding in this manner was the likelihood that the actors in the action arenas identified using this analytical focus would, in fact, be users of the LRGWQIDSS.

For analytical convenience and because the institutional environments under which these decision/actions occur are different in the United States and in Mexico, decision spaces linked to the water quality impairments specified in the LRGWQI TOR are separated into US and Mexican counterparts. To avoid speculation about how the development of the LRGWQIDSS tool would benefit from stakeholder involvement, the author concluded that the action arenas analyzed for this research would include, if not be composed entirely of, the intended users of the EDSS.

There are many factors that affect water quality, including pollutant load, flow volume, water temperature, turbidity, etc. However, two factors, pollutant loads and flow volume, contribute disproportionately to water quality in rivers. In fact, many of the other factors that influence water quality in rivers can be considered "pollutants" and can also be related to flow. Thus, in the language of the IAD framework, flow volume and the sources of fecal bacteria and dissolved solids are important physical and material conditions that frame the contexts of LRGWQI-associated action arenas. Other important factors are rules-in-use, community attributes, and historic antecedents/precipitating events (Figure 2-18).

Even a cursory analysis of the factors that define the context affecting LRGWQI-associated action arenas reveals that these factors are linked though complex cause-and-effect relationships. For example, watershed characterization efforts have shown that the physical and material conditions of the river (i.e., flow and water quality) are the result of a combination of natural factors (e.g., rainfall patterns [both local and upstream], natural-occurring pollutant loads [e.g., sedimentary evaporite salt contributions, fecal bacteria contributions from wildlife, etc.), the decision/actions of stakeholders, which are linked to rules-in-use (e.g., water allocation [both local and upstream], wastewater treatment requirements, agricultural practices, etc.), community attributes (e.g., nationality, economics, water usage patterns, sanitation, etc.) and antecedent events (e.g., droughts, floods, outbreaks of waterborne diseases, high salinity events in the river, fish kills, results of past pollution mitigation efforts, etc.).

The physical and material conditions of the Lower Rio Grande/Rio Bravo, in turn, have an effect on other contextual factors influencing the LRGWQI-associated action arenas, sometimes prompting changes in community attitudes and stakeholder opinions, which build pressure for changes in rules-in-use and can even affect community attributes. For example, in the late 1990s, poor water quality in the river motivated local agricultural stakeholders in the Lower Rio Grande Valley of South Texas to pressure the TCEQ to install continuous water quality monitoring stations in the river to alert irrigation districts in advance of high salinity events in the river; this action, in essence changed the information rules in that local action arena. One stakeholder interviewed stated:

> "But that system has helped us to be able to project what is getting ready to come to us. It takes four days for water to reach my plant from Falcon. So, we know

that if the salinity is building in the upper stretches in the river, in a few days it's going to be high for us. So, we look at that on a daily basis to see how it's going to affect us and we alert our farmers as to what to expect. Those kinds of things have been very beneficial to us."

Flow in the Rio Grande/Río Bravo is highly regulated, both binationally, through the US-Mexico Water Treaty of 1944 (IBWC) and through the systems of water rights, which are implemented and enforced unilaterally by each country within its respective jurisdiction. The LRGWQI TOR does not mention water allocation or usage as a subject to explore under the LRGWQI. Instead, the TOR limits the purview of the Initiative to the authorizations specified for IBWC/CILA under Minutes 261 and 289 of the US-Mexico Water Treaty of 1944, which deal with sanitation and water quality. Therefore, though some overlap with water allocation issues is inevitable when dealing with water quality issues, the identification of LRGWQI-associated action arenas for this analysis is limited to those in which the decision spaces relate directly to actions affecting pollutant loads.

ACTION ARENAS RELEVANT TO LRGWQIDSS DEVELOPMENT

The author identified three action arenas with direct relevance to the development of the LRGWQIDSS; two of which function at the local operational level: (1) the US wastewater treatment action arena(s), composed of five public utilities, one water supply corporation, a special utility district, and an independent school district; and (2) the Mexican wastewater treatment action arena(s), composed of five municipal water and drainage commissions (COMAPAs) and one municipal water and drainage board (JAD). These are presented in Figure 2-23 (shaded boxes) along with their hierarchical associations to higher level action arenas based on rules-in-use. The arrangement of action arenas in Figure 2-23 follows the method of Cowie and Borrett, (2005), with lower operational rule level action arenas depicted at the bottom of figure. Under Mexican law, only CONAGUA has authority to issue permits to discharge wastewater into Mexican national waters. However, CEAT, the environmental and water commission for the State of Tamaulipas has some nominal regulatory authority over wastewater operations in the state; CEAT is also a named participant in the LRGWQI. Conversely, through the federal NPDES delegation process, the State of Texas has sole permitting authority over wastewater dischargers in the state.

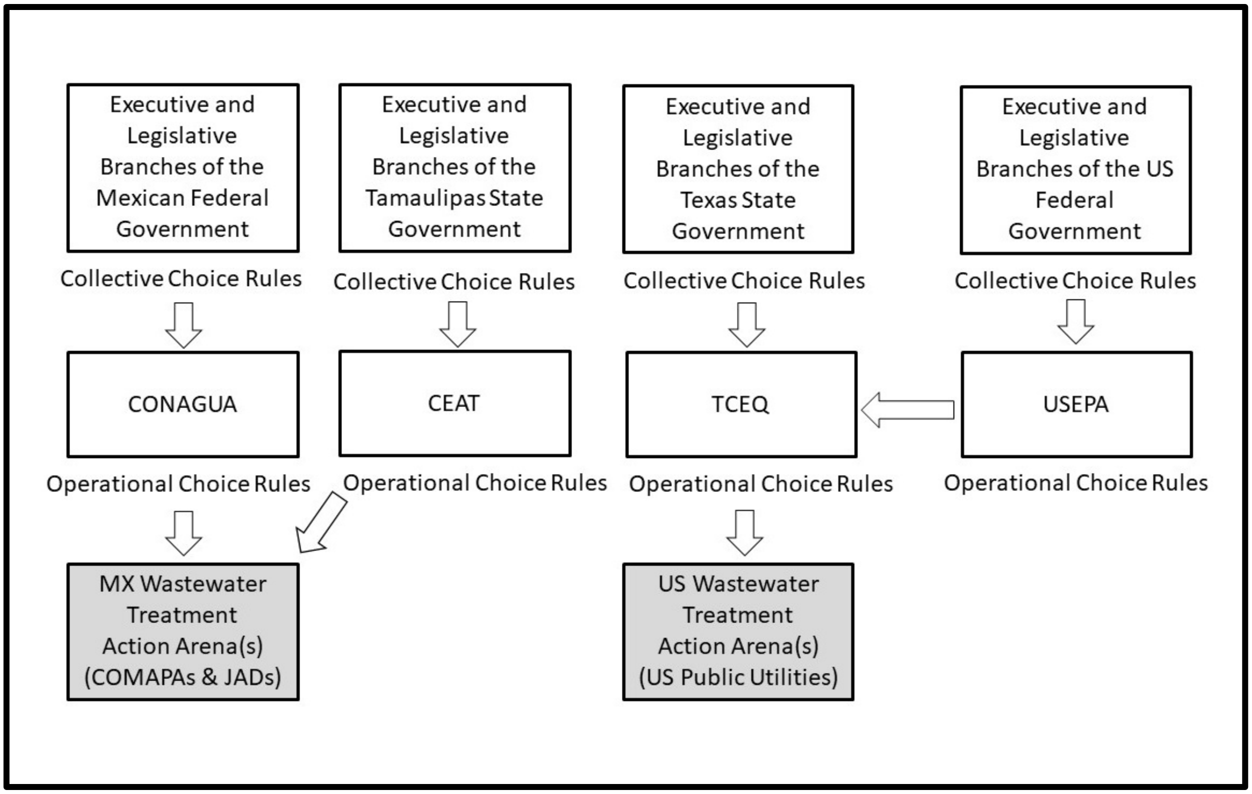


Figure 2-23. Local Operational Action Arenas with Relevance to the Development of the LRGWQIDSS and Their Hierarchical Associations to Higher Level Action Arenas Based on Rules-in-use (colored boxes denote the action arenas analyzed for this dissertation).

USEPA can and does issue NPDES permits for wastewater discharges, but to do so the federal agency would have to revoke NPDES delegation.

Even though agricultural practices are identified as potential sources of pollutants to the river, action arenas that include agricultural producers are excluded from this analysis because agricultural activities associated with pollutant loading are not regulated in the United States nor in Mexico. This makes it unlikely that US and Mexican agricultural producers would have an incentive to use the LRGWQIDSS, at least for operational purposes. Use of the LRGWQIDSS for simulating scenarios involving agricultural practices is likely to be conducted by participants in the LRGWQI as part of efforts to develop a binational watershed-based plan.

The third action arena identified as part of this analysis is that of the LRGWQI forum itself (Figure 2-24), which functions in a dual collective choice/constitutional choice level, except for the operational rule relationship between USEPA and TCEQ. That is, the individual actors, as representatives of federal and state agencies, function under the collective choice rules passed down to them from the collective choice action arenas that respectively govern them (i.e., state and federal executive and legislative branches of governments). The LRGWQI functions internally under at a constitutional choice rule level (i.e., the LRGWQI TOR). CEAT is included in Figure 2-24 because it is a named participant in the LRGWQI TOR and because it is considered a potential user of the LRGWQIDSS. Although having only nominal regulatory authority, CEAT is instrumental in the planning, financing, and management of water and wastewater infrastructure projects in the Mexican state of Tamaulipas. Possessing trained technical staff, CEAT plays an important role in assessing the potential impact, on the quality of surface water bodies, of proposed wastewater infrastructure projects. In this capacity, CEAT is an important intermediary between the local COMAPAS and CONAGUA in the federal infrastructure financing process.

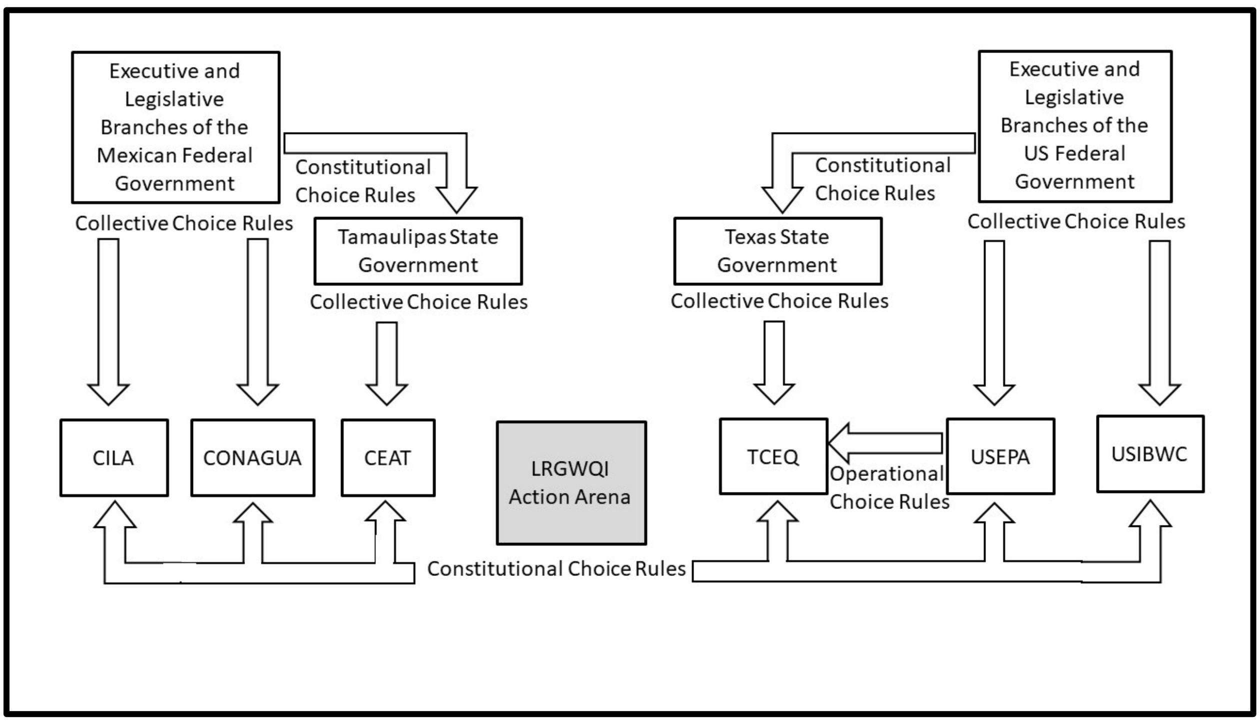


Figure 2-24. The LRGWQI Action Arena and Its Hierarchical Associations to Higher Level Action Arenas Based on Rules-in-Use.

It should be noted that the action arenas presented in Figures 2-23 and 2-24 have associations with numerous other action arenas that are neither included in the figures nor are substantively included in the study, even though they are process stakeholders. The author recognizes that organizations not included in this institutional analysis may become future users of the LRGWQIDSS. The lack of input, from these unidentified potential future users, in the elaboration of the LRGWQIDSS, may constitute a weakness in the tool's development. The weaknesses in DSS functionality related to use of the tool by individuals not originally envisioned as users during the development phase can be overcome by incorporating flexibility, such as modularity, in the DSS design.

The author chose to begin the institutional analysis by examining action arenas that function at an operational level because "actions at the operational level are the ones that directly affect resources and the distribution of outcomes of resource use" (Cowie & Borrett, 2005, p. 472). In addition to identifying and characterizing the individual actors and their roles (i.e., positions) within and outside of the action arena, a fuller understanding of the incentives and constraints that influence these actors can be gained by: (1) identifying and examining the contextual factors (i.e., exogenous variables) that affect the decision space (i.e., elements of the action situation); (2) identifying the working rules of the action arena; and (3) identifying and analyzing the interconnections of the action arena with other action arenas at different hierarchical levels, as discussed in the following sub-sections.

Operational Level Action Arenas

For the purpose of this analysis, LRGWQI-associated action arenas identified as functioning at the operational level are better described as groups of action arenas functioning in similar ways for similar purposes at the operational rule level. Thus, there is no single US wastewater treatment action arena, as there is, for example, a single Texas State Legislature, but rather eight different US wastewater treatment action arenas, with decision spaces of similar character, operating on the US side of the Lower Rio Grande/Rio Bravo watershed. To be sure, there are associations between the individual local US wastewater treatment arenas. For example, most of the US wastewater treatment arenas are affiliated with larger trade organizations such as the Rio Grande Valley Chapter of the American Water Works Association, which represent local forums of interaction. However, except for exchanges of high-level information, these local forums of interaction themselves do not function like action arenas as described in the IAD framework.

It is useful also to recall that the purpose of this analysis is to identify institutional factors relevant to the development of the LRGWQIDSS, which is why these action arenas are classified as functioning at an operational level. Each action arena functions under unique internal working rules which also interconnect with working rules in action arenas that exist at other hierarchical levels. For example, the Brownsville Public Utility Board (BPUB) operates under an (1960) amendment to the City Charter, which details the institutional structure of the BPUB, including how members are appointed by elected city officials (one board member is elected) and how decisions are made by the board. In contrast, the La Joya ISD, which operates the Sam Fordyce Elementary School wastewater treatment facility, functions under the administrative rules and procedures established by the La Joya ISD Board of Trustees. These rules allow the creation of an operations department, headed by a superintendent of operations who is in charge, among other things, of wastewater treatment and disposal for six large school facilities located in rural Hidalgo and Starr Counties.

US Wastewater Treatment Action Arena(s)

<u>The Context</u>

Chapter 1 of this dissertation provides a detailed description of the US sources of wastewater to the Rio Grande as well as a summary of the demographics in the US portion of the watershed. The information provided in Chapter 1 helps to outline the physical and material conditions that characterize the US wastewater treatment action arenas. This information is augmented by the knowledge obtained from the qualitative research conducted as part of this dissertation. For example, while Chapter 1 emphasizes that, with the exception of Brownsville which is located at the distal end of the river near the confluence with the Gulf of Mexico, most of the wastewater generated by the US urban population living near the Rio Grande/Río Bravo is discharged to the Arroyo Colorado, an adjacent watershed to the north that flows into the Laguna Madre on the US side. Thus, most of the US wastewater discharged to the river emanates from the small, relatively economically distressed communities located in the upper portions of the watershed (in Starr County and western Hidalgo County) and which are arguably the local US communities that can least afford expenditures in infrastructure. Stakeholders in these areas lamented recent cut backs in state and federal infrastructure funding resources available to them in the past highlighting the importance of economics in local decision making, including decisions on infrastructure spending. From stakeholder interviews:

> "And even though there is funding out there for these types of projects, the biggest issue that we have at Starr County is that Starr County is very economically deprived. In fact, something that I'm not proud of and we have to improve is that we are one of the poorest counties in the nation. So, when these funds are made available to the public they usually come with portions that must be matched by the entity."

> "And, we don't have the funding we used to from EPA, not from NADBank anymore unfortunately. EPA gave out hundreds of millions of dollars for that, and they're not doing that anymore."

An important historic antecedent/precipitating event that surfaces often in the information collected during the qualitative knowledge gathering efforts was the Texas drought of 2010 and 2011. The year 2011 was the driest year ever in Texas (NOAA, 2011), occurring in the middle of one of the most severe droughts in Texas history. Consequently, the attention paid to water issues, not just in the Rio Grande Valley but throughout Texas, was extraordinary at the time of the qualitative data collection effort. Although water availability issues were at the forefront of state and local governance discussions, water quality issues were also elevated to unprecedented ranks, especially in action arenas such as the US and Mexican water and wastewater treatment arenas. Alternatives for wastewater "treatment," such as direct reuse, which would normally not gain a place on discussion agendas at utility board meetings, suddenly surged as a discussion topic in such forums. From stakeholder interviews:

> "Reuse water for the Valley, to me, is the key. The City of (omitted to protect confidentiality), once again, is looking at how do we plan for this? Well, we just finished doing a master plan for reuse water. And once again the key is, it might take me ten years, but I gotta figure out a way to end up making sure that my citizens aren't gonna go through the drought situations that were going through now. In the 13 years that I've been here, this is the first year, in 2011, that I actually ran out of water."

Problems with infrastructure funding also acquired a sudden urgency at the local and state level during and after the Texas drought of 2010-2011.

Community attributes are difficult to investigate, especially those pertinent to the assessment of normative bounds on individual utility. However, certain themes are discernable from the qualitative data and information gathered for this research. For example, a full 70% of the US respondents to the UT LBJ survey of water quality preferences were willing to pay extra each month to make sure the Rio Grande is clean enough to swim in and 28% answered "everyone" to the question: "Who do you think should be responsible for making sure the Rio Grande is clean?" This responses was the most frequent by US respondents (UT-LBJ, 2013a). The transcripts of the stakeholder interviews and focus groups sessions are also filled with statements invoking the importance of water quality to the local community. From the stakeholder interviews:

> "And that's just it; at the end of the day it's how much are you willing to spend and making an investment, and not only for your present needs but for those down the road. For our children and their children."

The Decision Space

According to the IAD Framework, the decision space of an action arena is characterized by clusters of internal variables referred to as the "elements" of the action situation (Figure 2-19). They include the set of *participants*, the *positions* they occupy, the set of possible *decisions*/*actions* linked to *outcomes*, the *level of control* participants have over decision choices, and the *information* available to the participants for decision making. These elements are influenced by exogenous variables that are addressed in the decision space through a set of working rules. The following is an interpretation of these elements as they relate to the US wastewater treatment action arena.

The participants in the of the US wastewater action arena are US entities that discharge wastewater to the Lower Rio Grande/Rio Bravo; these actors are described in more detail in the following sub-section. Their positions and roles in the action arena are reflect their resources, interests, and individual needs, which determine their official category among the participants. While all participants have a need for water, sanitation, and wastewater treatment and an interest in acquiring these resources and services, the individual needs, degrees of desired services, and resource levels vary from participant to participant. Participants compete with each other for financial resources for wastewater services and, to a degree, for assimilative capacity of the resource they rely on for disposal of their wastewater (i.e., the Rio Grande/Río Bravo). In theory, participants in the US wastewater treatment action arena also compete for these resources with the participants of the Mexican wastewater treatment action arena, but in practice (at least currently), the participants in the US wastewater action arena do not compete with their Mexican counterparts for assimilative capacity and only marginally for funding.

As explained in Chapter 1, US regulators do not currently take Mexican discharges into account when assessing the impact of proposed US wastewater discharges to the river. Participants in the US wastewater action arena only compete with their Mexican counterparts for funding from NADB. But, evidence from interviews and focus group sessions with US stakeholders indicate NADB strives to split its funding evenly between the United States and Mexico and US stakeholder do not appear to view NADB as a first-choice financing option for infrastructure projects. From stakeholder interviews:

> "The 52 wastewater treatment plants [funded by NADB] that we have implemented through the US-Mexico border, half have been in the United States and half have been in Mexico." Also, "EDAP [a TWDB financing program] is one of the primary funding sources for the Rio Grande Valley for the colonias." And, "EDAP is on a first-come-first-served basis, depending on applications received."

While the representatives of the participants in the US wastewater action arena may vary in terms of decision-making capacity (e.g., head of city planning departments, general managers, superintendents, etc.), the roles of all actors is similar. Each participates to help make decisions about certain actions associated with wastewater infrastructure, such as expanding a wastewater treatment facility or providing first time sewer service to portions of their communities. These actions result in a set of perceivable outcomes, some of which are more clearly foreseeable than others. In the case of the US wastewater treatment action arena, the level of control the participants have over the choices of actions is constrained by a number of factors, including state requirements for environmental and public health protections and the requirements associated with project funding. For example, water supply corporations do not have taxing authority and must rely on revenues from other sources, mainly service fees, to expand services. All participants must adhere to pertinent environmental regulatory requirements, as well as the financial requirements of funding organizations.

One factor that constrains participants' ability to make decisions about actions on wastewater infrastructure is information. Knowledge about the physical resources (e.g., assimilative capacity of the intended receiving stream), the costs and benefits of actions being taken or contemplated, the actions by their fellow participants in the US wastewater treatment action arena and of Mexican dischargers could influence decisions. While greater availability of information benefits all participants in the US wastewater arena, it benefits the entities of more modest means disproportionately.

The Actors

The author identifies the actors within the US wastewater treatment action arena as the members of municipal planning, utility and/or engineering departments of several entities (such as the engineering departments of four cities [City of Roma, City of Rio Grande City, City of La Joya, and City of Peñitas]; the engineering department of an independent municipal utility board [BPUB]; the general managers of a water supply corporation [Union WSC] and a special utility district [AGUA SUD]; and the superintendent of operations of an independent school district [La Joya ISD]) in charge of planning and management of wastewater treatment services for these organizations. In the case of Union WSC, AGUA SUD and the La Joya ISD, the general managers and superintendent of operations delegate day-to-day wastewater management and planning activities to private engineering firms but oversee these activities and approve proposals (or approve the forwarding of proposals to a higher decision-making body), for infrastructure expenditures.

The decisions made by these actors make them accountable to other individuals in three ways: (1) the decisions they make regarding wastewater infrastructure proposals must be in accordance with the needs and expectations of the stakeholders receiving the wastewater services; (2) the recommendations/decisions they make regarding wastewater infrastructure expenditures must be in accordance with the authorizations delegated to them, and the constraints placed on them, by their respective governing bodies and constraints placed upon them by the providers of funding and/or financial assistance; and (3) the decisions they make regarding wastewater infrastructure project proposals must adhere to the regulations in place to protect human health and the environment.

Actors in this action arena can be assessed by examining the four general characteristics explored when applying the IAD framework: R*esources, Information Availability, Decision-making Strategies, and Norm-bounded Cost-Benefit.* Applying the framework reveals notable divergences among the actors in this action arena. For example, the human and financial resources available to BPUB are much greater than those available to to any of the other actors in the US wastewater action arena. Thus, the type of wastewater problems experienced by the City of La Joya, for example, are not common in more financially healthier utilities, such as BPUB. Similarly, with greater financial resources, more economically stable entities have greater access to information on current and future infrastructure needs, alternatives, and costs than actors of more modest financial means. In fact, the information asymmetry identified in this action arena is considerable when one compares the financial and human resources available to each actor. These factors (resources and information availability) have a visible effect on the decision-making strategies of the actors in this action arena; more financially-capable actors tend to make decisions based on more and better information, which reduces the chances of mismanagement due to a lack of planning or simply from mistakes made due to lack of expertise or due to incompetence.

Cost-benefit analysis is a well-established field of study and there would be great value in conducting a rigorous quantitative cost-benefit analysis with respect to the use of the LRGWQIDSS for each of the entities represented by the actors in the US wastewater action arena. However, such a study is beyond the scope of this dissertation. For the purposes of this research, it will suffice to acknowledge that the requirements of classical economic utility are satisfied if the actors and the entities they represent receive a measurable benefit at an affordable cost within the norms considered acceptable to the average member of the community.

Within the context of the IAD framework, the investigation of norm-bounded cost-benefit is usually in reference to the outcomes of decisions made within the decision space of an action arena. Using the IAD framework to analyze the action arena, cost-benefit is relevant only from the perspective of a particular decision or set of decisions, the author has chosen to investigate this aspect of the actors in this action arena from the perspective of the cost-benefit associated with use of the LRGWQIDSS. With this in mind, the benefits identified by the author for the US wastewater action arena are the savings in engineering and planning cost involved in assessing the impacts, to water quality of the receiving stream, of proposed infrastructure projects and of gaging the preliminary costs of those projects (e.g., upgrading and expanding wastewater treatment facilities, building new wastewater treatment facilities, installing wastewater connections to unsewered communities, etc.). A second benefit would be the availability of additional information about the activities of other dischargers to the river, including Mexican dischargers, and a broader picture of assimilative capacity and water conditions in the river. This second benefit would be especially valuable to downstream actors such as BPUB. This is, of course, assuming the LRGWQI partner agencies agree, at some point, to allow the release of the LRGWQIDSS for use by this action arena (perhaps once the Declaratoria for the Lower Rio Bravo is promulgated in Mexico).

At least at this time, neither the author nor the LRGWQI development team envisions a cost to the user of the LRGWQIDSS other than the time involved in using the software and, perhaps supplying input to the developers for improvement of the LRGWQIDSS. Similarly, the author cannot identify any normative impediments to the use of the LRGWQIDSS by the US wastewater action arena, as defined in this research. This leads to the conclusion that the norm-bounded cost-benefit of using the LRGWQIDSS in the US wastewater treatment action arena is slanted heavily towards benefit at minimal cost. This conclusion is subject to change if the usage parameters of LRGWQIDSS were to change from those originally envisioned by the author and the LRGWQIDSS development team.

The Working Rules

According to the IAD framework, the working rules of an action arena are the rules-in-use in the decision space of the arena. These are a combination of enforced rules-in-form, which are typically codified in some way, and self-enforced uncodified rules of order, norms or conventions adhered to by the actors. It should be noted that the set of working rules in an action arena is a configuration in the sense that the effect of a change in one rule may depend upon the other rules-in-use and the change may also affect other rules-in-use (Ostrom, 2011).

The author used the IAD framework to identify the working rules of the decision space of the US wastewater treatment action arena using guidance provided in the framework (Table 2-2). Due to the nature of the action arena being analyzed (i.e., a group of action arenas with similar functions) and the inherent difficulty in identifying and characterizing uncodified rules-in-use, the analysis presented in this sub-section is focused primarily on identifying and characterizing codified and enforced rules-in-use utilizing the categorization of rule types described in the IAD framework.

Boundary Rules

Boundary rules determine which individuals/entities are allowed to participate in the action arena. Using this definition, entry of entities as participants in the US wastewater treatment action arena is limited to those organizations that qualify as providers of wastewater services under the regulations of the State of Texas (Texas Water Code, Chapters 13.016, 13.043, and 13.187). These rules specify the registration, certification and reporting requirements for providers of wastewater services in the state of Texas. In Texas, unless an entity providing wastewater services is a non-profit water supply corporation with less than 15 connections, the entity is required to apply for a Certificate of Convenience and Necessity (CCN). The holders of these certificates must comply with a number of regulatory requirements, which vary depending on the type of and size of the utility. Once certified by the Texas Public Utilities Commission, the entity must also apply for a permit, from the TCEQ, to discharge, or otherwise dispose of wastewater. Failure to comply with these requirements, including permit requirements, leads to legal action such as fines, administrative actions (e.g., receivership), and, in extreme cases, criminal prosecution. Hence, the exit rules for participants in the US wastewater treatment action arena are also specified in the Texas Water Code and the applicable implementing regulations in the Texas Administrative Code.

A second source of boundary rules for the US wastewater treatment action arena relates to the scope rules of its decision space. Entry and exit of entities into the US wastewater treatment action arena is also determined by where and how the utility choses to treat and dispose of its wastewater. For example, the utility could choose not to discharge to the Lower Rio Grande/Río Bravo and thus would cease to be part of the US wastewater treatment action arena. The reality is that, except for BPUB, the US utilities which are participants in the US wastewater treatment action arena are all located in the uppermost portion of the watershed, which leaves them with limited options for wastewater treatment and disposal, as all riverine water bodies in the upper portion of the watershed flow to the Lower Rio Grande/Río Bravo. Options such as no-discharge permits are difficult to implement and unconventional wastewater treatment options, such as wastewater reuse, are expensive and human resource intensive. Therefore, discharge to the Lower Rio Grande/Río Bravo must be mentioned as one of the boundary rules for the US wastewater treatment action arena.

Position Rules

Position rules specify a set of positions (i.e., functional ranks) within the action arena. Each position comes with corresponding resources, opportunities and responsibilities. The position rules specify how individuals/entities are assigned to these positions. This conceptualization is based on a model of the classic IRC stakeholder forum (i.e., irrigation districts, watershed partnerships, etc.) and is difficult to apply to the analytical construct represented by the US wastewater treatment action arena. While, different types of wastewater providers occupy different positions in the US wastewater treatment action arena, based on their nature and size (e.g., large public utility v. small municipality v. water supply corporation v. school district, etc.), the positions reflect the statutory authorizations and constraints placed externally on the actors by the regulatory and infrastructure financing community, action arenas to which the US wastewater treatment action arena is interconnected at a higher hierarchical levels.

The positions in the US wastewater treatment action arena do not directly affect the internal deliberations of the arena(s), as would the traditional functional ranks in a classical IRC stakeholder forum (e.g., a chairman or a ranking committee member or a treasurer, etc.). However, there are differences in opportunities and responsibilities associated with the different classifications of the utilities, as described in the Texas Water Code. For example, under Texas Public Utility Commission rules, a district or municipality may not provide services within an area for which another utility holds a CCN unless the district or municipality has a CCN itself for that area. And, a CCN holder is required to demonstrate financial, managerial, and technical capability to provide continuous and adequate service to any requested area within the CCN as a condition for retaining the CCN. In some cases, entities can lose control of their utility service areas to a bigger, more financially stable utility. So, while position rules in decision spaces, as originally conceptualized in the IAD framework, are not directly applicable to the US wastewater treatment action arena, the classifications of utilities specified in the Texas Water Code create virtual position rules in the US wastewater treatment action arena.

Scope Rules

Scope rules bound the potential outcomes that can be affected by decisions/actions made by the actors in the decision space of an action arena. The outcome boundaries are typically, but not always, tangible (i.e., measurable) domains. An obvious source of scope rule for the decision space associated with the US wastewater treatment action arena is represented by the boundaries of the service areas and the CCNs of the eight entities included in the US wastewater treatment action arena. The physical domain comprised of these geographic areas effectively bounds the outcomes of the decision space of the US wastewater treatment action arena. An equally discernable source of scope rules affecting the US wastewater treatment action arena is the water body receiving the treated wastewater from these entities, the Lower Rio Grande/Río Bravo. As previously mentioned, the scope and boundary rules of the US wastewater treatment action arena are related through the choice of wastewater treatment and disposal made by the actors in this action arena. However, assuming the boundary rules apply, the scope rules for actors in the US wastewater treatment action arena are related directly to the available pollutant assimilative capacity of the Lower Rio Grande/Río Bravo or the amount of pollutants a utility is allowed to discharge to the Rio Lower Rio Grande/Río Bravo.

Choice Rules

Choice rules assign sets of actions that actors, in their positions at particular decision situations, may, must, or must not take. Combined with the scientific laws about the relevant decision subject being acted upon (e.g., collection, treatment and disposal of wastewater), choice rules determine the shape of the decision tree that links actions to outcomes (Ostrom, 2011). Choice rules, more than any other working rule in the decision space, constrain the operational actions of the participants in an action arena. In the stakeholder forums studied by Ostrom, choice rules govern the actual management of the common pool resource.

As was the case with position rules, the concept of choice rules does not fit neatly into the analytical construct of the US wastewater treatment action arena. Choice rules that govern the operational behavior of the actors in the US wastewater treatment action arena are largely imposed exogenously by the State of Texas and, indirectly, by the US federal government (Figure 2-24). There are differences in the choice rules that apply to different types of utilities based on their legal classification. A utility can change the choice rules under which it operates if it changes its classification. Also, a change in the classification of a utility may occur involuntarily and could result in more restrictive choice rules under which it must operate.

Aggregation Rules

Aggregation rules affect the level of control an individual actor, in a position within the action arena, exercises in the selection of an action during a particular decision situation. These rules aggregate the interests of stakeholders by placing conditions on the activities of individual actors not just to protect the resource, but to protect the interests of other stakeholders. Within the context of the US wastewater treatment action arena, the source of aggregation rules is a combination of external rules and internal rules. An example of internal aggregation rules are the rules used by the individual utility boards for decision making. This includes how infrastructure needs are determined by engineering or planning departments; how proposals for infrastructure projects are developed and promoted; how decisions are made internally to finance infrastructure projects, etc. Examples of external aggregation rules affecting the US wastewater treatment action arena include the permitting procedures used by regulatory agencies, such as the TCEQ, and prioritization and approval procedures used by infrastructure financing organizations, such as the TWDB, USDARD or NADB.

Information Rules

Information rules affect the knowledge-contingent information sets of the participants in an action arena (Ostrom, 2011). The immense importance the role information plays in decision making is not only intuitive but well-documented (Barnard, 1948; Gorry & Morton, 1971; Simon, 1976). Information, however, also plays an important role in the strategic behavior of the participants of action arenas. In game theory, certain types of information are determining variables in the strategic behavior of the players in a game. Similarly, participants in an action arena may find advantages and disadvantages in sharing information with other participants or with individual/entities outside of the action arena. Because they can constrain the information made available to participants in the action arena, information rules also have an impact on other types of working rules in the action arena.

In the case of the US wastewater treatment action arena, participants are required to provide operational and economic information to state and federal agencies, which are action arenas to which the US wastewater treatment arena is interconnected, but which exist at higher hierarchical levels. For example, utilities must report effluent flows and concentrations to the TCEQ and USEPA and must provide economic information to funding organizations such as the TWDB which is used for rate studies and financing formulas. Although it is to the advantage of utilities to keep some information confidential, such as annexation or CCN expansion plans, these entities typically have difficulty keeping information from the public domain due to obligations associated with public accountability and legal requirements. In general, for local utilities, the limiting factor in acquiring information useful in decision making is financial in nature. Economically distressed communities, especially, may lack the means to obtain the kind of information they need to make better informed decisions.

As discussed in the previous sub-section titled "Preface," information rules in action arenas connected to the US wastewater treatment action arena at a higher hierarchical level (i.e., the LRGWQI action arena), effectively limit the information available to the participants in the US wastewater treatment action arena. Information such as the location and nature of existing Mexican wastewater outfalls, the quality of water in Mexican tributaries and the expansion and upgrade plans of Mexican wastewater treatment facilities could become valuable knowledge to the participants in the US wastewater treatment action arena. A decision support system that could provide access to some of this information would improve the decision-making capabilities of all participants in the US wastewater treatment action arena. As information rules can affect other working rules in an action arena, access to the aforementioned information could affect operational controls specified in the scope rules and choice rules and may also affect other working rules of the US wastewater treatment action arena.

Payoff Rules

Payoff rules affect the benefits and costs that will be assigned to combinations of actions and outcomes. They establish the incentives and deterrents for action (Ostrom, 2011). To guide the analyst in identifying payoff rules, the IAD frameworks suggests the following questions be asked: How large are the sanctions that can be imposed for breaking any of the [working] rules?

How is conformance to rules monitored? Who is responsible for sanctioning nonconformers? How reliably are sanctions imposed? The vast majority of sanctions, compliance monitoring, and enforcement of sanctions are effected by external entities, such as the TCEQ and the TWDB; again, action arenas to which the US wastewater treatment arena is interconnected, but which exist at a higher hierarchical level.

The costs to participants of providing sewer services to the communities they serve include the costs of wastewater collection, treatment, conveyance, and discharge, along with the engineering and administrative costs of planning and regulatory compliance. The benefits include improved quality of life, which typically translates to increased economic opportunity, public support of local government, and in rare cases, increased revenues. The balance of costs and benefits is dependent on variables that affect the payoff rules. These include, ostensibly on the cost side, the multi-faceted repercussions resulting from breaking any of the working rules previously discussed.

To identify payoff rules directly affecting benefits to participants in the US wastewater action arena, Ostrom includes the following question in her set of suggested questions for characterizing pay off rules: Are any positive rewards offered to appropriators for any actions they can take? As mentioned, many of the payoff rules affecting costs in the US wastewater action arena are imposed externally. However, payoff rules that enhance benefits are not necessarily tied to the rules exogenously imposed on the US wastewater action arena. For example, an increase in the effectiveness and/or the efficiency of wastewater collection and treatment systems can increase the benefits to the utilities providing these services. Participants in wastewater treatment action arenas can derive benefits indirectly by lowering of the costs of providing sewer services to their communities. If costs of planning and general decision making were to be lowered through increased access to information, this would affect the cost-benefit balance, effectively redefining the payoff rules in the action arena.

<u>Institutional Factors Relevant to the Development of the LRGWQIDSS</u>

Several contextual factors identified during the analysis of the US wastewater treatment action arena are relevant to the design of the LRGWQIDSS. Assuming participants in the US wastewater treatment action arena are also users of the LRGWQIDSS, the context within which the actors in this action arena make decisions about wastewater infrastructure includes depressed economic conditions, substantial geographic areas lacking centralized wastewater services, and extremely dry conditions. It stands to reason that a DSS designed to aid decision makers in this action arena include capabilities such as the simulation of the costs of options for providing and/or improving wastewater services to low income communities in their service areas or CCNs. These costs include the price of providing wastewater collection and treatment services to new customers. Because flow in the Lower Rio Grande/Río Bravo affects its pollutant assimilative capacity and thus determines the level of treatment needed, it stands to reason that the LRGWQIDSS be able to simulate the effects of wastewater discharges under variable flow conditions, including drought conditions.

Certain kinds of information provide specific benefits. For example, the level of control the participants have over the choices of actions is constrained by state requirements for environmental and public health protections and the requirements associated with project funding. Therefore, the LRGWQIDSS should provide information that helps the actors in this action arena make decisions within these constraints (e.g. simulation thresholds pegged to state water quality criteria and displays of the geographic locations of outfalls and drinking water intakes). Another kind of information determined to be useful to actors in the US wastewater treatment action arena is operational information about other actors in the arena, which would help each individual actor to better plan and manage of their systems. Including information of this type in the LRGWQIDSS, would be useful to participants in the US wastewater treatment action arena.

Beyond a commitment to serve their communities and to comply with pertinent state regulations and requirements, the actors in the US wastewater action arena understand the value of a healthy Lower Rio Grande/Río Bravo. Although the TCEQ currently does not adequately take into account the effect on water quality of pollutant loading from Mexican sources, actors in the US wastewater treatment action arena would be concerned enough about water quality in the river to want to include this loading in simulations of water quality using the LRGWQIDSS.

Finally, an examination of the rules-in-use in the US wastewater treatment action arena reinforces the need to design the LRGWQIDSS to provide information that helps the actors in this action arena make decisions within the regulatory constraints that so intensely influence the arena's decision space. The analysis of the working rules of the US wastewater treatment action arena also shows how a change in the information rules (in this action arena and in action arenas connected to it), prompts changes in other types of working rules within the action arena; particularly affected by changes in information rules are scope rules, choice rules and, most importantly, payoff rules.

Mexican Wastewater Treatment Action Arena(s)

The Context

Analogous to the US wastewater treatment action arena, the Mexican wastewater treatment action arena shares many functional similarities with its US counterpart. However, there are also differences in the context within which the two action arenas operate. The volume of wastewater discharged to the Rio Grande/Río Bravo from Mexican wastewater outfalls is greater than that which emanates from US outfalls. Loadings of fecal bacteria and biochemical oxygen demand from Mexican point source is several orders of magnitude greater than that of US point sources (Table 1-11; Page 80). This is mainly due to the wastewater outfalls located near the Mexican city of Reynosa, but also from those of other Mexican riparian communities located in the upper portion of the Lower Rio Grande/Río Bravo watershed. In fact, the riparian population on the Mexican side of the watershed exceeds that of the United States by a factor of four (see Table 1-12; Page 82). On the US side of the watershed, most of the wastewater generated by the US urban population is discharged to a water body other than the Lower Rio Grande/Río Bravo (i.e., the Arroyo Colorado). A large portion of the wastewater emanating from Mexican urban communities is discharged to the river.

There are also substantial demographic differences between the communities living on either side of the river. The median income of the Mexican population in Northern Tamaulipas is well below the US poverty level and is only 11% of the median income on the US side. The need for wastewater services is also much higher on the Mexican side, especially in large urban areas, such as Reynosa, where as much as 12.5 percent of the urban population lacks adequate sanitation (INEGI, 2010). Mexican utilities also rely more heavily on government funding sources for expenditures on infrastructure, with 61% coming from the federal government, 23% from state governments and only 11% from local municipalities on average (CONAGUA, 2012). While US utilities rely on government funding for infrastructure, they also rely on customer fees to pay for infrastructure projects and, for large projects, US municipalities rely on their constituent tax base to issue bonds. Mexican utilities, on the other hand, rarely are as fiscally efficient. For example, as of 2012, Reynosa's COMAPA recovered only 62% of its costs from customer rates and CONAGUA rated the Reynosa COMAPA's overall fiscal efficiency at only 57% (CONAGUA, 2012).

Qualitative information collected as part of this research indicates that this difference in efficiency may be due to dissimilarities between US and Mexican normative attitudes towards the role of government. From interviews:

> "In Mexico, you talk to any Mexican, and they tell you right away that water belongs to the nation, it's derived from Article 27 of their constitution."

> "I would also say that in Mexico, and this has been a big problem in financing wastewater infrastructure on the Mexican side, as there is this culture of not paying for your water."

> "There's a lot greater expectation along the whole range of services in Mexico, for the government to intervene and do things."

The conditions of high demand, scarce financial means, and systematic fiscal inefficiency relegate the Mexican wastewater treatment action arena to physical and material conditions that are substantially less favorable to success the than those of the analogous US wastewater treatment action arena. It should be noted, however, that in this portion of the US-Mexico border region, several large wastewater infrastructure projects were completed, on the Mexican side of the watershed between 2000 and 2018, including new wastewater treatment facilities for the Mexican cities of Mier, Miguel Alemán, Reynosa, Rio Bravo and Matamoros. These projects were financed largely through a combination of funding from the NADB and the Mexican federal government.

Although arid conditions are the norm for all of northern Mexico, the drought of 2010 and 2011 that so drastically affected Texas also had a lasting effect on northeastern Mexico. As with their neighbors to the north, water availability issues were at the forefront of discussions among professionals in the COMAPAS of northern Tamaulipas. Consequently, alternatives for wastewater “treatment,” including direct reuse, also featured prominently in these discussions.

As far as community attributes affecting the Mexican wastewater treatment action arena, the aforementioned Mexican normative attitudes towards water and sanitation present a challenge to the participants of this action arena, in that there is a public expectation that the COMAPAS and JADs provide water and sanitation services without necessarily a commensurate sense of obligation on the part of the public to pay the real costs of such services. There is also a general reluctance, on the part of utilities and the state and federal government, to rely on the rate payer and tax payers to fully finance infrastructure projects. This is reflected in the lower percentage of Mexican respondents (67%) that were willing to pay extra each month to make sure the Rio Grande is clean enough to swim in. A lower percentage of Mexican survey respondents (18.8%) also answered “everyone” to the question: “Who do you think should be responsible for making sure the Rio Grande is clean enough to swim in?” Surprisingly, “Local Government” ranked only as the third highest response to this question among Mexican respondents.

In 2012, CONAGUA rated the Reynosa COMAPA’s overall functional efficiency at 37% (CONAGUA, 2012). Functional inefficiency in the Mexican wastewater treatment action arena, is related to the fiscal inefficiency of COMAPAS and JADs, as the need to reduce infrastructure debt burdens often leads decision makers, especially those in interconnected action arenas at higher hierarchical levels, to call for a reduction in local COMAPA staffs and/or salaries (Torres, 2019).

The qualitative information gathered for this research indicates that the Mexican riparian communities share, with the riparian US communities, an appreciation of the Lower Rio Grande/Río Bravo as a valuable natural resource, with 79.8% of respondents to the UT LBJ survey of water quality preferences choosing the highest option (5), “very important,” to the question: “On a scale of 1-5, how important is it to you that the Rio Grande/Rio Bravo be clean?”

The Decision Space

Like their US counterparts, the participants in the of the Mexican wastewater action arena hold different positions in the arena based on their resources and individual needs and interests and also compete with each other for financial resources. However, unlike their US counterparts, participants in the of the Mexican wastewater action arena do not currently compete for assimilative capacity of the water bodies receiving their wastewater. This is because the effluent limitations placed on the outfalls for which these actors are responsible are based on technology-based performance standards (BPT), not on the effects the outfalls have on the ambient water quality of the receiving stream (i.e., the Rio Grande/Río Bravo and its tributaries). This is a significant policy difference between Mexican and US regulatory frameworks that not only obviates competition between participants in the Mexican wastewater treatment action but effectively shields them from competition with US dischargers for assimilative capacity of the river. There rules fail to adequately protect water quality in the Lower Rio Grande/Río Bravo.

In terms of funding, participants in the Mexican wastewater action arena have fewer choices at than US counterparts; their decision-making ability is also limited within the more centralized Mexican governance system. CONAGUA selects and approves financial resources for wastewater infrastructure funding on a national level under its two main federal infrastructure programs APAZU and PRODDER. Some regional planning is conducted by state agencies, such CEAT, which assesses infrastructure needs in the State of Tamaulipas and also provides limited financial resources for infrastructure funding. As previously described, the bulk of the financing of wastewater infrastructure projects on the Mexican side of the Lower Río Bravo since 2000 has involved a combination of CONAGUA programs and NADB loans, with some grant funding provided by the BECC though the USEPA's BEIF program.

Like the categorization scheme used to classify Texas utilities, the prioritization process used by CONAGUA and CEAT places COMAPAS and JADs in certain funding categories, which within the context of the IAD framework, can be thought of as "positions." These positions afford a certain leverage in obtaining funding for infrastructure. However, Mexican wastewater treatment action arena participants have less control over their positions as compared to US utilities because they have less options at their disposal for the infrastructure funding. Nevertheless, participants in the Mexican wastewater treatment action arena are responsible for making decisions about certain actions associated with wastewater infrastructure, such as prioritization of repairs and treatment options. These actions, like those of their US counterparts, result in a set of perceivable outcomes. As with their US counterparts, the level of control the participants have over the choices of actions is constrained by regulatory and funding requirements. Furthermore, regulatory requirements are likely to change after the promulgation of the Declaratoria, as the effluent limits for Mexican wastewater treatment facilities discharging to the Lower Rio Grande/Río Bravo will change from technology based performance standards to water quality-based limits. As in the US wastewater treatment action arena, information is perhaps the most important factor that constrains the ability of the participants in the Mexican wastewater treatment action arena to make decisions about actions on wastewater infrastructure, especially after promulgation of the Declaratoria.

The Actors

The actors within the Mexican wastewater treatment action arena are the representatives of the COMAPAs of the Nueva Ciudad Guerrero, Ciudad Mier, Ciudad Miguel Alemán, Ciudad Camargo, Ciudad Gustavo Díaz Ordaz, Reynosa, and of the JAD of Matamoros. COMAPAs were created as an indirect result of the 1988 reforms to Mexican water law, which also created CONAGUA (Piñeda, 2002). Following these federal reforms, CONAGUA issued a series of recommendations aimed at strengthening the decentralization process and promoting rate autonomy, based on the actual costs of the service provision. These recommendations prompted Mexican state governments to introduce new laws or amended existing ones, partly following CONAGUA's guidelines. By 1996, 21 Mexican states had transferred service provision to municipal service providers known as COMAPAs.

The structure of COMAPAs is similar for all Mexican municipalities under which they operate. Commissioners are appointed by elected city officials, but the number of commissioners on the boards can vary depending of the size of the municipality. Typically, one commissioner is assigned the duty of reporting to city government on the activities of the COMAPA, which is operated by hired administrative and professional staff. Small COMAPAs often lack licensed engineering or planning staff, in which cases the general manager (genrente) is often tasked with performing these functions. JADs generally operate much the same way as COMAPAs, but they predate COMAPAs, so their structure can vary depending on their pre-1988 reform history. Matamoros' JAD is composed of utility board members that are appointed by elected city officials much the same way as COMAPAs. The participants in the Mexican wastewater treatment action arena are accountable to other individuals in the same ways as their US counterparts.

Both the JAD for the City of Matamoros and Reynosa's COMAPA have significantly more resources than the COMAPAs of the other smaller utilities that make up the Mexican wastewater treatment action arena, including planning and engineering departments staffed with dozens of professional, administrative, and operations employees. The greater human and financial resources of these utilities give them the ability to acquire and access more information, which allows decision makers in these utilities to make better informed decisions. Due to the higher population densities, coupled with the fiscal and operational inefficiency problems discussed in the previous sub-sections, the greater human and financial resources of these utilities do not always translate to better sewer services for the communities they serve. Nevertheless, an information asymmetry similar to that of the US wastewater treatment action arena also exists in the Mexican wastewater treatment action arena.

Upon the promulgation of the Declaratoria, Mexican utilities will be expected to plan for compliance with new water quality-based effluent requirements. Therefore, access to information helpful in these assessments would have the same cost-benefit effects as they will have on the US utilities participating in the US wastewater treatment action arena, such as savings in engineering and planning costs involved in assessing the water quality impacts and costs of proposed infrastructure projects. Information about the activities of other dischargers to the river and a broader picture of assimilative capacity in the river under various conditions. A tool such as the LRGWQIDSS would disproportionately benefit smaller, less financially capable Mexican wastewater treatment action arena participants and those located farthest downstream, such as Matamoros.

Assuming use of the LRGWQIDSS is made available to the participants of the Mexican wastewater treatment action arena for free, the author cannot identify any normative impediments to the use of the LRGWQIDSS by such actors, which leads to the same conclusion about the norm-bounded cost-benefit of users of the LRGWQIDSS in the Mexican wastewater treatment action arena. However, as with the US wastewater treatment action arena participants, this conclusion is subject to change if the usage parameters of LRGWQIDSS were to change from those originally envisioned by the author and the LRGWQIDSS development team.

The Working Rules

The author used the IAD framework to identify the working rules of the decision space of the Mexican wastewater treatment action arena using guidance provided in the framework. As with the analysis of the US wastewater treatment arena, the analysis focuses primarily on identifying and characterizing codified and enforced rules-in-use.

Boundary Rules

Entry of entities as participants in the Mexican wastewater treatment action arena is limited to those organizations that qualify as operating organisms (organismos operadores [OOs]) under Mexican federal law. Although Article 115 of the Mexican constitution places responsibility for sewage collection and treatment on Mexican municipios, Mexico's 1992 National Water Law (Ley de Aguas Nacionales) and its 2004 reauthorization specifies the role of OOs in the provision of sanitation services and places oversight responsibility of OOs on the federal government, represented by CONAGUA. There exists a hierarchical classification system for OOs based on geographic service area and population served. However, OOs can be publicly owned, privately owned or a combination of these two (e.g., publicly owned but privately administered). OOs can serve an entire municipio, a portion of a single municipio, or portions of two or more minicipios. In some instances, Mexican state agencies have been certified as OOs and provide water and wastewater services to municipios.

In addition to federal certification and reporting requirements, OOs must comply with federal requirements for financial viability. OOs are also subject to federal health and environmental regulations and must be permitted under federal discharge regulations administered by CONAGUA. As in the United States, failure to comply with these requirements can lead to legal action at the federal level by the Mexican agency in charge of enforcement of environmental laws, PROFEPA. Therefore, the exit rules for participants in the Mexican wastewater treatment action arena are specified in the Mexican National Water Law and the Mexican Federal Code of Civil Procedures (Código Federal de Procedimientos Civiles). Another other source of boundary rules for the Mexican wastewater treatment action arena is the location of its wastewater discharge. If a participant in the Mexican wastewater treatment action arena decides to relocate its wastewater outfall to a water body that is not the Lower Rio Grande/Río Bravo or one of its tributaries, they will automatically exit the Mexican wastewater treatment action arena. Conversely, any Mexican OO discharging to the Lower Rio Grande/Río Bravo or one of its tributaries is a participant in the Mexican wastewater treatment action arena. Thus, as is the case with the US wastewater treatment action arena, the boundary rules for the Mexican wastewater treatment action arena are linked to its scope rules.

Position Rules

Position rules in the Mexican wastewater treatment action arena are analogous to those of the US wastewater treatment action arena. The positions reflect the statutory authorizations and constraints placed externally on the arena participants by Mexican federal law (i.e., the Mexican national water law administered by CONAGUA). It is useful to point out that CONAGUA represents an institutional action arena to which the Mexican wastewater treatment action arena is interconnected at a higher hierarchical level. As with their US counterpart, the positions of the participants in the Mexican wastewater treatment action arena do not directly affect the internal deliberations of the individual wastewater arena(s). However, there are differences in opportunities and responsibilities associated with the different classifications of the OOs, as described in the Mexican national water law.

The higher federal influence in the financing of water and wastewater infrastructure projects creates a difference in the positional dynamics of the Mexican wastewater treatment action arena, as compared to its US counterpart. For example, CONAGUA has been known to place conditions of financial assistance to Mexican OOs it deems overly financially inefficient (Torres, 2019). Although some COMAPAs have wider access to financial resources than others, especially those in Mexico’s northern border region where NADB financing is available to some OOs, the majority of water and wastewater infrastructure projects financed using non-governmental resources also rely on some Mexican federal and/or state funding.

Scope Rules

Like the US wastewater treatment action arena, the first source of scope rules in the Mexican wastewater treatment action arena is the geographic boundary of the combined service areas of the seven OOs included in the Mexican wastewater treatment action arena. Under Mexican law the activities of these actors are confined to this boundary. As the wastewater effluent limitations currently enforced by CONAGUA are established by technology-based performance standards, the second source of scope rules affecting the US wastewater treatment action arena, the assimilative capacity of the Lower Rio Grande/Río Bravo, does not currently constrain the participants of the Mexican wastewater treatment action arena. That is, in terms of the discharge of wastewater, the participants in the Mexican wastewater treatment action arena are not currently constrained by the pollutant assimilative capacity of the Lower Rio Grande/Río Bravo. This situation is likely to change once the Declaratoria for the Lower Río Bravo is promulgated, as effluent limitations for participants of the Mexican wastewater treatment action arena will cease to be granted on technology-based performance standards and will instead be based on the effect of effluent discharges on ambient water quality.

Choice Rules

Like in the US wastewater treatment action arena, the choice rules applicable to the Mexican wastewater treatment action arena are imposed exogenously under Mexican federal law, which is administered by CONAGUA and enforced by PROFEPA. There are differences in the choice rules that apply to different types of OOs based on their legal classification. Mexican OOs have little control over their classification under Mexican federal law, and thus less control over the choice rules under which they operate. The choice rules for Mexican wastewater treatment action arena participants are also likely to change as a result of the promulgation of the Declaratoria for the Lower Río Bravo. As the volume and quality of treated wastewater is evaluated against the assimilative capacity of the Lower Rio Grande/Río Bravo, adjustments will likely be necessary in the choice rules governing the activities of the participants in the Mexican wastewater treatment action arena, including conditions and constraints on wastewater collection efficiency and treatment levels.

Aggregation Rules

The source of aggregation rules in the Mexican wastewater treatment action arena is a combination of internal rules that govern decision making in the local OOs and external rules, which in this case are imposed directly by the Mexican federal government and also the Mexican state of Tamaulipas. The internal rules for decision making in local COMPAPAS and JADs are similar to those used by US utility boards, although in many small Mexican COMAPAS the number of people involved in decision making regarding infrastructure projects is typically smaller and their level of accountability to the public is also generally less than that of their US counterparts.

As is the case on the US side of the watershed, many administrative rules and procedures used by CONAGUA to issue wastewater discharge permits and to prioritize and finance wastewater infrastructure projects for local OOs are specified in the operational choice rules that originate from the collective choice rules that authorize CONAGUA to develop and implement them. In the case of CONAGUA these collective choice rules are Mexican federal law. However, in addition to CONAGUA's operational choice rules, Mexican wastewater treatment action arena participants are affected directly by regulations administered and enforced by CEAT. Both sets of operational rules, federal and state, include administrative procedures for wastewater permitting as well as selection for financing of infrastructure projects under federal and state programs. The same aggregation rules that apply to participants in the US wastewater treatment action arena also apply to the participants in the Mexican wastewater treatment arena when seeking financing of infrastructure projects through NADB.

Information Rules

The sharing of information within the Mexican wastewater treatment action arena follows patterns similar to those of the US wastewater treatment action arena. Participants in the action arena may find advantages and disadvantages in sharing information with other participants or with individuals and entities outside of the action arena. The scarcer resources of smaller OOs prevent these actors from obtaining information useful in decision making. Larger OOs may have the resources to acquire or access more and higher quality information to make better informed decisions.

In a similar fashion as that of their US counterparts, participants in the Mexican wastewater treatment action arena are required to provide operational and economic information to Mexican federal and state authorities. These authorities operate in action arenas existing at higher hierarchical rule levels (e.g., the LRGWQI action arena) but are connected to the Mexican wastewater treatment action arena though their influence on the working rules of the Mexican wastewater treatment action arena. One of the ways these agencies influence the working rules of the Mexican wastewater treatment action arena is by providing access to information. As previously discussed, CONAGUA currently restricts the access to the information collected and acquired as part of the LRGWQI project. Ostensibly, this information will be made available to the participants of the Mexican wastewater treatment action arena once the Declaratoria for the Lower Río Bravo is promulgated. Information such as the location and nature of existing Mexican wastewater outfalls, the quality of water in Mexican tributaries and the expansion and upgrade plans of Mexican wastewater treatment facilities would be valuable knowledge to the participants in the Mexican (and US) wastewater treatment action arena(s).

A decision support system such as the LRGWQIDSS could provide information that could improve the decision-making capabilities of all participants in the Mexican wastewater treatment action arena.

Payoff Rules

As is the case with the US wastewater treatment action arena, the rules that affect the costs incurred and benefits received by the actors in the Mexican wastewater treatment action arena are tied to the commitments these actors make to provide adequate water and sanitation services to the communities they serve. This includes material costs as well as the administrative and engineering costs of wastewater collection and treatment, including the costs of planning for these services in the future. Costs to the participants of the Mexican wastewater treatment action arena also include the consequences of non-compliance with the other working rules of the action arena (i.e., scope rules, choice rules, etc.), including the consequences of fiscal and operational inefficiencies. To the participants of the Mexican wastewater treatment action arena, the benefits of effective and efficient provision of sanitation services are the same as those for the participants in the US wastewater treatment action arena, improved quality of life, increased economic opportunity and increased public support of local government.

The balance of costs and benefits to the participants of the Mexican wastewater treatment action arena is dependent on variables that affect the payoff rules in this arena. In the case of the US wastewater treatment action arena, these variables were largely limited to reductions in the cost of providing sanitation services. While this is also the case in the Mexican wastewater treatment action arena, the difference in operational and, especially fiscal efficiency between Mexican OOs and US utilities introduces an additional variable that could also affect the payoff rules of the participants of the Mexican wastewater treatment action arena. To be sure, an increase in efficiency would affect the payoff rules in both the United States and Mexican wastewater treatment action arenas. However, this variable would affect the payoff rules in the Mexican arena in a disproportionate manner.

Increased access to information could reduce the costs of planning and general decision making and can also increase the efficiency of wastewater collection and treatment systems. Thus, increased access to information can affect the cost-benefit balance, effectively redefining the payoff rules in the Mexican wastewater treatment action arena.

Institutional Factors Relevant to the Development of the LRGWQIDSS

Many of the contextual factors affecting the US wastewater treatment action arena also affect the Mexican wastewater treatment action arena, including depressed economic conditions, substantial geographic areas lacking centralized wastewater services, and extremely dry conditions. However, these factors are magnified in the Mexican portion of the watershed by the greater numbers of people living in the riparian areas and the higher volume of wastewater being generated by the urban communities on the Mexican side. Of particular importance is the large and dense urban population living in the city of Reynosa, which contributes the biggest share of the wastewater emanating from the Mexican side of the watershed (Table 1-11; Page 80).

A contextual factor that is magnified on the Mexican side of the watershed is the size of the riparian population receiving inadequate wastewater collection or lacking sanitation services altogether. The average fiscal and operational efficiency of Mexican OOs is lower than that of their US counterparts. With these contextual factors in mind, it stands to reason that the simulation of water quality in the Lower Rio Grande/Río Bravo would need to take into account the contributions not only of the wastewater discharged to the river from specific wastewater outfalls, but also of partially treated and untreated wastewater produced from underserved Mexican riparian populations and associated with conveyance losses in wastewater collection systems.

Following the promulgation of the Declaratoria for the Lower Rio Bravo, the participants in the Mexican wastewater treatment arena will be required to treat the wastewater they discharge to the Lower Rio Grande/Río Bravo, or one of its tributaries or contributing drains or ditches, to water quality levels that are commensurate with the assimilative capacity of the river. Initially, these new treatment levels will be communicated to existing dischargers by CONAGUA, which will have determined them from water quality simulations. However, for future planning purposes, participants in the Mexican wastewater treatment arena would benefit from having at their disposal a means to simulate the effect, on water quality in the Lower Rio Grande/Río Bravo, of proposed increases in effluent flows, or of new wastewater outfalls, using the same model of water quality used by CONAGUA. Assuming the participants in the Mexican wastewater treatment action arena will be given access to the LRGWQIDSS, it stands to reason that the system be designed to provide this capability as well as the ability to estimate the costs of options for providing and/or improving wastewater services to low income communities in their service areas.

The LRGWQIDSS should provide information that helps the actors in Mexican wastewater treatment action arena make decisions within their regulatory constraints (e.g. simulation thresholds that reflect Mexican water quality criteria and loading limits commensurate with the Declaratoria). As is the case for participants in the US wastewater treatment action arena, participants in the Mexican wastewater treatment action arena would also benefit from operational information about other wastewater dischargers, which would help each individual actor to better plan and manage their systems. As the Declaratoria will take all wastewater dischargers into account in the estimates of assimilative capacity of the river, information about US dischargers would need to be included in the LRGWQIDSS.

As with the US wastewater treatment action arena, an examination of the rules-in-use of the Mexican wastewater treatment action arena reinforces the need to design the LRGWQIDSS to provide information that helps the actors in this action arena make decisions within the Mexican regulatory constraints. The stronger financial constraints, as compared to their US counterparts, and the changes in scope rules and choice rules likely to be brought about by the promulgation of the Declaratoria for the Lower Río Bravo make the benefits of a tool such as the LRGWQIDSS a factor that could help offset negative changes in payoff rules.

The Lower Rio Grande Water Quality Initiative Action Arena

<u>The Context</u>

Section 1.0 of this dissertation (Introduction) describes the motivation of the actors, the legal backdrop, and the institutional interactions that led to the establishment of the LRGWQI. As a binational decision-making forum where decisions are made by institutional actors to "address water quality issues" in a shared transboundary water resource, the LRGWQI action arena, at least

superficially, reflects aspects of a classical IRC stakeholder forum. The physical and material conditions that concern the decision space of the LRGWQI action arena are directly related to the quality of the shared resource. Participants enter the LRGWQI forum with the explicit goal of working cooperatively to protect the resource. However, unlike classical IRC stakeholder forums, the participants in the LRGWQI action arena not only represent the interests of the resource users (i.e., local stakeholders), but also the interests of the agencies they represent, which may include interests related to national sovereignty, agency-specific legal and regulatory requirements, and strategic bureaucratic concerns. In this sense, the LRGWQI diverges from the theoretical architype of the IRC stakeholder forum, as the influence of governmental authority, or at least government oversight, is superimposed on the resource management process which, according to IRC theory, is not an optimal common pool resource management situation.

In the LRGWQI action arena, each participant's evaluation of the physical and material conditions concerning the decision space is framed by the processes each actor uses to assess the resource. These processes are based on the legal standards and regulatory procedures under which each actor operates (e.g., the federal Clean Water Act, the Texas Surface Water Quality Standards, the Ley Nacional de Aguas, the 1944 US-Mexico Water Treaty, etc.). Consequently, each actor's notion of acceptable water quality is based on self-selected standards and the processes used by the actors to determine compliance with these standards is based on each actor's regulatory procedures. This situation is not a common circumstance in archetypical IRC stakeholder forums and, in fact, presents a barrier to cooperative decision-making in transboundary water resource management. According to IRC theory, one of the goals of common pool resource management institutions is to create common understandings among stakeholders about how to manage the resource sustainably. In order to move in a direction that advances sustainability, it is advantageous for the LRGWQI action arena to seek ways to create common understandings among the participants about how to protect water quality in the Lower Rio Grande/Río Bravo. This is an important insight for developers of transboundary DSSs, as is an acknowledgement of the institutional individualities associated with the participants' assessment of the physical and material conditions concerning the decision space of the action arena.

In the discussion earlier in this chapter about contextual water resources management (Sub-section 2.1.1.3), the author mentions that implementation of water resources management rarely occurs in "blank slate" situations where no prior institutional form of management exists. In the case of the LRGWQI, a number of historic antecedents frame the initiative's efforts to protect water quality. Foremost is the cooperative relationship that has existed for over a century between the United States and Mexico with regard to the allocation of water from the Lower Rio Grande/Rio Bravo, under the 1944 US-Mexico Water Treaty. Article 3 of the treaty and Minutes 261 and 289 of the treaty compel the IBWC and CILA to cooperate to resolve sanitation issues and other problems affecting water quality in the river. The sense of responsibility the treaty confers on these two agencies, to address water quality problems in the river, coupled with local stakeholder concerns (on both sides of the border) about increasing salinity in the river motivates both sections to reach a binational agreement to protect water quality.

In addition to this antecedent, other precursor events, such as CONAGUA's decision to establish a Declaratoria for the Lower Río Bravo and the TCEQ's listing of the Rio Grande as an impaired water body, also frame the LRGWQI by identifying the factors that motivate participants beyond general protection of water quality. These precursors compel the developers of the LRGWQIDSS to ensure that the specific legal and regulatory requirements associated with these antecedents are taken into account in the design of the DSS.

In the AID framework, the purpose of exploring the attributes of the community undergirding an action arena is to identify the contextual factors, shared by the actors, that influence the cultural and normative bounds of the decision space. In the case of the LRGWQI action arena, it is difficult to conceptualize the community or communities that underly the action arena. As a forum composed of agency representatives, many of whom have never been residents of the Lower Rio Grande/Río Bravo watershed, the LRGWQI action arena is not reflective of a particular community or set of communities, as the term is used in the IAD framework. Nevertheless, as a binational group of actors, a basic community grouping applicable to the LRGWQI action arena is nationality.

As previously mentioned, it is difficult to characterize the pertinent attributes of any community, much less a country. However, it would be fair to say that issues of sovereignty play an important role in the LRGWQI action arena. That is, cooperation among participants is affected by factors associated with the difference in sovereignty of the actors; a lack of trust or respect or, simply, strategic behavior between actors of different nationalities can present potential barriers to cooperation. Some of the qualitative information acquired for this research yields helpful insights into how these attributes may affect the decision space of the LRGWQI action arena. From interviews:

> "I think historically the big issue with Mexico has been, what I call, sovereignty. This comes from when we took away 2/3 of their natural territory in the Mexican–American war. Mexicans have always been very concerned about sovereignty. Though (sic), when we tried to take some issue and shove it down their throat, they get upset."

Overcoming cooperation barriers associated with issues of sovereignty is a distinctive challenge which developers of transboundary DSSs must confront and the LRGWQI development team is no exception.

<u>The Decision Space</u>

The LRGWQI action arena participants are identified in the TOR document, which specifies, by name, the agencies participating in the US and Mexican Core Groups. The TOR also describes the operational structure of the initiative's decision-making forum and details the rules for participation in the forum. In doing so, the TOR also outlines the roles of the participating agencies, each country's "stakeholders," and other potential participants in the initiative, such as other agencies, nongovernmental organizations, and technical experts. The description of these roles effectively assigns positions to each of the participants, or potential participants, according to their respective designations in the TOR. For example, the TOR designates the US and Mexican Principal Engineers of the IBWC, or their representatives, as chairpersons of the LRGWQI. Thus, the IBWC presides over a Binational Core Group, the main decision-making body of the LRGWQI, composed of federal and state government representatives. Two additional groups, the US and Mexican Core Groups, set the decision-making agenda for the Binational Core Group. US and Mexican Core Groups ostensibly base their agenda recommendations on input from their respective stakeholders. The stakeholders, which may include local government officials or non-governmental organizations (NGOs), may participate in the Binational Core Group, but only by invitation of the Binational

Core Group and approval of the IBWC. Except for the participation of David Eaton, Ph.D., who was invited by the IBWC to participate in an advisory capacity, only representatives of the six agencies that form the US and Mexican Core groups have participated in the LRGWQI's Binational Core Group meetings.

The structure of the LRGWQI action arena creates a two-tiered decision-making process, where proposals for binational deliberation are generated by the respective national core groups. The decision-making dynamics in the national core groups is between entities operating at different hierarchical levels, whereas that of the Binational Core Group is between parties represented at one level (i.e., the national level). Differences between actors in the national core groups are expected to be worked out prior to elevating proposals to the Binational Core Group.

The LRGWQI TOR describes, only in general terms, the set of possible actions that can be linked to the outcomes described in the TOR document. The expected outcomes of the LRGWQI are also described only in general terms, namely as "significant and sustainable improvements in ambient water quality within the main stem of the Lower Rio Grande/Rio Bravo from the Falcon Reservoir to the Gulf of Mexico." The set of possible actions include those that advance the following objectives specified in the TOR:

a) Addressing current and future water quality issues of the Lower Rio Grande/Río Bravo;
b) Implementing management procedures and programs that enable affected parties to manage wastewater discharges and improve water quality conditions;
c) Evaluating current wastewater discharge infrastructure and management strategies for the potential for improving the quality of effluent discharges into the Lower Rio Grande/Río Bravo;
d) Evaluating new mechanisms and strategies for system operations that could improve ambient water quality and address border sanitation concerns;
e) Improving salinity management for return flows into the Lower Rio Grande/Río Bravo; and
f) Based on the results of the evaluations carried out, implementing programs and projects to meet these objectives as appropriate

The range of specific decisions/actions that are feasible for each participant in the LRGWQI action arena is related to the set of rules that allow and constrain the actions of each participant, and which generally dictate the manner in which the actions can be carried out. This is important knowledge for the design of a DSS, as these rules and procedures bound the decisions/actions of the participants in the LRGWQI action arena. For example, both TCEQ and CONAGUA have the authority, within their respective jurisdictions, to set surface water quality standards and to grant or deny wastewater discharge permits. Both agencies also have the responsibility of monitoring surface water quality and of taking measures to restore water quality in surface water bodies in which water quality is impaired. CONAGUA is compelled to carry out these actions by the mandate and authority granted it by the collective choice rules enacted by the Mexican federal government. The TCEQ carries out its actions following the operational rules laid out by the USEPA, which receives its mandate and authority via collective choice rules from the US federal government.

Of course, the level of control these agencies have is limited to their respective jurisdictions. For example, the TCEQ cannot use its authority to control wastewater discharges emanating from Mexico any more than CONAGUA can control wastewater discharges from the United States. Any influence either entity wishes to have on sources of pollution in foreign soil must be negotiated by international agreement. One of the barriers in reaching these types of agreements is the difference in the mandates and obligations stemming from the collective choice rules of each country. For example, the EPA delegates authority for controlling pollutant loadings from stormwater to the TCEQ, which issues TPDES permits to manage these loadings. US water quality restoration plans, such as TMDLs or watershed-based plans, must take into account pollutant loadings from stormwater. In contrast, Mexico's lack of stormwater regulations consigns CONAGUA to evaluate pollutant loadings to surface water bodies only under steady state conditions, including Declaratorias de Clasificación for surface water bodies. It should be noted that, as part of its adaptive management approach, USEPA allows the phasing of TMDLs or equivalent water quality restoration plans. That is, USEPA will suspend some of the requirements it imposes on water quality restoration plans, as long as there is a commitment by the stakeholders participating in these plans to eventually comply in full with the all USEPA requirements.

Another factor that affects decision making in the LRGWQI action arena is the information available to participants. One of the first activities of the LRGWQI's BTWG was an official exchange of data and information between the US and Mexican Partners. In 2012, technical representatives from both countries exchanged historical data compiled for the period 2000-2011. These data included geospatial, meteorological, environmental, and demographic data and also information on water and wastewater infrastructure on both sides of the river. The IBWC and TCEQ provided CONAGUA 12 years of water quality data collected quarterly by the TCEQ and IBWC at 16 water quality monitoring stations located along the Lower Rio Grande/Río Bravo and 1 tributary; a total of over 11,000 individual water quality measurements. CONAGUA, in turn, provided the LRGWQI US Partners water quality data it had collected since 2000 at 16 surface water quality stations located along the river and in 7 tributaries and contributing drains and ditches; a total of over 2,400 individual water quality measurements. Following the technical approach outlined in the Annex to the TOR, the data were reviewed and analyzed jointly by the members of the BTWG to identify data gaps. While the US members of the BTWG deemed the historical data sets adequate for model calibration, Mexican technical representatives in the BTWG insisted on the need for binational synoptic data collection efforts to collect flow and water quality data for the Declaratoria study.

An important aspect of the LRGWQI action arena is how it influences the US and Mexican wastewater treatment action arenas. Although there is no mention in the LRGWQI TOR of any specific local stakeholder, the structure of the joint cooperative process outlined in the TOR document makes reference to US and Mexican stakeholders other than the participants in the national Core Groups and the Binational Core group. The TOR document states that "Other stakeholders, which may include local government officials or non-governmental organizations (NGOs), may be invited to participate in the [Binational] Core Group." However, their participation must be approved by the Principal Engineers of the IBWC and CILA. The TOR further states that "non-governmental organizations or local government institutions may participate if invited by the [Binational] Core Group, but not as members of the US [or Mexican] Core Group[s].

The TCEQ and CONAGUA have undertaken separate efforts to involve local stakeholders in the LRGWQI. For example, the TCEQ, convened a set of meetings with local stakeholders to describe the initiative and to gather their input on issues related to water quality and wastewater infrastructure. CONAGUA conducted similar efforts with Mexican stakeholders. The TCEQ's US stakeholder outreach efforts included demonstrations of prototypes of the LRGWQIDSS to members of planning and engineering departments of local utilities, who provided invaluable input for the development of the software.

To date, however, the LRGWQI's Binational Core Group has not invited stakeholders other than those named in the TOR to participate in the LRGWQI action arena. This aspect of the LRGWQI action arena further dissociates it from classical IRC stakeholder forums, as the distance between the decision makers and the resource users is widened by the LRGWQI action arena's boundary rules-in-use and the lack of invitations to local stakeholders to participate in the arena. The influence the LRGWQI action arena has on the US and Mexican wastewater treatment action arenas is exercised through the operational choice rules administered and enforced by the TCEQ and CONAGUA, respectively. These rules are likely to change, most notably for the Mexican wastewater treatment action arenas, following the promulgation of the Declaratoria for the Lower Río Bravo. Effluent requirements for participants in the US wastewater treatment action arena may also change if, as a result of the LRGWQI, the TCEQ begins evaluating permit requests using a model or decision support system, like the LRGWQIDSS, that takes into account pollutant loading from all dischargers to the Lower Rio Grande/Río Bravo, including contributions from Mexican wastewater discharges.

The Actors

The actors in the LRGWQI are currently the representatives of the US and Mexican LRGWQI partner agencies identified in the LRGWQI TOR document (i.e., IBWC, CILA, CONAGUA, USEPA, CEAT, and TCEQ). In the US and Mexican Core Groups, these agencies are represented by mid-level managers and in the Binational Core Group, the agencies are represented by upper level managers. While, the structure of the LRGWQI action arena places the stakeholders at the top of the diagram in Figure 1-1 (Page 12), the qualitative information collected as part of this study helps to frame the actor's specific incentives for participating in the LRGWQI action arena. In addition to improving water quality in the Lower Rio Grande/Río Bravo (a goal very much in the interest of the local US stakeholders) other related and unrelated utilitarian motivations can be identified for the participation of IBWC, CILA, CONAGUA, USEPA, CEAT, and TCEQ in the LRGWQI action arena.

Concerns over increasing salinity in the Lower Rio Grande/Rio Bravo caused local stakeholders on both sides of the river to complain directly to the IBWC about this problem. From interviews:

> "For agricultural purposes, our biggest problem with water quality is salinity. And the salinity is controlled more than any other reason by the inflows into the river and most of those are controlled by how much water is diverted into the river from Mexico from the El Marin (sic) [Morillo] drain."

Agricultural stakeholders in particular, realizing that this type of problem would require binational cooperation to properly address it, appealed to the upper echelons of the IBWC for a binational solution. From Interviews:

> "So when we're talking about our issues and really talk about bi-national issues and any, uh, remedy any solution will obviously have to involve a bi-national solution, because we only have, uh, I don't want to use the word control, but we, um, we have influence over one half of that river."

For the IBWC, the LRGWQI is not just a means to address these local stakeholder concerns, thereby relieving some of the pressure placed on it by these complaints but is also a means to achieve a success story with the IBWC as a major part of the solution.

As small federal agencies, the resources available to the IBWC and CILA are primarily diplomatic. The two sections possess the ability to create a binational forum to address water problems using protocols established under the 1944 US-Mexico Water Treaty. Another important resource of the IBWC is the information it routinely gathers on flow and water quality in the river, including its tributaries on both sides of the watershed. This information is critical to both sections of the IBWC for decision making and, through the long relationship between the IBWC and CILA, a system of information sharing has evolved that benefits both agencies. Decision making strategies for these entities tend to result from a need to balance their obligations to address stakeholder's concerns with their obligations under the 1944 US-Mexico Water Treaty, with this balance strongly affected by the domestic politics of each nations. For this reason, the

USIBWC and CILA often play the roles of brokers of agreements between US and Mexican stakeholders.

The interests of the USEPA and the TCEQ are aligned through the provisions of the federal Clean Water Act. Although addressing water quality problems in the Lower Rio Grande/Río Bravo is a strong motivating factor for both agencies, the river's status as a transboundary water body and the abundance of binational information indicating large pollutant contributions from Mexico cause local US stakeholders to direct their complaints about water quality in the river more toward the IBWC. Thus, much of the motivation for TCEQ and EPA to participate in the LRGWQI is the delisting of Segment 2302 from the state's list of impaired water bodies and the reduction of "concerns" in the state's Integrated Report of Surface Water Quality. There are economic and bureaucratic costs to both agencies when water bodies linger on these lists/reports and economic and bureaucratic benefits gained when water bodies are removed from the lists and/or appear favorably in assessment reports. Under the federal Clean Water Act, the EPA is compelled to ensure states address impaired water bodies through the development of TMDLs or other comparable restoration mechanism.

In 1995, the USEPA introduced the concept of watershed-based plans (WBPs). Unlike TMDLs, which characteristically focus on a water quality impairment, WBPs are comprehensive water quality restoration plans which holistically address the health of entire watersheds. The development of TMDLs and WBPs typically opens the door to federal programs designed to fund water quality restoration efforts. In 2007, the TCEQ completed the development of a WBP for the Arroyo Colorado; as of 2019, more than $4.8 million in federal grant funding has been spent on water quality restoration projects in the Arroyo Colorado watershed (Cawthon, Personal Communication, June 1, 2019). Most of the funding comes from federal programs dedicated to the implementation of the Clean Water Act that are awarded to the state. Some of this funding can be used to develop the plans themselves.

In addition to substantial financial resources, mainly through access to federal funding, the TCEQ also has at its disposal a comprehensive database of water quality information, including water, sediment and fish tissue data for over 1,800 surface water quality monitoring stations on 1,407 water bodies in the state, including 16 active stations in the Lower Rio Grande/Río Bravo. The TCEQ also collects information about water diversions from its major rivers, including the Lower Rio Grande, in its Rio Grande Water Master database. The USEPA's ICIS database contains daily average effluent flow and pollutant concentrations for all permitted wastewater treatment facilities in the United States, including the facilities with outfalls to the Lower Rio Grande/Río Bravo. The decision-making strategies of the TCEQ and the USEPA are influenced by the federal-state relationship that exists between the two agencies. The familiar carrot-and-stick approach used by US federal regulatory agencies to incentivize states to collect data manifests itself in the granting or withholding of federal dollars to the TCEQ by the USEPA, which influences the state agency's decision making. USEPA approval or disapproval of state actions, such as the lists of impaired water bodies or water quality management plans, are strong incentives for TCEQ decision making, as they are tied to federal funding and also to the conditions for federal delegation of permitting programs to the state.

One of the largest and most powerful Mexican federal agencies, CONAGUA holds significant financial resources; CONAGUA's annual budget was $1.2 billion in 2005. CONAGUA also manages several important national databases with information on water quantity and water quality, including some ten years of semi-annual water quality data collected at 16 sites on the Lower Río Bravo and in 7 tributaries and contributing drains and ditches. In addition to this information, CONAGUA has access to effluent flow quality data collected by its wastewater permittees and by state environmental commissions (CEAs). Because of its wide-ranging national authority and resources, CONAGUA occupies an outsized position among the Mexican LRGWQI Partners. However, CONAGUA's decision to develop a Declaratoria in the Lower Rio Bravo means it must rely on CILA to facilitate the acquisition of relevant information. It should be noted that, although CONAGUA counts with resources of a magnitude not equaled among other Mexican federal agencies, most of CONAGUA's budget goes to fund the myriad functions under its responsibility. For special projects such as Declaratorias de Clasificación, CONAGUA often seeks grant funding from Mexican government grant sources, such as CONACYT.

The balance of costs and benefits of CONAGUA's participation in the LRGWQI action arena, and of the decisions CONAGUA makes in this arena, are connected to the success of the Declaratoria for the Lower Río Bravo. The TCEQ and the USEPA enter the LRGWQI having fulfilled important requirements under the Clean Water Act, such as designating beneficial uses, developing standards and criteria, and developing water quality-based wastewater effluent limits. CONAGUA is relying on the Declaratoria to fulfill similar requirements under the Ley Nacional de Aguas; the most important of these requirements being the development of water quality-based effluent limits.

CEAT is included in the LRGWQI TOR by name as one of the Mexican LRGWQI Partner agencies and is therefore a participant in the LRGWQI action arena. With an annual budget of just over $35.8 million (in 2010), CEAT is one of the most active CEAs in Mexico. CEAT operates under the State of Tamaulipas' Ley de Aguas del Estado de Tamaulipas, which is described in the CEAT web site as a state law "assisting" (ley coadyuvadora) the federal Ley Nacional de Aguas. While CEAT has some operational authority over OOs in Tamaulipas, the bulk of the regulatory authority over these organizations rests with CONAGUA. The role of CEAT is that of facilitator of water and wastewater infrastructure in the state, while also acting to increase the efficiency of the state's OOs. CEAT puts its substantial technical resources to use on engineering and planning efforts. The information collected by the agency is often relied upon by CONAGUA and the state's OOs to prioritize the expenditures of federal infrastructure financing under the APAZU, PROSSAPyS, and PROTAR programs. CEAT also has a small state budget that it uses to finance small scale infrastructure projects.

CEAT maintains a database, Sistema Estatal de Información, which contains, for each municipio and region of the state of Tamaulipas, the current status of the availability of water, the volumes used for each of the uses, as well as the operational status of OOs and user associations within each CONAGUA irrigation district within Tamaulipas. Although lacking considerably in regulatory authority, as compared to the TCEQ, CEAT enjoys a significant amount of autonomy with regard to decision making, as CEAS are not under direct regulatory control by CONAGUA unless they provide water or wastewater services. Even though CEAT does not provide those services in the Rio Grande/Río Bravo watershed, it is likely that CEAT would find a decision support tool such as the LRGWQIDSS useful especially following the promulgation of the Declaratoria, as CEAT is and will be a key player in water and wastewater infrastructure planning in the Lower Rio Grande/Río Bravo watershed. As is the case for OOs in the watershed, it is conceivable that CEAT could reduce the costs of planning using the LRGWQIDSS.

The Working Rules

The analysis of the working rules of the LRGWQI action arena presented in this sub-section, while focusing primarily on identifying and characterizing codified rules, also identifies a number of unenforced rules and uncodified, informal, rules-in-use.

Boundary Rules

Under the LRGWQI TOR, the current participants in the main decision-making body of the LRGWQI, the Binational Core Group (USIBWC, CILA, CONAGUA, USEPA, TCEQ and CEAT) have the discretion to invite other actors to participate in the LRGWQI action arena, but the participation of the invitees is conditioned on the approval of their participation by the Principal Engineers of the IBWC. The other LRGWQI groups are the US and Mexican Core Groups, which are the participant groups that set the agenda for the Binational Core Group. The TOR stipulates that no stakeholders other than those specified in the TOR may participate in the US and Mexican Core Groups (page 5 of the LRGWQI TOR). This is, ostensibly because the US and Mexican Core Groups are designed to receive input separately from their stakeholders and are expected to advance the interests of these stakeholders through the groups' agenda-setting capabilities.

This institutional structure gives federal and state agencies the ability to identify, filter and consider their own stakeholders' input and it effectively gives the IBWC the authority to regulate the participation of stakeholders in the LRGWQI action arena other than those actors currently in the US and Mexican Core Groups. As previously mentioned, the boundary rules and operational policy regarding stakeholder interactions of the LRGWQI action arena present a barrier to the direct involvement of local stakeholders in decision making within the arena. These rules and policy also make it difficult for developers of a DSS to properly design a system for use by stakeholders other than those currently participating in the LRGWQI action arena.

The TOR does not specify the exit rules for the LRGWQI action arena and it is difficult to envision a circumstance or condition in which any of the current participants would be removed from the LRGWQI action arena involuntarily. However, given the authority conferred the IBWC to approve or disapprove the participation of stakeholders other than the current participants in the LRGWQIDSS, which are constitutionally entitled to participate as codified in the TOR, the exit rules in the TOR hinge on the IBWC's approval authority.

Position Rules

The LRGWQI TOR creates three positional levels in the LRGWQI action arena. At the highest level, the IBWC presides over the action arena, with discretion over what actors participate in the main decision-making body of the LRGWQI, the Binational Core Group. The IBWC also has approval authority over the choice of technical advisors to the Binational Core Group (LRGWQI TOR, Page 4) and also schedules, convenes and leads the proceedings of the LRGWQI action arena. At the middle positional level, the US Core Group, composed of the USEPA and TCEQ, and Mexican Core Group, composed of CONAGUA and CEAT, have the ability to set the agenda for the Binational Core Group, which is ostensibly based on the input received from local stakeholders who occupy the most basic level of participation in the LRGWQI action arena.

Unless invited to participate by the LRGWQI's Binational Core Group, and their participation approved by the IBWC, local stakeholders must rely on the advocacy of their representatives in their respective national Core Group and Binational Core Group to advance their issues in the LRGWQI action arena.

Scope Rules

The scope of the LRGWQI is described in general terms in the main TOR document. The TOR describes the subject of the initiative only as "the Lower Rio Grande/Rio Bravo" and it outlines the six general objectives previously listed in the portion of this sub-section titled "Decision Space." The scope of the LRGWQI is defined in more detail in the Annex to the TOR titled "The Lower Rio Grande/Rio Bravo Water Quality Initiative Pilot Project," in which: (1) the geographic extent of the Lower Rio Grande/Río Bravo is detailed (i.e., the Lower Rio Grande/Rio Bravo from below Falcon Dam to the Gulf of Mexico); (2) the water quality issues to be addressed are specified (i.e., fecal bacteria and salinity); (3) the technical approach that is to be followed is described; (4) the mechanism for identifying feasible options to improve water quality is outlined; (5) a commitment is made to develop a binational plan to restore and protect water quality; (6) options are described for institutionalizing and implementing the plan; (7) a schedule is proposed for developing and completing the plan; and (8) a commitment is made to sustain the effort beyond the development and implementation of the initial plan (Appendix B).

Despite the specificity in scope found in the Annex to the TOR, the potential scope rules represented by several of the specifications in the Annex are not actually enforceable and do not confine participant's activities. For example, despite a stated focus on fecal bacteria and salinity, and a determination by the BTWG that enough historical data was available to calibrate a water quality model of the Lower Rio Grande/Río Bravo, the LRGWQI Mexican Partners insisted on conducting binational synoptic surveys of water quality in the river that included some 105 water quality parameters. The purpose of the data collection effort proposed by IMTA and promoted by CONAGUA was to fulfill requirements of the Declaratoria for the Lower Rio Bravo. Another specification of scope in the Annex to the TOR that did not, in the end, constrain the actors was the schedule for development of the binational plan, which as of this writing, is still in development. With the exception of the geographic limits and the focus on improving water quality in the Lower Rio Grande/Río Bravo, the scope rules proposed in the Annex to the TOR have not been enforced in the LRGWQI action arena.

Sovereignty is an important scope rule of the LRGWQI action arena that is not codified in the TOR. It is understood among the participants of the LRGWQI that the limit of the jurisdictions of the participants in the LRGWQI action arena includes the international border.

Aggregation Rules

No aggregation rules for the core groups within the LRGWQI are defined in the LRGWQI TOR. The TOR document states only that "The co-chairing Principal Engineers will make every effort possible to achieve a consensus among the Binational Core Group for all those activities under consideration" (page 6 of the LRGWQI TOR). Neither the TOR document nor the Annex to the TOR describe how this consensus is to be achieved and the general (International Boundary and Water) commission process outlined in the TOR does not describe the procedures of the "Commission Joint Work" normally followed by the IBWC when addressing binational issues. The casual mention in the TOR of the US Department of State and the Mexican Foreign Ministry implies that the IBWC will elevate matters for which consensus cannot be reached to action arenas that exist at higher hierarchical political and diplomatic levels. However, unless an issue or dispute is deemed critical to the mission of the Commission, IBWC commissioners are generally reluctant to elevate issues to action arenas above that of the IBWC.

Information Rules

No restrictions regarding the internal sharing of information among the actors named as participants of the LRGWQI action arena are apparent in the LRGWQI TOR. In fact, formal and informal exchanges of information are a common occurrence in the LRGWQI forum, especially within the BTWG. In general, there are few documented instances of restrictions in the exchange of data or of the withholding of information among the participants of the LRGWQI action arena. However, the TOR specifies that the IBWC must approve the invitation of technical experts to advise the Binational Core Group. The TOR also states that the two sections of the IBWC are official repositories of records generated by the national or Binational Core Groups and work groups, which gives the IBWC the sole discretion to release or not release information compiled and generated as part of the Initiative. Furthermore, the Mexican LRGWQI Partner agencies' insistence that data collected as part of the LRGWQI efforts not be shared with US or Mexican stakeholders prior to the promulgation of the Declaratoria for Lower Río Bravo currently limits the ability of US and Mexican Core Group members to interact with their respective stakeholders, and thereby diminishes the role of these stakeholders in decision making in the LRGWQI action arena. While these information rules are subject to change in the near future, there are currently no indications as to what the extent of those changes will be.

Coupled with the operational policy against the interaction of US agency representatives with Mexican stakeholders, the insistence that data collected as part of the LRGWQI efforts not be shared with either US or Mexican stakeholders presents a serious barrier to the proper development of the LRGWQIDSS.

Payoff Rules

The working rules of the LRGWQI action arena appear to create asymmetries in the payoff rules for current and potential participants in the arena. An analysis of the boundary, position, and information rules of the LRGWQI action arena show a clear advantage for the IBWC, giving it approval authority over participation, partial control over the flow of information, and almost complete control over the conduct of the proceedings of the action arena. This situation reduces the risks of negative outcomes to the IBWC and enhances the potential benefits to the IBWC of producing an agreement designed to improve water quality in the Lower Rio Grande/Río Bravo. CONAGUA is also a beneficiary of the payoff rules of the LRGWQI action arena. Although not codified in the TOR, the agreement by the participants of the LRGWQI action arena not to share data collected as part of the LRGWQI efforts with US or Mexican stakeholders and the other participants' deference to CONAGUA's opposition to interactions between US agency representatives and Mexican stakeholders creates two informal rules that minimize risks of interference with CONAGUA's objectives and enhance CONAGUA's opportunity to achieve its goal of developing a Declaratoria for the Río Bravo. The formal information rules also advance this objective by providing CONAGUA access to information about the US portion of the Lower Rio Grande/Río Bravo watershed, including pollutant loads, surface water flow and water quality; information it needs for the Declaratoria study. The technical work on the Declaratoria was completed in 2017 and the Declaratoria is expected to be promulgated in 2019.

The TCEQ also benefits from the information rules of the LRGWQI, having received information about pollutant loads, surface water flow and water quality in the Mexican portion of the Lower Rio Grande/Río Bravo watershed; information to which it would not normally have had access. However, absent a binational WBP institutionalized as a part of the 1944 US-Mexico Water Treaty, the benefit to the TCEQ and USEPA is only marginal, unless data sharing with CONAGUA continues. It should be noted that the TOR document, as well as the Annex to the TOR, make it clear that the LRGWQI is "intended to serve as a pilot project for the development of binational mechanisms to improve water quality throughout the Rio Grande/Rio Bravo." In view of this, the working rules for the LRGWQI action arena can be considered to still be in development, including the scope rules, information rules and, most importantly, the payoff rules for each participant.

Institutional Factors Relevant to the Development of the LRGWQIDSS

The physical and material conditions that concern the decision space of the LRGWQI action arena are directly related to the quality of the shared resource (i.e., water quality in the Lower Rio Grande/Río Bravo). Although the participants enter the LRGWQI forum with the goal of working cooperatively to protect the resource, the means by which the different actors assess these conditions are based on different legal standards and regulatory procedures. This presents a serious barrier to cooperation that is unique to transboundary settings, where national sovereignty is an important contextual factor affecting the decision space of stakeholder action arenas. The literature on transboundary agreements that involve water quality shows that much effort and time can be spent on efforts to harmonize water quality standards and that these efforts are not necessarily a prerequisite for cooperation on transboundary water quality protection (Schmueli, 1997).

This notion is reinforced by other qualitative information gathered for this dissertation. From interviews:

> “And so if we say, this is the way we do things: we have these surface water quality standards, all you have to do is adopt them – and everything will be fine – we are doing the same sort of thing. So, if we don’t do that; if we say, this is the way we do things, how do you do things? And we work together to improve our respective standards or try to meet our standards. We’re not going to say we’re going to adopt yours, you’re going to adopt ours, I think that’s what does it. When we tell them, you gotta do what we say, and do it from the barrel of a gun, that’s when things don’t work.”

> “If we can just come to this agreement to say, we are going to do things a certain way, you guys are going to do things a certain way and lets just work towards progress”

> “But we are also recognizing that loads from the river enter from both sides and we need to respect the sovereignty of both countries. And that’s where the most critical work becomes, how is it that we find a way to make that happen? And we have a partner project that we’re working on for the lower Valley where we would assess the load that each country is providing below Falcon to the Rio Grande, the water quality impacts and impairments that are associated with that loading, and what is it that each country could do under their own regulations to be able to go forward and try to address and mitigate the impairments.”

Case studies of other transboundary water quality agreements show that fostering a common understanding of the physical and material conditions of the resource can be accomplished successfully in an incremental manner. For example, consider the case study for the Danube River Basin in which a common understanding of water quality among riparian nations evolved over time. A first step in creating this common understanding is cooperation at basic levels under the existing national standards and criteria. In the case of the LRGWQI action arena, even this approach is complicated by CONAGUA’s efforts to develop the Declaratoria for the Lower Río Bravo. The Declaratoria effort represents a transition in Mexico’s understanding of the physical and material conditions of the Lower Rio Grande/ Río Bravo. Since the decision-making ability of Mexican LRGWQI action arena participants depends on this understanding, any decision support tool designed for their use must include standards and criteria commensurate with the Declaratoria. So, the LRGWQIDSS, in addition to including the standards and criteria needed by the US decision makers, must also include Declaratoria-compatible criteria.

Analysis of the decision space of the LRGWQI action arena leads to an examination of the set of possible actions that can be linked to outcomes. Although, the expected outcomes of the LRGWQI are described only in general terms in the TOR, this general outcome information confines the set of possible actions the actors can undertake. The LRGWQIDSS ought to include the ability to link a set of potential actions to these general outcomes (e.g., increase in provision of wastewater services, improvements in wastewater collection, conveyance and treatment, increase in the use of agricultural practices that minimize saline return flows, diversion of saline irrigation return flows, etc.). As funding constrains the range of potential actions, the LRGWQIDSS ought to be able to assess the financial feasibility of the potential actions. Any link between potential actions and outcomes ought to take into account the constraints under which each actor operates and, in the case of the LRGWQI action arena, also the regulatory processes of each participant. An in-depth analysis of these processes was instrumental in the development of the LRGWQIDSS, which is presented in Chapter 3.

Another subject of analysis in the decision space of the LRGWQI action arena is the availability of information, which was also assessed in the analysis of its actors and of its working rules. While a conclusion of the analysis is that the participants of the action arena had ample access to existing information from US and Mexican sources and that US participants felt the existing data was adequate for the calibration of a water quality model to assess the assimilative capacity of the Lower Rio Grande/Río Bravo, the Mexican participants displayed a preference for collecting binational synoptic data for use in the water quality model. This preference is a manifestation of both, the regulatory processes that influence the Mexican participants and the contextual influence of sovereignty on the Mexican actors. Accordingly, the successful design of the LRGWQIDSS is dependent on its ability to incorporate all data pertinent to the decision-making process of the LRGWQI action arena.

Understanding how the internal and external organizational constraints that affect a decision domain can serve to enhance the use and longevity of EDSSs (McIntosh et al., 2011). The knowledge gained from an analysis of the rules enabling and constraining the actions of the participants of the LRGWQI action arena, and of the processes by which the actors in that arena can carry out these actions, not only enhances efforts to design a transboundary EDSS tailored to the LRGWQI but can identify opportunities to institutionalize its use. Chapter 3 describes in more detail how such knowledge was used to design the LRGWQIDSS as an institutional tool.

CHAPTER 3: THE LRGWQIDSS: DECISION SUPPORT TOOL DEVELOPMENT

3.1 LRGWQIDSS Design

3.1.1 EVOLUTION OF LRGWQIDSS DEVELOPMENT

In addition to the six general objectives stated in the LRGWQI TOR, the Annex to the TOR cites, as a specific goal of the Initiative, the identification of potential feasible pollution prevention and control options that will result in the improvement of the water quality in the Lower Rio Grande/Rio Bravo (Appendix B). The Annex to the TOR also specifies the technical approach for achieving this goal, outlining a set of four technical tasks that include: (1) historical data review; (2) identification of data gaps; (3) data collection; and (4) data analysis and modeling (Appendix B). Over the three-year period that followed the formation of the LRGWQI's BTWG in September 2013, the participants of the BTWG developed detailed plans and technical procedures for accomplishing the technical tasks outlined in the Annex to the TOR. During that period of binational technical cooperation, the author, representing the TCEQ in the BTWG, proposed the development of a decision support system to aid the participants of the BTWG and members of the Binational Core Group in decision making associated with the identification of potential feasible pollution prevention and control options. The author's proposal was accepted by members of the BTWG in October 2013. Following best practices for DSS design and development, the author's proposal included the development of scoping and system requirement documents for the LRGWQIDSS.

In 2013, the TCEQ authorized the author to submit a Proposal for Grant Activities (PGA) to the University of Texas at Austin's Bureau of Economic Geology (UT-BEG) for the development of a System Design Description and System Requirement Specifications for the LRGWQIDSS. In November 2013, the TCEQ approved a Grant Activities Description (GAD) authorizing UT-BEG to develop the Description and Specifications requested under the PGA for the LRGWQIDSS. The GAD was funded through the CIAP grant awarded to the TCEQ by USFWS for the LRGWQI. Dr. Alex Sun was named the UT-BEG Project Manager for the GAD. The author had previously collaborated with Dr. Sun on a project to develop an EDSS for the Arroyo Colorado (Sun, Miranda

& Xu, 2014). The final System Requirement Specifications (Appendix D) and System Design Description (Appendix E) were completed in December 2013.

3.1.1.1 Functional Requirements of the LRGWQIDSS

The System Requirements Specifications document defines the purpose of the LRGWQIDSS as "improve[ing] partner access to critical data and facilitate[ing] use of the water quality model developed by the partner agencies." The document further states that "The users will use the DSS to examine the effect of different wastewater management scenarios on instream water quality." The System Requirements Specifications document defines the geographic scope of the LRGWQIDSS in terms of the assessment unit designations given by the TCEQ and the names of Mexican water bodies as they are named in the BEHI hydrography layer:

- Rio Grande Tidal, Segment 2301 – Assessment Units 2301_01, 2301_02
- Rio Grande below Falcon Reservoir, Segment 2302 – Assessment Units 2302_01, 2302_02, 2302_03, 2302_04, 2302_05, 2302_06, 2302_07
- Arroyo Los Olmos, Segment 2302A (unclassified water body) – Assessment Unit 2302A_01
- Various Mexican tributaries, arroyos and drains that contribute flow to Segments 2301 and 2302, including (but not limited to), Rio San Juan, Rio Alamo, Puertecitos Drain, Rancherías Drain, El Morillo Drain, and Anhelo Drain"

The System Requirements Specifications document for the LRGWQIDSS describes the intended users of the LRGWQIDSS as the "binational group of stakeholders involved with LRGWQI project," including:

- International Boundary and Water Commission – US Section (IBWC)
- Comisión Internacional de Límites y Agua (CILA)
- US Environmental Protection Agency (EPA)
- Comisión Nacional del Agua (CONAGUA)
- Texas Commission on Environmental Quality (TCEQ)
- Comisión Estatal del Agua de Tamaulipas (CEAT)

- Border Environmental Cooperation Commission (BECC)
- Local US and Mexican municipal and county governments

Although the BECC is neither a participant in the LRGWQI's national Core Groups nor in the Binational Core Group and did not officially participate in the LRGWQI's BTWG, it was included in this list of "users" of the LRGWQIDSS because it is mentioned by name in the LRGWQI TOR.

The decisional framework and general functionality of the LRGWQIDSS are based on the six general objectives stated in the LRGWQI TOR and the project goal, cited in the Annex to the TOR, of identifying "potential feasible pollution prevention and control options." Therefore, the System Requirements Specifications states

> "The DSS will help stakeholders examine options for improving instream water quality. Examples of such options may include (a) emplacement of infrastructures (e.g., installation of collection lines and lift stations, repair of existing collection system components such as broken collection lines and leaking lift stations); (b) non-urban best management practices (e.g., keeping livestock and wildlife away from ditches, tributaries, or the river itself)."

The conceptual design of the LRGWQIDSS was intended to facilitate the simulation and evaluation of scenarios in which these activities are implemented, thereby facilitating and accelerating decision making by system users. This is stated in the System Requirements Specifications document as the "main scope" of the LRGWQIDSS: "The main scope of the DSS is to provide necessary software tools with graphic user interface (GUI) for LRGWQI partners to (a) Develop nonpoint source loading scenarios (b) Perform computer simulations of water quality and (c) Visualize modeling outputs for each scenario."

To further describe "scenarios" assessed using the LRGWQI, the System Requirements Specifications document states that a "*scenario* may be created to model the effect of improvements in urban collection infrastructures such as the installment of wastewater treatment facilities or other infrastructures along Rio Grande/Río Bravo that can potentially improve water quality in the Lower Rio Grande/Río Bravo. Other examples may include installation of collection lines and lift stations, repair of existing collection system components, such as broken collection lines and leaking lift stations. Scenarios can also be created to model the effect of non-urban best management practices, such as keeping livestock and wildlife away from ditches, tributaries or the river itself." The net effect of the scenarios described in the System Requirements Specifications document is to alter the point and/or nonpoint source loading rates of specific pollutants at specific locations on the Lower Rio Grande/Río Bravo. The System Requirements Specifications document describes the information needed for in-stream water quality simulation when creating a scenario as:

(a) Pollutant loading rate (or changes in loading rate) due to each individual control action or management measure), for example,

   Ammonia, nitrate, and organic nitrogen loading rates

   Phosphorous loading rates

   Bacteria (mainly fecal coliform) loading rates

   Dissolved and suspended solids loading rates

(b) Pollutant Sources:

   Irrigation return flow volumes

   Population served by public sewage system

   Population incompletely served by public sewage system

(c) Sub-basin-specific collection system infrastructure failure rate

The System Requirements Specifications document describes the different categories of pollutant sources of human waste, stating that:

> "Loading due to human waste is divided into four types of waste treatment (treated sewage, partially treated sewage, untreated sewage, and other) and two types of communities (rural and urban). In theory, a household that has access to a public sewer system does not pollute rivers or stream beyond what is permitted by the regulating entity. Households with septic systems are assumed to pollute only when the septic system fails; only septic systems near rivers or streams or their tributaries are assumed to pollute (a riparian corridor or buffer around pertinent rivers or streams or their tributaries will be used). Populations lacking any sewage treatment are assumed to contribute waste directly to the river if they live within the riparian corridor of a relevant river, stream or tributary."

The System Requirements Specifications document stipulates that the methods for estimating pollutant loading rates, would use information from Lynch (2012). However, Lynch (2012) addresses only human and animal pollutant sources. Therefore, the methods for estimating pollutant loading rates from other important sources, such as dissolved solids from irrigation return flows were addressed in the System Requirements Specifications document by stating that these loadings would be estimated based on user specified parameters. As the development of the LRGWQIDSS progressed and additional stakeholder input was received, it became clear that the loadings of pollutants from nonpoint sources were best processed by separate modules within the DSS, each with its own set of inputs and pollutant loading estimation method. A more detailed description of the design of the LRGWQI is provided in Sub-section 3.1.1.5 and in Section 3.2 of this chapter.

As discussed in Sub-section 2.4.2.1, (Preface to Sub-section 2.4.2, Institutional Analysis and the LRGWQIDSS), by necessity the DSS was designed to be a standalone application to be downloaded from a file transfer protocol site (ftp) site and deployed on a Microsoft Windows-based operating system. The final product was to be a self-contained installation file with all necessary components included. It was developed using open source software and packaged using a Python-based graphical user interphase (GUI). Although the Python programming language is platform independent, the development team tested the functionalities of the DSS only on Microsoft Windows Operating Systems. It should be noted that the LRGWQIDSS development team is exploring options for converting the LRGWQIDSS into a web-based application, which the author considers an important step in increasing the functionality of the LRGWQIDSS. However, under the scope of the current effort, the LRGWQIDSS is designed to be distributed as a self-extracting Microsoft Windows Operating System-based executable.

3.1.1.2 Model Selection

The importance of the role of models in DSSs was discussed in detail in Sub-section 2.2.1.5 (The Role of Models). Because predictive models provide decision makers the ability to, at least, formulate educated guesses about the outcomes of their decisions, models are considered fundamental components of most decision support tools. Modeling is mentioned, in the Annex to the LRGWQI TOR, as one of the four main tasks in the technical approach of the Initiative. It therefore follows that the principal model used for decision making in the action arenas associated with the LRGWQI be a central component of the LRGWQIDSS. One of the first major decisions of the BTWG was the choice of models to be used in the LRGWQI.

The eventual choice of modeling software used by the LRGWQI was the result of weeks of deliberations by the members of the BTWG. During those deliberations, the LRGWQI US Partners made a series of proposals that were based partly on the institutional analysis conducted by the author and his collaborators at the UT LBJ School of Public Affairs. In November of 2013, the BTWG unanimously approved the use of the LA-QUAL surface water quality simulation software for use in the LRGWQI. LA-QUAL was the water quality modeling software proposed by the TCEQ in the final proposal submitted by the LRGWQI US Partners to the BTWG. The following Sub-section describes how the qualitative knowledge obtained by the author and his co-researchers at the UT LBJ School of Public Affairs, and the associated institutional analysis conducted by the author, was used to develop the final LRGWQI US Partner modeling software proposal to the BTWG.

INSTITUTIONAL ANALYSIS AND MODEL SELECTION

The examination of the context, decision space, actors, and working rules of the LRGWQI action arena and the US and Mexican wastewater treatment action arenas detailed in Chapter 2 were instrumental in providing insight and guidance to the LRGWQI US Partners during their development of model selection proposals to the BTWG. The analysis of the components of the IAD framework were used to guide the process that culminated in the choice of LA-QUAL as the modeling software proposed by the TCEQ and its US partners and accepted by the participants of the BTWG.

Insights Provided by the Analysis of Context

As discussed in Sub-section 2.4.2.3, the institutional actors' assessment of the physical and material conditions of the resource are based on the rules and procedures under which each actor operates. In the case of the LRGWQI, the differences in collective choice and operational choice rules between USEPA/TCEQ, on the US side, and CONAGUA, on the Mexican side, present a barrier to cooperative decision-making. CONAGUA's insistence on using a steady state water quality model to determine assimilative capacity of the Lower Río Bravo as part of their efforts to develop the Declaratoria is based on the lack of stormwater regulations under Mexican collective choice rules. However, this insistence runs counter to the USEPA's requirement that TMDLs and WBPs take stormwater pollutant loadings into account, which under typical circumstances would require a dynamic watershed modeling approach. However, under its adaptive management approach, USEPA will allow the phasing of water quality restoration efforts such as WBPs.

This insight opened a negotiation path in the LRGWQI in which members of the BTWG presented to their respective representatives in the national Core Groups a trade off. The US participants in the LRGWQI action arena were presented with the prospect of approving the use of a steady state model to assess the assimilative capacity of the Lower Rio Grande in return for a commitment on the part of the Mexican participants to assess pollutant loadings from stormwater in the future. While such a commitment had the potential to mitigate USEPA opposition to using a steady state model for the current effort, the commitment did not mitigate the USIBWC's concern over how the use of a steady state model would affect the investigation of dissolved solids loads from Mexican irrigation return flows, one of the historic antecedents compelling the USIBWC to establish the LRGWQI. After deliberations within the US and Mexican Core groups CONAGUA signaled that it would be willing to commit to eventually assess pollutant loadings from stormwater under a separate effort. Also, IMTA committed to developing separate steady state models covering a range of flows, including "wet weather-related" flows. The outcome of these deliberations was an acceptance, by all participants in the LRGWQI, of the use of a steady state model for the simulation of water quality in the Lower Rio Grande/Rio Bravo as part of the LRGWQI.

Insights Provided by the Analysis of the Actors

The elimination of dynamic water quality models from consideration narrowed the realm of modeling choices to steady state models. An appealing category of steady state models that immediately came under consideration by the BTWG is the QUAL family of models. This is because these models are currently used as part of the decision-making strategies of several of the participants. As previously mentioned, the interests of the USEPA and the TCEQ are aligned through their regulatory relationship under the provisions of the federal Clean Water Act. Unlike water quality restoration efforts, such as TMDLs and WBPs, routine evaluations of wastewater discharge permit requests under the TCEQ's TPDES program are assessed (i.e., simulated) under critical low flow conditions. Critical condition analysis is needed because the capacity of the receiving water body to assimilate point source pollutant discharges is at its lowest under critical low flow conditions. The TCEQ's permitting procedures, including the determination of assimilative capacity for the Lower Rio Grande described in the MOA between the TCEQ and USEPA, are part of the TCEQ's Water Quality Management Plan (WQMP), which must be approved quarterly by the USEPA. To conduct these routine permit reviews, the TCEQ uses the QUAL-TX modeling software, which is a one-dimensional, steady state surface water quality modeling software of the QUAL family of water quality modeling tools. In 2013, the version of QUAL-TX used by the TCEQ was version 3.4, which could be run on a windows operating system using the "command" DOS simulation prompt.

In Texas, wastewater discharge permits must be acquired by utilities during the facility planning phase of infrastructure projects. The TWDB and the USDA's Rural Development Office (USDA-RD) require these permits be issued prior to the approval of project financing. Permit reviews by the TCEQ often involve the use of the QUAL-TX model. In addition to state requirements, the North American Agreement on Environmental Cooperation (NAAEC) agreement requires the BECC (now part of NADB) to submit Environmental Information Documents (EIDs) detailing infrastructure project plans to the TCEQ for review prior to project certification. The EID documents often contain QUAL-TX modeling results showing how effluent flows and concentrations proposed for projects involving wastewater treatment facilities affect surface water quality.

As part of its decision-making strategies, CONAGUA uses procedures similar to those used by the TCEQ to determine the capacity of streams to assimilate pollutants from point sources. For this purpose, CONAGUA routinely uses QUAL2E, which is also a one-dimensional, steady state surface water quality modeling software of the QUAL family. QUAL2E uses many of the same deterministic equations used in QUAL-TX. QUAL2E is largely considered a legacy water quality modeling software tool in the United States, as it is one of the first generations of models to evolve from the QUAL-I code, originally developed in 1970 by the Texas Water Development Board in collaboration with Frank D. Masch & Associates. In fact, in 2005, the USEPA's Office of Science and Technology (OST) stopped supporting QUAL2E, opting instead to distribute and support more advanced versions of the QUAL-based modeling tool, such as QUAL2K. For this reason, USEPA was reluctant to use QUAL2E as the principal modeling tool for the LRGWQI. It should be noted that, despite the fact that the TCEQ routinely uses QUAL-TX to assess permit requests, the USEPA was also reluctant to allow the use of QUAL-TX as the principal modeling tool for the LRGWQI for the same reason (i.e., QUAL-TX is also not supported by OST).

The most advanced version of the QUAL-based modeling tools, QUAL2K incorporates a semi-dynamic dissolved oxygen feature that is capable of simulating dissolved oxygen over a diurnal period. Although this feature did not disqualify it from consideration, use of this modeling software would have been a significant procedural departure for both the TCEQ and CONAGUA. A slightly older version of the QUAL-based modeling tool, LA-QUAL retains much of the same features of both QUAL2E and QUAL-TX. In fact, the TCEQ has used LA-QUAL to conduct permit evaluations for water bodies in east Texas prior to 2013. Moreover, USEPA's OST continues to support the LA-QUAL model. Figure 3-1 shows graphically how the LA-QUAL water quality modeling software suits the decision strategies of the actors in the US and Mexican wastewater action arenas and the LRGWQI action arena.

Insights Provided by the Analysis of the Decision Space and Working Rules

In addition to selecting a model that suits the decision strategies of the participants of the LRGWQI action arena, the model choice was also dependent on the capabilities offered by the modeling software selected for use by the Initiative. In analyzing the decision space of the LRGWQI action arena the author examined the set of possible actions available to the actors. These were identified first by examining the objectives specified in the TOR and then by examining the set of rules that both authorize and constrain the actions of each participant. These include the internal working rules of the US and Mexican wastewater treatment action arenas and the LRGWQI action arena and the collective choice and operational choice rules imposed on these

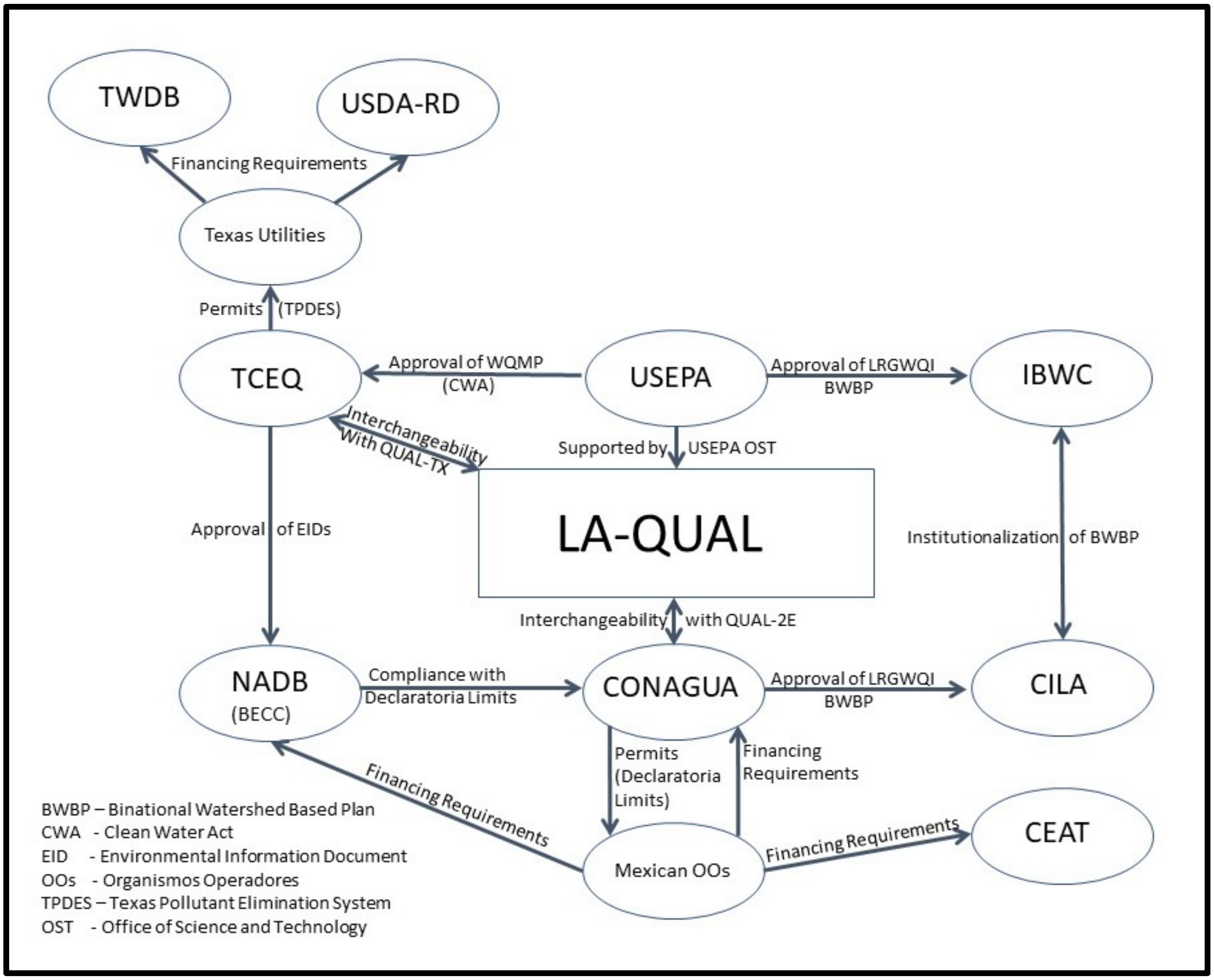


Figure 3-1. The Conceptual Role of LA-QUAL in the Decision Strategies of Institutional Actors in the Action Arenas Associated with LRGWQI

action arenas by action arenas existing at hierarchically higher levels and the operational procedures developed to comply with these rules. The rules and procedures most observably pertinent to the objectives of LRGWQI are those associated with the issuance of permits, for which the QUAL-based modeling tools are well suited. However, as described in the earlier sub-sections, the range of possible actions available to the participants of the LRGWQI extends well beyond these activities.

Constrained by the Mexican collective choice rules which omit stormwater pollutant loading, the set of possible actions by participants in the LRGWQI action arena is confined, at least in this phase of the LRGWQI, to scenarios in which steady-state nonpoint source pollution is addressed; these sources are detailed in Chapter 1 and Sub-section 3.1.1.1 (Functional

Requirements of the LRGWQIDSS). All available modeling tools of the QUAL family have the capability to input flows from nonpoint sources as incremental inflows. In addition to this capability, QUAL-TX and LA-QUAL have data types dedicated to the input of nonpoint source pollutant loadings. This makes these two modeling tools preferable options to accommodate the set of possible actions potentially included in the scenarios to be simulated by the participants in the LRGWQI. While irrigation return flows can be simulated as incremental inflows, steady state flows from human and animal sourced pollutant are not measurable and are not well suited for simulation as incremental inflows; the dedicated nonpoint source data types available in QUAL-TX and LA-QUAL can be used for this purpose.

At least in the case of the LRGWQI, the IAD rule type most pertinent to model selection were the scope rules. The TOR and Annex to the TOR identify (and "codify") salinity (i.e., dissolved solids) and fecal bacteria as the pollutants of concern to be addressed as part of the LRGWQI. Informally, however, the LRGWQI participants are actually addressing a wider pollutant set associated with the CONAGUA's Declaratoria effort and the water quality concerns included in the Texas Integrated Report of Surface Water Quality (Chapter 1). The LA-QUAL modeling software has the capability of simulating all water quality parameters of interest to all participants in the action arenas associated with the LRGWQI. A more detailed description of the capabilities of the LA-QUAL model is presented in Sub-section 3.1.1.3.

As part of the LRGWQI US Partner's proposal to the BTWG, the TCEQ arranged a series of demonstrations of the LA-QUAL software and presented additional technical proposals for estimating pollutant loadings from steady state nonpoint sources and for incorporating those loadings into a water quality model of the Lower Rio Grande/Río Bravo using the LA-QUAL software. The Mexican LRGWQI Partners evaluated the proposals and suggested a number of modifications. In December 2013, the BTWG approved the final LRGWQI US Partner technical modeling proposal, which included the use the LA-QUAL model and the methods described in Sub-section 1.0.11.2 (Characterization of Steady state Nonpoint Sources of Pollutants) for estimating and incorporating steady state nonpoint source pollutants into a water quality model of the Lower Rio Grande/Río Bravo using the LA-QUAL software.

3.1.1.3 The LA-QUAL Surface Water Quality Modeling Software

LA-QUAL is a surface water quality simulation program developed by the Louisiana Department of Environmental Quality (LDEQ) and Wiland Consulting, Inc. The program is considered open source software and can be downloaded free of charge from the TMDL home page of the LDEQ (http://deq.louisiana.gov/page/tmdl). Like its predecessors, QUALII, QUAL2E and QUAL-TX, the base FORTAN code of LA-QUAL was derived from the QUAL-I water quality simulation software developed in 1971 by the TWDB in cooperation with Frank D. Masch & Associates. In 1999, the LDEQ and Wiland Consulting, Inc. developed LA-QUAL based on Version 3.4 of the QUAL-TX software. During its development, the base code for QUAL-TX was converted from running on a DOS-based operating system to running on a Windows-based operating system. A graphical user interface with enhanced graphics was added to the program. Other enhancements made in subsequent years to LA-QUAL include the addition of features that enable assessment of model performance. The capabilities of LA-QUAL include the simulation of constituents and biochemical processes associated with dissolved oxygen dynamics (i.e., BOD, nitrification, eutrophication, etc.) and the fate and transport of conservative constituents (i.e., constituents that do not undergo biochemical decay in the environment, such as dissolved salts), and non-conservative constituents, which decay in the environment (i.e., organic chemicals, metals, pesticides, etc.). LA-QUAL is capable of simulating fecal indicator bacteria and biochemical nutrient interactions in the water column. Simulations involving denitrification and algal dynamics are also possible with LA-QUAL. Figure 3-2 shows in schematic form the biochemical constituents and their interactions as they are simulated in LA-QUAL.

Although the LRGWQI TOR mentions only two constituents of common concern among the participants, fecal indicator bacteria and salinity, LA-QUAL is capable of simulating the physical and biochemical processes that affect the in-stream behavior of chlorophyll a, dissolved oxygen, nitrate nitrogen, and ammonia, which are cited as water quality concerns for the Lower Rio Grande/Río Bravo in the 2014 Texas Integrated Report on Surface Water Quality.

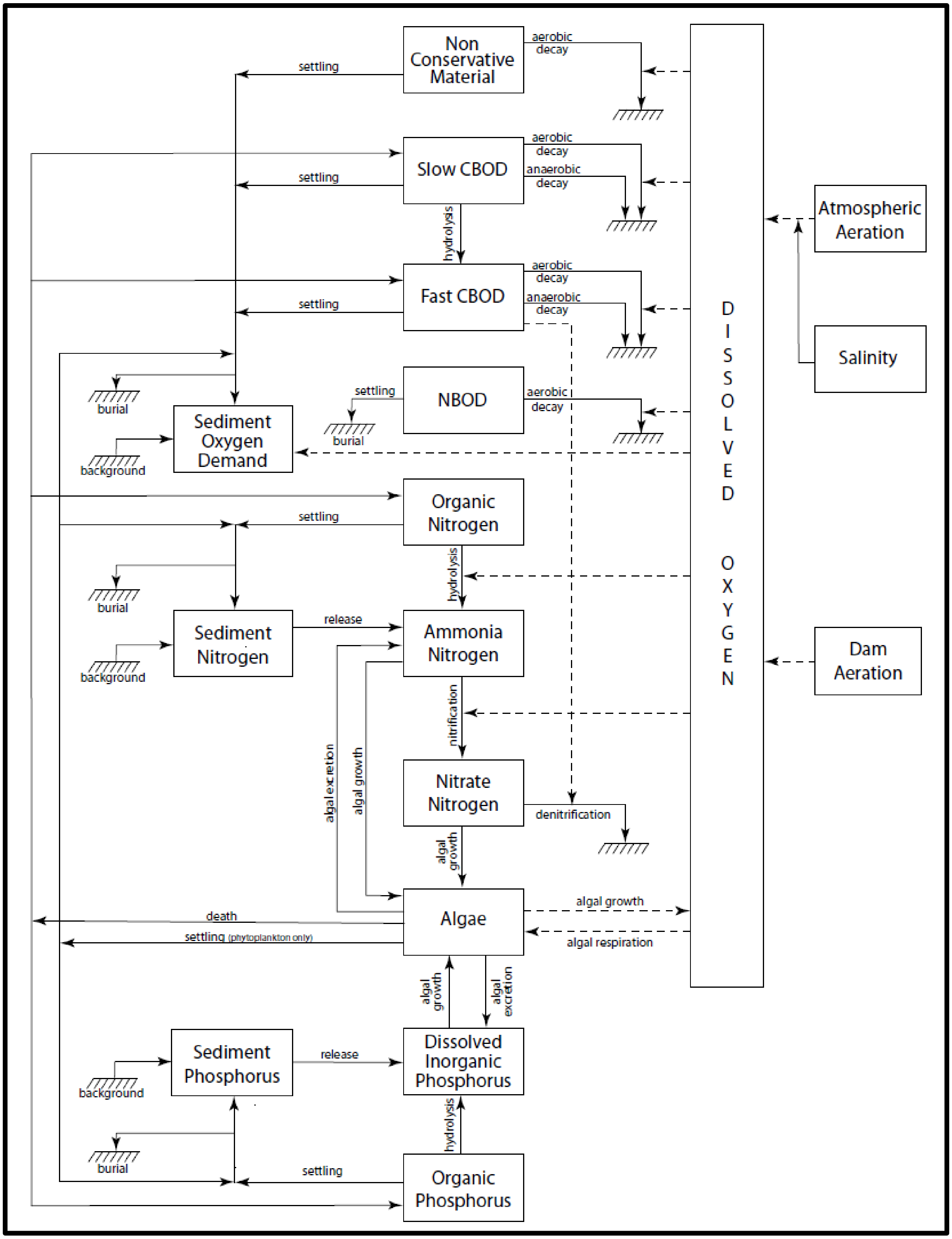


Figure 3-2. Water Quality Constituents and Constituent Interactions in LA-QUAL. Source: LA-QUAL User's Manual.

The Declaratoria conducted by IMTA and CONAGUA on the Lower Río Bravo also requires simulation of constituents associated with dissolved oxygen, in addition to the fate and transport of conservative and non-conservative constituents, such as dissolved and suspended solids, pesticides, toxic organic compounds and water column nutrient interactions (e.g., organic and inorganic forms of nitrogen and phosphorus). All these constituents can be simulated using LA-QUAL. LA-QUAL simulates water quality processes in one dimension under steady state conditions. This means that the model's output is a "snapshot" of water quality in the river at a specified flow condition and temperature.

Water bodies modeled using LA-QUAL are discretized into computational elements and reaches (Figure 3-3). Each computational element is assumed to be instantaneously mixed and homogenous with respect to vertical and horizontal dimensions. The volume of water in each computational element is the result of the balance of inflow from the computational element upstream of it, the outflow to the computational element immediately downstream and the gains and losses in volume to the element specified in the model, including evaporation. Flow can be contributed to, or diverted from, any element as a point source using the "waste load" data types or as a nonpoint source using "incremental" inflows and outflows. In a single time step, LA-QUAL calculates the water volumes and the mass of water quality constituents in each computational element, from boundary and initial conditions, using a finite difference solution method to solve deterministic differential equations which mimic the physical and biochemical processes shown in Figure 3-2, in addition to advective and dispersive transport.

The LA-QUAL surface water quality simulation software is used by the LDEQ and environmental protection agencies in other US states to evaluate municipal and industrial wastewater discharge permits and for general water quality planning and management purposes, such as the development of TMDLs and watershed-based plans under critical flow conditions. From a technical perspective, LA-QUAL has advantages over more sophisticated water quality modeling software precisely because of its simplicity, low data requirements and ease of use. More sophisticated modeling software, although affording additional capabilities, require much higher levels of parameterization, which often forces the user to make assumptions and "guestimations" of critical parameters.

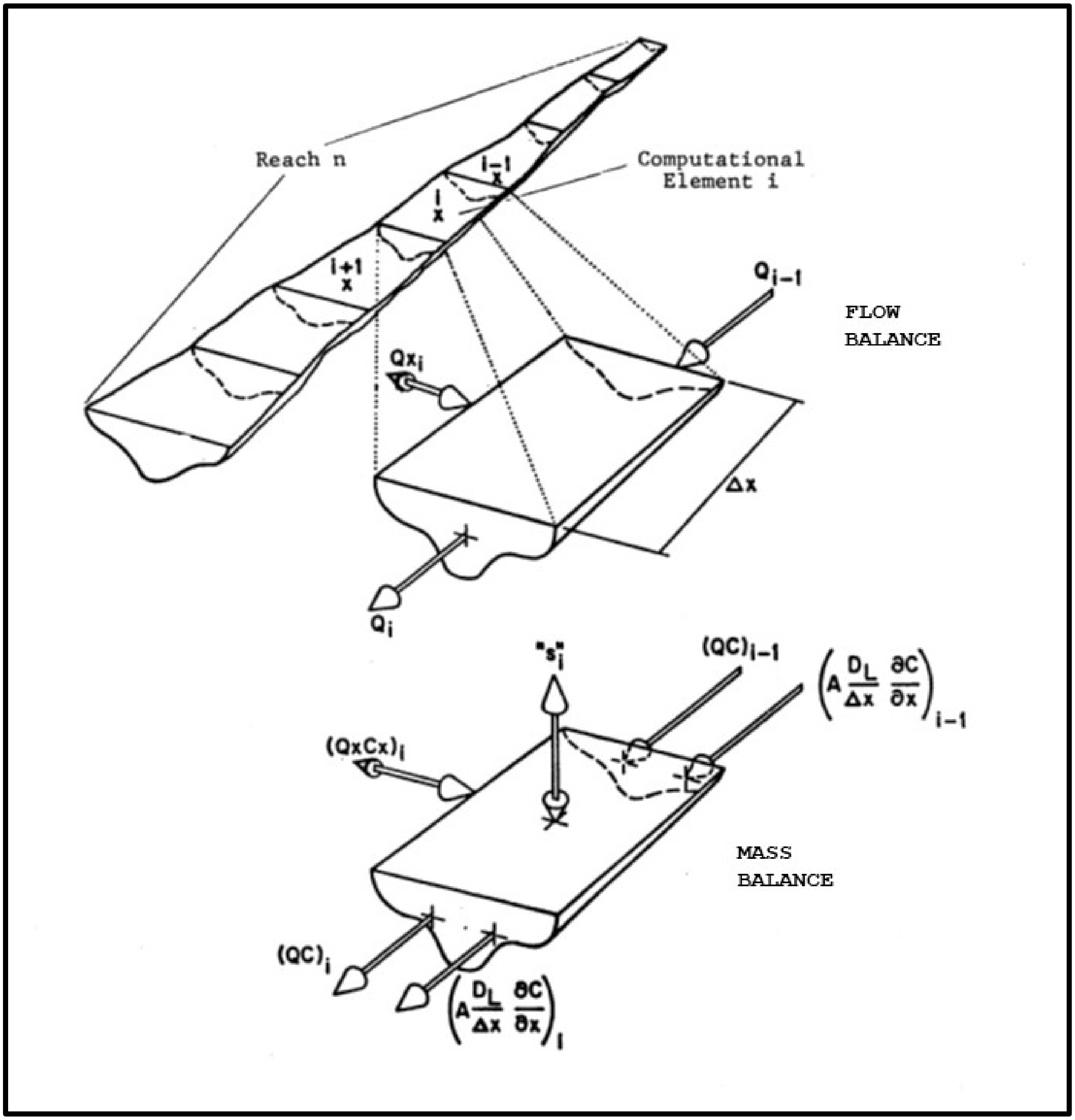


Figure 3-3. Volume and Mass Balance LA-QUAL Computational Elements. Source: Brown & Barnwell, 1987.

The relative simplicity of LA-QUAL extends to its file management system (i.e., production and storage of input and output files) which, unlike more sophisticated software, can be incorporated seamlessly into the LRGWQIDSS GUI with relatively less effort. The focus of the design of the LRGWQIDSS is largely on the production of LA-QUAL input files by the user through the LRGWQI's GIS-based GUI and on the visualization of LA-QUAL output using the LRGWQI's visualization tools. To sharpen this focus, the LRGWQIDSS development team worked with the developer of LA-QUAL, Bruce Wiland of Wiland Consulting, Inc. Mr. Wiland also provided advice and support to the author during the set up and calibration of the LRGWQI models of water quality in the Lower Rio Grande/Rio Bravo.

3.1.1.4 The LRGWQI (LA-QUAL) Water Quality Model(s)

To parameterize and calibrate the LRGWQI model, the members of the BTWG agreed to use existing data, including historical data and common literature values for some parameters, and data collected as part of a series of binational synoptic surveys of water quality conducted cooperatively by the participants of the LRGWQI between June 2014 and April 2016.

MODEL SCHEMATIC

The process of developing and discretizing the hydrography used in the LRGWQI model is detailed in Sub-section 1.0.11.2 (Empirical Methods and Research Design). The author based the lengths of the computational elements and reach segments, in part, on the locations of: (1) major confluences of tributaries, drains and ditches to the main stem or to other drains or ditches; (2) major diversion points, such as diversion dams or irrigation pumps; (3) wastewater outfalls; (4) historical and synoptic water quality monitoring stations; and (5) flow gages. In building the schematic diagram of the model (i.e., the model schematic), the author arranged, whenever possible, to begin and end LA-QUAL reaches at these features. Also, to increase model resolution, the author minimized the sizes of computational elements in the reaches receiving wastewater from point source outfalls and directly downstream of the confluences with tributaries and agricultural drains and ditches.

The spatial attributes of the features and other landmarks used by the author to develop the LRGWQI model schematic were acquired and compiled as part of a binational exchange of information conducted by the BTWG in 2013. The author created a GIS point layer of these features which he overlaid on the LRGWQI polyline hydrography layer to discretize the hydrography layer into LA-QUAL reaches (Figure 3-4) using the "Split Line at Point" command in ArcGIS. At this stage, the hydrography layer is only discretized to the LA-QUAL reach level, but this intermediate stage can provide the reach lengths needed to discretize the hydrography further into the computational elements required by LA-QUAL.

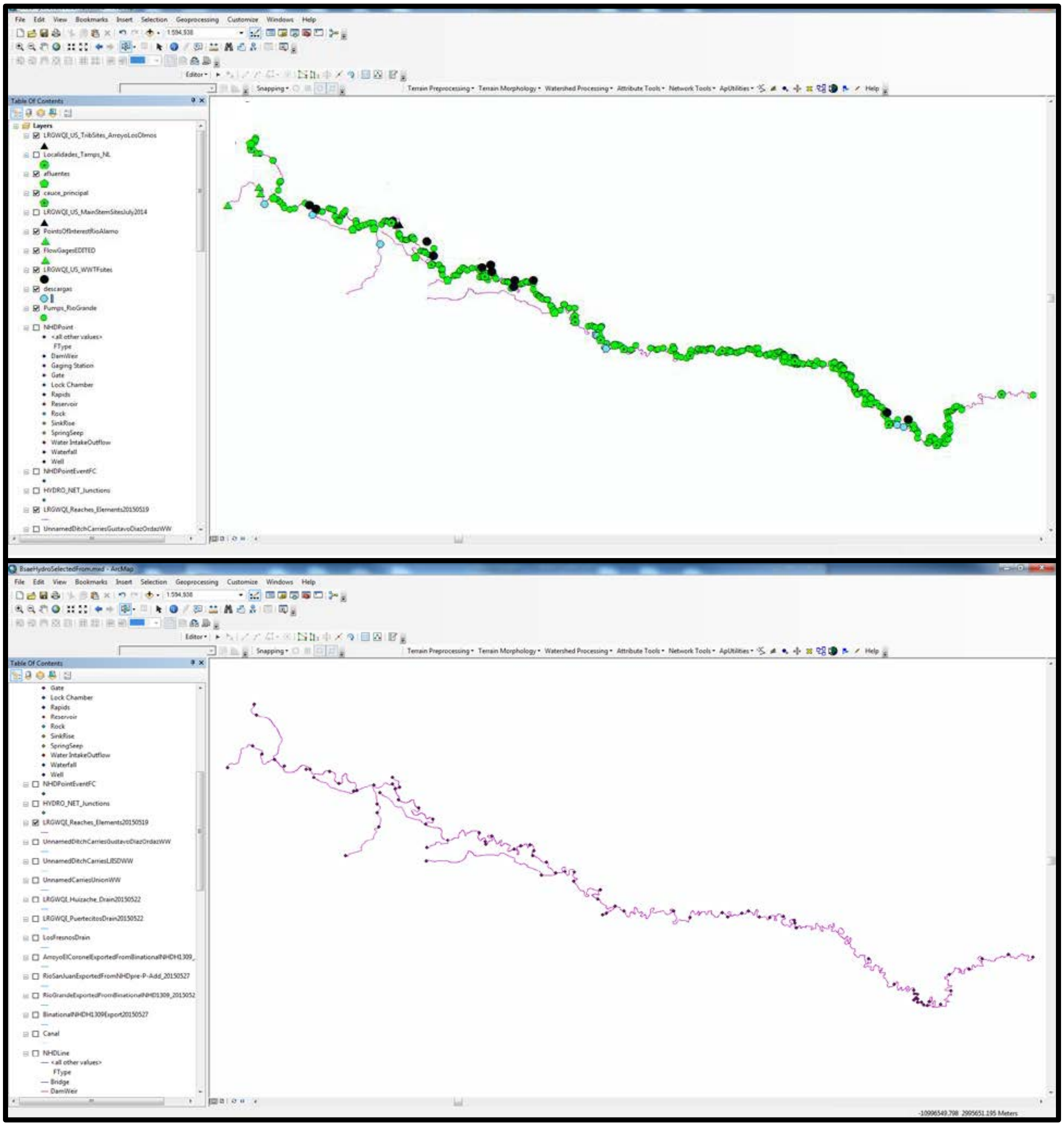


Figure 3-4. Discretization of the Lower Rio Grande /Río Bravo Hydrography Using a Binational Instream Feature Point Layer

The LA-QUAL reach lengths can be determined using the “Calculate Geometry” command in ArcGIS, which populates the attribute tables with this information. The detailed information from the attribute tables is then exported out of ArcGIS and used to develop the numbering and the kilometer distances of each element and reach of the model schematic; this can be done in Microsoft EXCEL. The information produced during the development of the model schematic is used to populate the Reach ID Block of the LA-QUAL input file (Data Type 8). The Reach ID Block (Data Type 8) essentially internalizes the model schematic in the LA-QUAL input file (Figure 3-5).

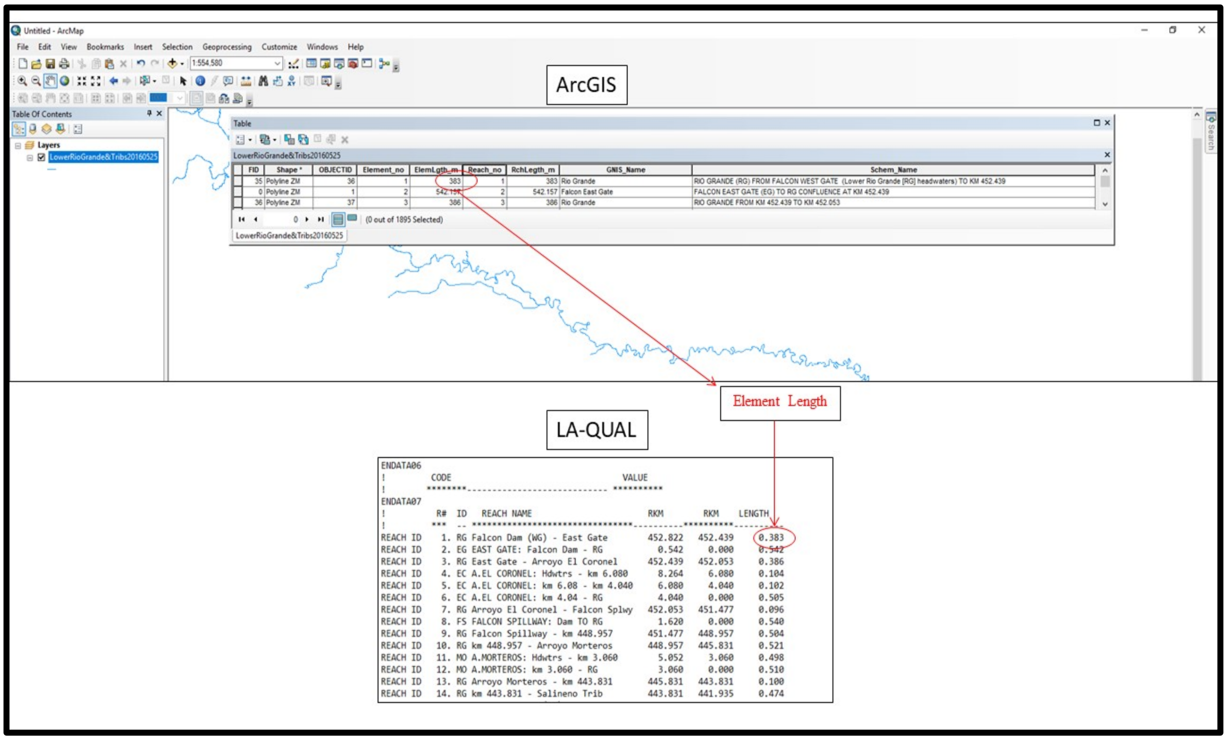


Figure 3-5. Parameterization of the LA-QUAL Reach ID Block with Information Exported from the Model Schematic Discretization Effort in ArcGIS.

MODEL PARAMETERIZATION FOR HYDROLOGY AND HYDRAULICS

Advective Hydraulic Coefficients and Exponents

The estimation of advective transport parameters is an important component of water quality modeling. In order to achieve an overall water balance in LA-QUAL, steady state water volumes and flows must be estimated accurately for each reach. Flow velocities and water depths must also be simulated accurately, as these affect deterministic processes associated with water quality, such as dilution, reaeration, and residence time for decay and settling, etc. LA-QUAL offers two methods for simulating advective transport processes: Method 1 uses stream velocity and depth and Method 2 uses stream widths and depths. Based on the advice received from the developer of LA-QUAL, Bruce Wiland, advective transport was simulated in the LRGWQI water quality model using LA-QUAL's Hydraulic Calculation Method 2. Using this method, in-stream flow (Q) is related to stream width and stream depth using the following power equations:

$$W = aQ^b + c \qquad (4)$$

$$D = dQ^e + f \qquad (5)$$

Where:

W = average surface width of reach

D = average depth per reach

Q = average flow per reach

a = width coefficient

b = width exponent

c = width constant

d = depth coefficient

e = depth exponent

f = depth constant

Method for Deriving Width-related Coefficient "a" and Exponent "b"

To estimate the width-related coefficient "a" and exponent "b" in Equation 4, the author made measurements of stream widths on georeferenced satellite images using ArcGIS (Figure 3-6). The author paired these width measurements with measurements of average daily flow made on the days the satellite images were taken. The flow measurements come from an IBWC dataset of daily average flow from six hydrometric stations (flow gages) in the main stem of the Lower Rio Grande/Río Bravo and two other stations located on the major tributaries of the river, the Río Alamo and Río San Juan. The coefficients "a" and exponents "b" were adjusted in the HYDR-1 block of LA-QUAL (Data Type 9) for each reach during the hydraulic calibration phase to match the average reach widths measured from the satellite images.

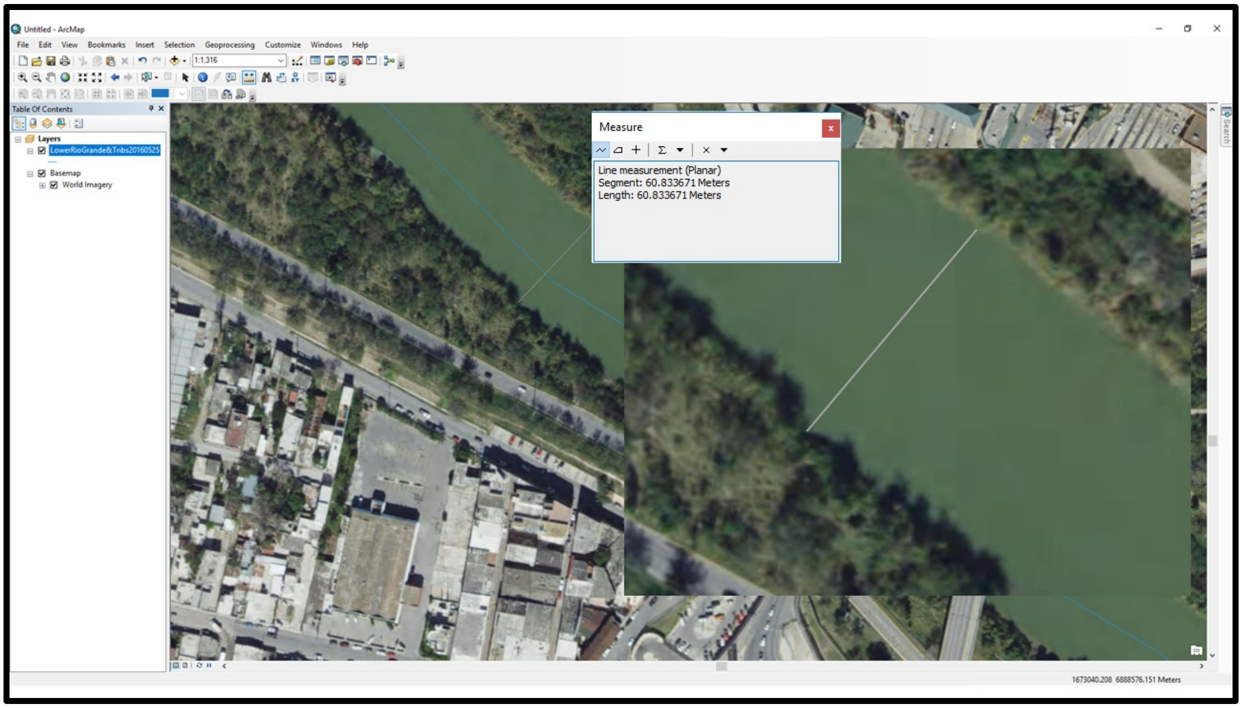


Figure 3-6. Estimating Surface Width Measurements from Satellite Images in ArcGIS.

Method for Deriving Depth-related Coefficients "d" and Exponents "e"

The USIBWC provided the BTWG a dataset, in Microsoft EXCEL, of cross-sections it measured on the Lower Rio Grande/Río Bravo in MSEXCEL format. The data was originally collected for the development of a comprehensive floodplain model of the river using the FLO-2D software. Consequently, all cross sections measured included areas outside the banks and bed of the river. The author used the channel width measurements made from satellite images to extract the portion of the cross-sections that delineated the wetted perimeter of the stream under various flow conditions (Figure 3-7).

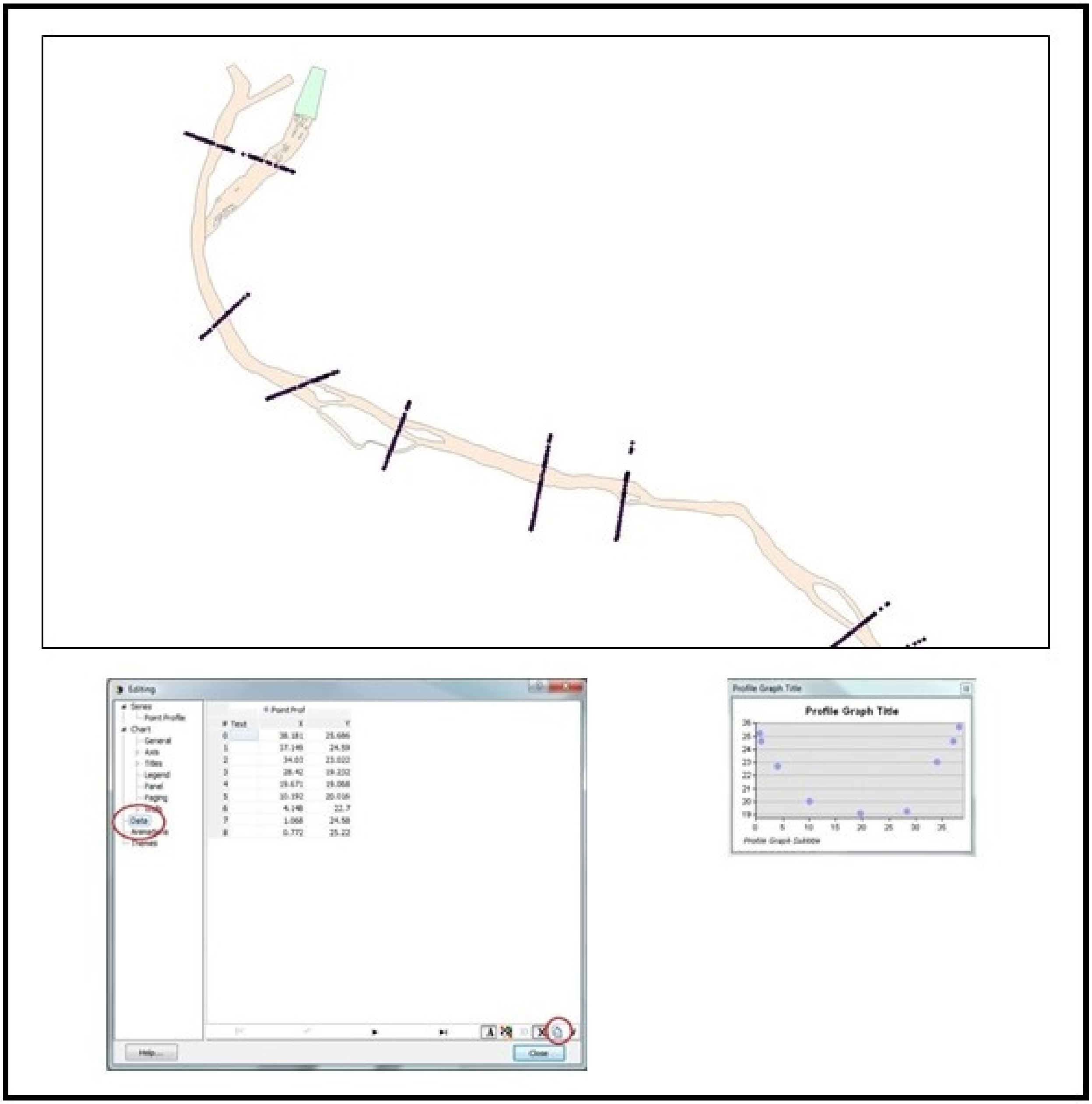


Figure 3-7. IBWC (FLO-2D) Cross-Section Data Used to Derive Depth-Related Hydraulic Coefficients and Exponents for Use in LA-QUAL.

From these flow-specific cross-sections the author estimated average depths for all reaches at various flow conditions. The coefficients "d" and exponents "e" in Equation 5 were adjusted in the HYDR-1 block of LA-QUAL (Data Type 9) for each reach during the hydraulic calibration phase to match the depths estimated in this manner.

Dispersive Hydraulic Coefficients and Exponents

Dispersion is also an important transport mechanism in water quality modeling because it affects the residence time of pollutants in the river system. Dispersive pollutant transport, however, is multidirectional. It can, at once, enhance and counteract advective pollutant transport and it is used in LA-QUAL primarily to simulate tidal forcing. Dispersive hydraulic coefficients and exponents are specified in the HYDR-2 block of LA-QUAL (Data Type 10). LA-QUAL offers three options for simulating tidal dispersion; each option uses a different equation to estimate dispersion:

$$E = a \qquad (6)$$

$$E = aD^b Q^c V_T^d, \qquad (7)$$

$$E = aD^b Q^c V_m^d, \qquad (8)$$

Where:

E = dispersion

D = average depth

Q = Flow

V_t = shear tidal velocity

V_m = mean tidal velocity

a = depth coefficient for dispersion

b = depth exponent for dispersion

c = flow exponent for dispersion and

d = velocity exponent for dispersion

Most of the input data needed to simulate tidal dispersion in LA-QUAL is entered in the Program Constants (Data Type 3) which determines the base values for the major components of the dispersion equation; the information needed to derive these values (e.g., tide height) are available from the NOAA (2014-2017). Unless there is detailed quantitative data on tidal hydrodynamic behavior in the tidal portion of the Rio Grande/Río Bravo, however, the coefficients and exponents in equations 7 and 8 cannot be easily estimated. As part of the binational synoptic monitoring events conducted between 2014 and 2016 by the BTWG, the TCEQ and its collaborators conducted a series of salinity profiles in the tidally-influenced portion of the Lower

Rio Grande/Río Bravo (Figure 3-8). The author used the data collected during these salinity profile monitoring events to set the salinity values for the lower boundary condition (Data Type 27) and to derive initial values of the tidal dispersion coefficient (*a*) in the equation for option 1, Equation 6, two values which highly influence the salinity gradient in the tidal portion of the Rio Grande/Río Bravo. The adjustment of hydraulic coefficients and exponents associated with advection and dispersion were components of the hydraulic calibration of the model to ensure the physical parameters affecting water volume, reaeration, time of travel, sedimentation and organic decay are properly represented in each computational element of the model.

WATER BALANCE AND HYDROLOGIC CALIBRATION

As is common practice in water quality modeling, calibration of hydraulic parameters is performed concurrently with hydrologic calibration. While the main objective of hydraulic calibration is to ensure the physical characteristics of the river channel are properly represented in the model, the main objective of hydrologic calibration is to achieve a water balance in the river system. Hydrologic calibration is achieved when observed flow values are matched at all flow gage stations after accounting for all known flows into, and out of, the river system. The water balance begins with the specification of headwater flows (Data Type 20 in LA-QUAL). In terms of headwater flows, initial conditions should be set at the steady state flow condition that is being modeled.

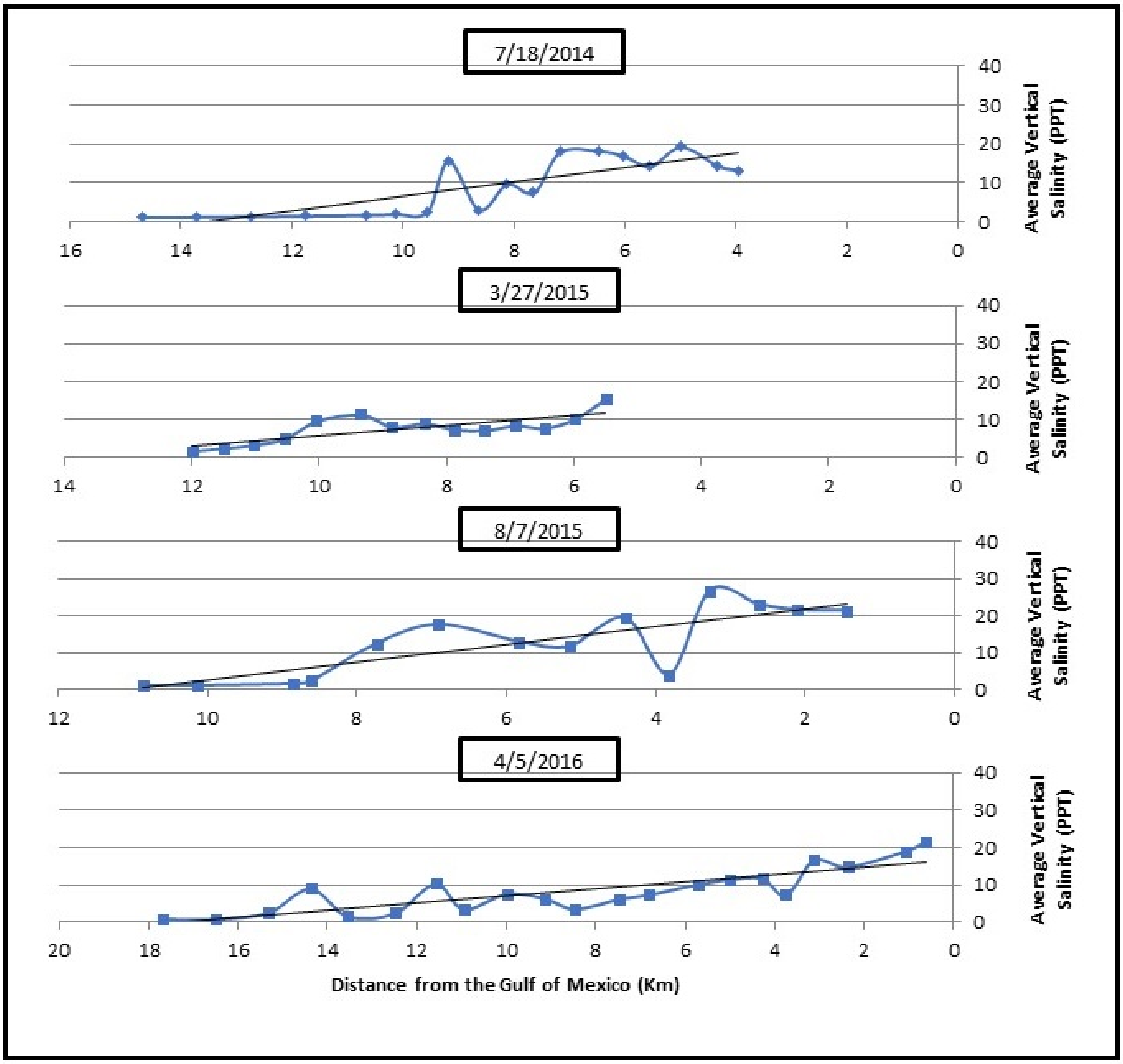


Figure 3-8. Longitudinal Salinity Profiles Measured During the LRGWQI's Binational Synoptic Surveys of Water Quality in the Lower Rio Grande/Río Bravo

As previously mentioned, the IBWC maintains nine flow gage stations located in the LRGWQI study area (Figure 3-9). Table 3-1 shows the IBWC gage numbers and the official IBWC location descriptions for the gages.

Figure 3-9. Location of IBWC hydrometric stations (flow gages) in the LRGWQI Study Area.

Table 3-1. IBWC Flow Gages Located on the Lower Rio Grande/Río Bravo and Two of Its Major Tributaries (Río Álamo and Río San Juan)

IBWC Gage No.	Gage Location Description
08-4613.00	Rio Grande below Falcon Dam near Falcon, TX and Nueva Cd. Guerrero, Tamaulipas
08-4620.00	Rio Alamo at Cd. Mier, Tamaulipas
08-4642.00	Rio San Juan at Camargo, Tamaulipas
08-4647.00	Rio Grande at Rio Grande City, TX near Camargo, Tamaulipas
08-4663.00	Rio Grande at Los Ebanos, TX near Cd. Díaz Ordaz, Tamaulipas
08-4692.00	Rio Grande below Anzalduas Dam near Reynosa, Tamaulipas and Mission, TX
08-4725.30	Rio Grande near Progreso, TX and Nuevo Progreso, Tamaulipas
08-4637.00	Rio Grande near San Benito, TX and Ramirez, Tamaulipas
08-4650.00	Rio Grande near Brownsville, TX and Matamoros, Tamaulipas

The nine flow time series of average daily flows for each of these gage stations were part of the binational dataset exchanged in 2013 and the USIBWC and CILA. In addition to using these time series to derive advective and dispersive hydraulic coefficients and exponents for hydraulic and hydrologic calibration, the IBWC also provided average daily flows measured at these flow gage stations during the binational synoptic surveys conducted by the BTWG in 2014-2016. For the water balance exercise, headwater flows are set in the main stem according to the average daily flow value measured at IBWC gage 08-4613.00 located directly downstream from Falcon Dam. Headwater flows for the Río Álamo and Río San Juan are set at a value that yields the observed average daily flow values measured at IBWC gages 08-4620.00 and 08-4642.00, respectively, after known upstream inflows and outflows are applied.

The TCEQ supplied information on the pump locations of US irrigation districts and municipal water supply pumps from the TCEQ's Rio Grande Water Master database. Similarly, CONAGUA provided the location of municipal water supply pumps drawing water from the river. Along with major diversion points, such as Anzalduas Dam, this diversion and withdrawal location information was compiled into a GIS point layer (Figure 3-10) used to specify, in the WSTLD-1 block of LA-QUAL (Data Type 24), the computational elements in the model schematic from which these points withdraw water from the river.

Flow Diversions and Withdrawals (gaged)

The model input for major US point diversions (i.e., irrigation district pumps and municipal pumps) also comes from the TCEQ's Water Master's database (Figure 3-10). These data are reported to the IBWC along with pumpage data from minor US diverters. The IBWC compiles the data and builds time series of daily US diversions which it aggregates into values of total US diversions over certain portions of the river which coincide with the IBWC's reach designations.

Figure 3-10. Location of Major US and Mexican Diversion points on the Lower Rio Grande/Río Bravo.

The author processed the TCEQ Water Master diversion data to derive model inputs for major US point diversions and he input these values into the WSTLD-1 block of LA-QUAL. Since the minor US diversions are too numerous to include in the WSTLD-1 block (Figure 3-11), the author instead subtracted the large and municipal point diversions from the IBWC time series of total US diversions and modeled the resulting small US diversions as incremental outflows (INCR-1; Data Type 16) distributing them amongst the LA-QUAL reaches according to the density of small pumps found along each LA-QUAL reach.

Figure 3-11. Location of Minor US Diversion Points on the Lower Rio Grande/Río Bravo.

Inputs associated with major Mexican diversions come from information supplied by CONAGUA (i.e., municipal withdrawals) and by the IBWC (e.g., Mexican diversions at Anzalduas Dam), which the author entered as point diversions in the WSLD-1 block of LA-QUAL. Minor Mexican diversion data originates from the IBWC Mexican reach diversion dataset. Like the US minor diversions data, the author subtracted the major Mexican diversions from this dataset and distributed the processed values amongst the LA-QUAL reaches within each IBWC reach proportioned according to the amount of irrigated land found in the sub-basins associated with each of the appropriate LA-QUAL reaches. These minor Mexican diversions do not amount to a great deal of flow diverted from the Lower Rio Grande/Río Bravo, as most of the water from the Lower Rio Grande used by the Mexicans for irrigation is diverted from the two reservoirs on the tributaries (i.e., Las Blancas and Marte R. Gómez) and from the Lower Rio Grande/Río Bravo at Anzalduas Dam, near the city of Reynosa.

Flow Contributions (gaged)

Point flow contributions data come from three main sources, (1) Mexican wastewater outfall flow values measured during the synoptic surveys (2) US wastewater treatment facility outfall flow values observed during the synoptic surveys and (3) data from US Discharge Monitoring Reports downloaded from the EPA's ICIS database. The author used ICIS data in instances where effluent flows or concentrations were missing from the US synoptic survey data. These values are not as accurate as the values measured during the synoptic surveys, as the ICIS values represent daily averages.

Although there are two sources of data on large scale flow contributions, separate datasets of IBWC reach level contributions from the United States and Mexico and a dataset of monthly flow measurements conducted by CILA on tributaries and drains that contribute flow to the Lower Rio Grande/Río Bravo, the Mexican data is the same and comes from CILA's flow gages on the large Mexican drains and tributaries. The IBWC converts the monthly flow volumes from the various drains into daily time series, dividing by the days in each month and using conversion factors, then aggregating the daily flows into two IBWC-CILA reaches. For the purpose of model setup, the CILA data is much more useful because it is more geographically detailed. The IBWC data is helpful for distributing inflows in the INCR-1 block of LA-QUAL. The author used the CILA drain and tributary data in two ways, for flow calibration in the major Mexican tributaries and ditches and as a starting point for estimating irrigation return flows as sub-basin yields.

Estimation of sub-basin irrigation return flow yields

Sub-basin irrigation return flow yields are important mainly for use in the LRGWQIDSS. Without these yields, users would not be able to simulate the effects, on flow and water quality, of implementing agricultural BMPs to particular agricultural areas within the sub-basins associated with each of the reaches being modeled using LA-QUAL. As a starting point for estimating sub-basin yields, the author used the average flow values from the CILA drain and tributary data for the synoptic months and divided these values by the irrigated land in the sub-basins of the corresponding Mexican drains. In some instances, the author used the flow measurements reported by IMTA for synoptic surveys for this purpose. The author extrapolated the sub-basin yields calculated for the Mexican drains to other non-drain sub-basins using the distributions used by IBWC for their larger reaches (e.g., Puertecitos yields also used for the non-drain reaches between Rio Grande City and Los Ebanos). Yields were also extrapolated to US sub-basins in the IBWC reaches. Some of the sub-basin yield values were adjusted during the hydrologic calibration process.

Hydrologic and Hydraulic Calibration Processes

The primary hydrologic calibration data comes from the seven IBWC flow gage stations on the Lower Rio Grande/Río Bravo and the two IBWC flow gage stations on the major tributaries (Río Alamo and Río San Juan). As the synoptic surveys were conducted over a period of several days, the flow at the gages show the range of flow occurring over the span of each synoptic survey. In addition to flow data from these gages, the author also used instantaneous flow measurements measured in the field during the synoptic surveys. These instantaneous field flow measurements were important for hydrologic calibration of ungagged water bodies. The two main parameters were instrumental in the hydrologic calibration process to estimate adjustments to the subwatershed yields (upwards or downwards and within reason – see explanation below) and for applying "ungagged" diversions in the IBWC reaches where instream flows were too high even after reducing subwatershed yields to zero. As mentioned previously, adjusting headwater flows was also one of the calibration methods, but this parameter was used sparingly and only when warranted.

The author used certain rules of thumb to ensure parameter adjustments were within the reasonable range. The first rule was keeping the volume of ungagged diversions applied to the models to a minimum. Secondly, keeping the sub-basin yields (on a flow/area basis) within the boundaries of the scant values found in the agricultural technical literature (e.g., Enciso, 2012). It is important to remember, however, that irrigation return flow yields (flow/area) represented in the LRGWQI model cannot be compared directly with any edge-of-field measurements, as what is represented in the model is an average value for all irrigated land in the subject sub-basins. That is, one cannot make the assumption that all irrigated land parcels in a given sub-basin are being irrigated at the same time, at any given time. In fact, it is extremely unlikely that this can ever be the case, so what the model represents is an average instantaneous yield per hectare in the subject watersheds, which changes predictably on a seasonal basis. Nevertheless, whereas the downward limit of the per-hectare yield can be zero (i.e., no or minimal irrigation occurring), the upward limit of irrigation return flow yield per hectare must be within the bounds established by edge-of-field measurements found in the agricultural BMP technical literature.

Concurrently with the hydrologic calibration, the hydraulic calibration consisted of adjusting the original coefficients in the HYDR-1 and HYDR-2 blocks until simulated stream depths and surface widths matched those estimated from satellite imagery and cross-section data. A scant amount of instantaneous depth, width and flow velocity data were also available from the flow measurements conducted during the synoptic surveys.

Calibration Results

For the most part, the hydrologic calibrations adhere well to the ranges of the gaged instream flows (Figure 3-12). Simulated flows matched the flows observed at the IBWC gage stations better than those measured in the field during the synoptic surveys. Average absolute percent error between simulated and observed flow ranged from 3.6% in the model of the July 2014 synoptic survey to 20.6% in the model of the August 2015 synoptic survey. With regard to hydraulic calibration, the models appear to match the widths measured from satellite images for days with similar flows (Figure 3-13). Average absolute percent error between surface widths ranged from 1.3% in the model of the July 2014 synoptic survey to 18.3% in the model of the August 2015 synoptic survey. The models perform less well with the simulation of depths, mostly under-simulating these. Using the rating curve depths for calibration, the average percent absolute error between simulated and "observed" hydraulic depths ranged from 60.8% in the model of the November 2015 synoptic survey to 104% in the model of the July 2014 synoptic survey.

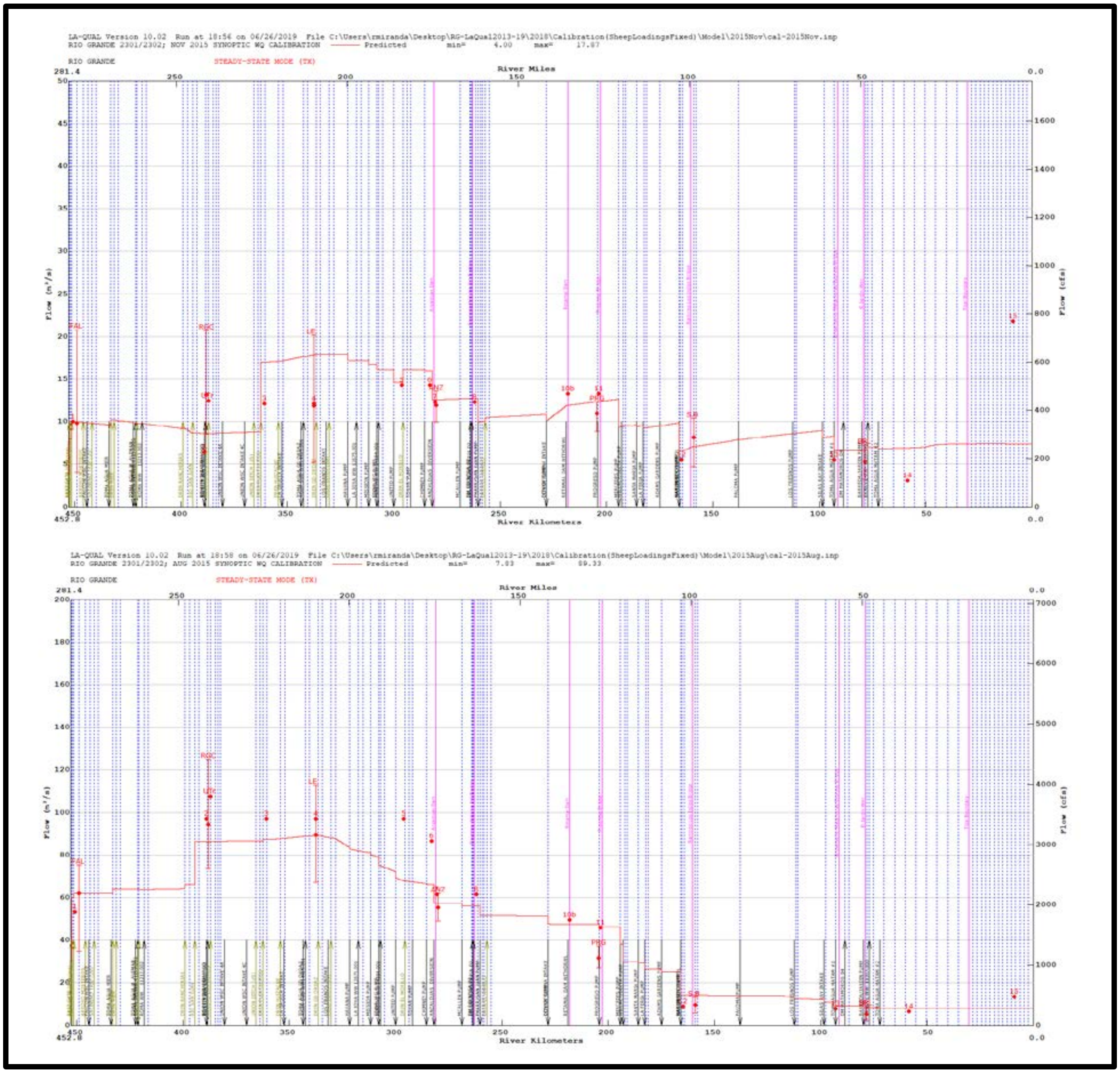


Figure 3-12. Flow Calibration Curves for the Main Stem of the Rio Grande/Río Bravo; Synoptic Survey Data from November 2015 (upper) and August 2015 (lower).

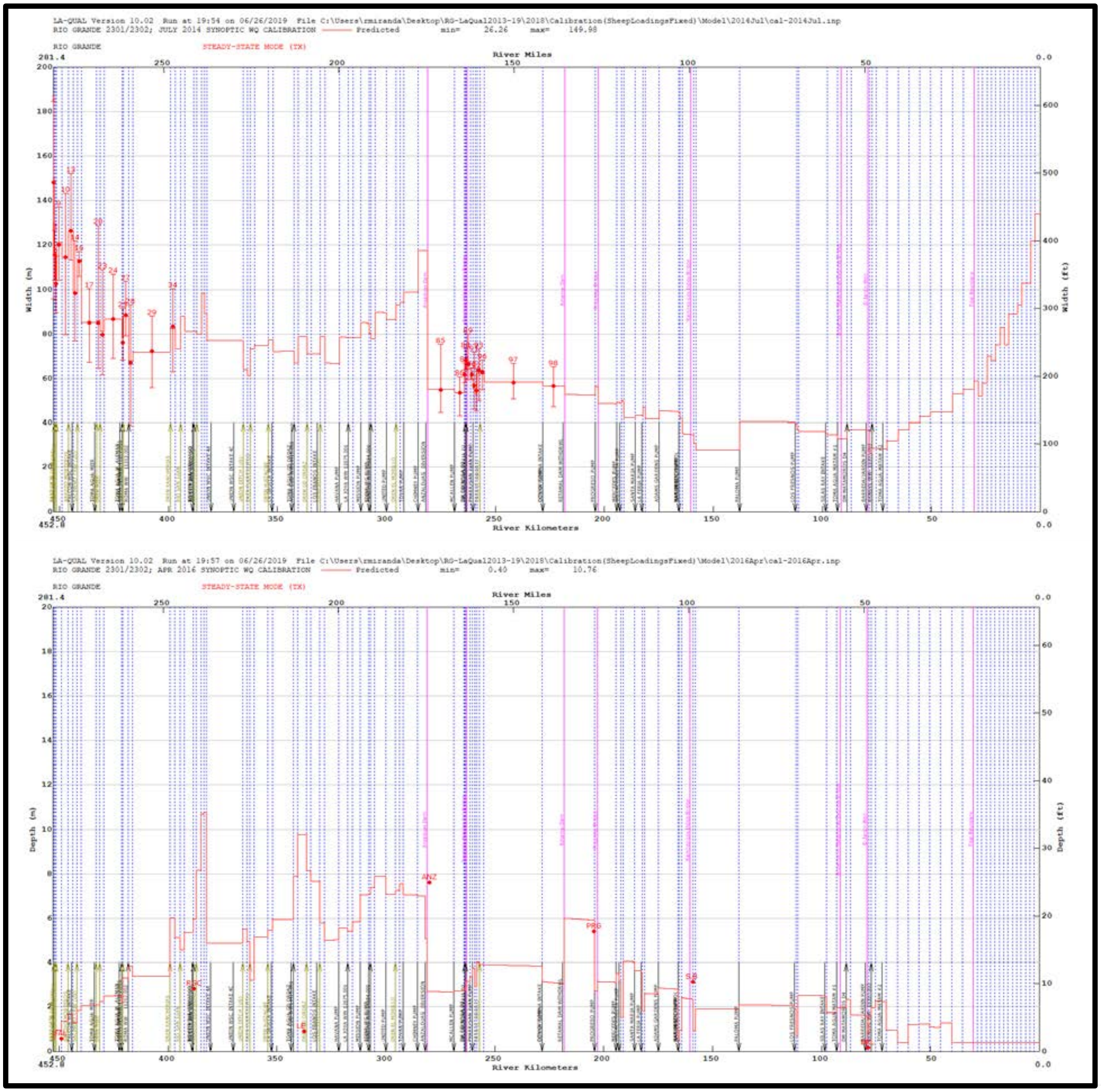


Figure 3-13. Hydraulic Calibration Curves for the Main Stem of the Rio Grande/Río Bravo for Widths (April 2016 [upper]) and Depths (August 2015 [lower]).

While the model performance results for simulation of depth are less than ideal, it is important to point out that the average absolute difference between simulated and "observed" depths in the LRGWQI models was less than 2 meters. The depth coefficients and exponents were initially estimated for the models using the Flo2D cross sections, which often include as few as five points per cross section. The author adjusted many of these parameters during the hydraulic calibration process, testing the simulated depth against depths extracted from the rating curves of the IBWC flow gages, which only supplies calibration points for nine locations in the river. An important measure of the fidelity of hydraulic model parameters is how well the model simulates flow velocity. One source of this hydraulic data, albeit scarce, are the flow measurements conducted during the synoptic survey. IMTA provided the author the velocity data gathered during IMTA's field flow measurements. Though scant, this information shows the models reproduce, at least, the IMTA-measured velocities with reasonable accuracy.

The models were generally able to simulate the range of salinity gradients observed during the synoptic surveys (Figure 3-14). the average percent absolute error between simulated and "observed" salinity ranged from 23.3% in the model of the July 2014 synoptic survey to 55.8% in the model of the November 2015 synoptic survey. The model calibration process is always a compromise. Parameter adjustments made to alleviate one concern create other concerns, so modelers tend to split the difference on decisions involving calibration parameter adjustments. Of course, field measurement error is often a source of uncertainty in water quality modeling.

MODEL PARAMETERIZATION FOR WATER QUALITY

The main sources of water quality data used to parameterize the LRGWQI models include the binational synoptic surveys conducted as part of the LRGWQI, binational geospatial and census data. Published literature values provided additional information used in the calculation of steady state nonpoint source loadings.

Data Used for Initial Conditions

The temperature and chlorophyll *a* values entered in the initial conditions block of LA-QUAL (INITIAL; Data Type 11) were measured at the sampling locations during the synoptic surveys. Chlorophyll data was only available for the July 2014 synoptic model and only for the main stem of the river and one US tributary, Arroyo Los Olmos.

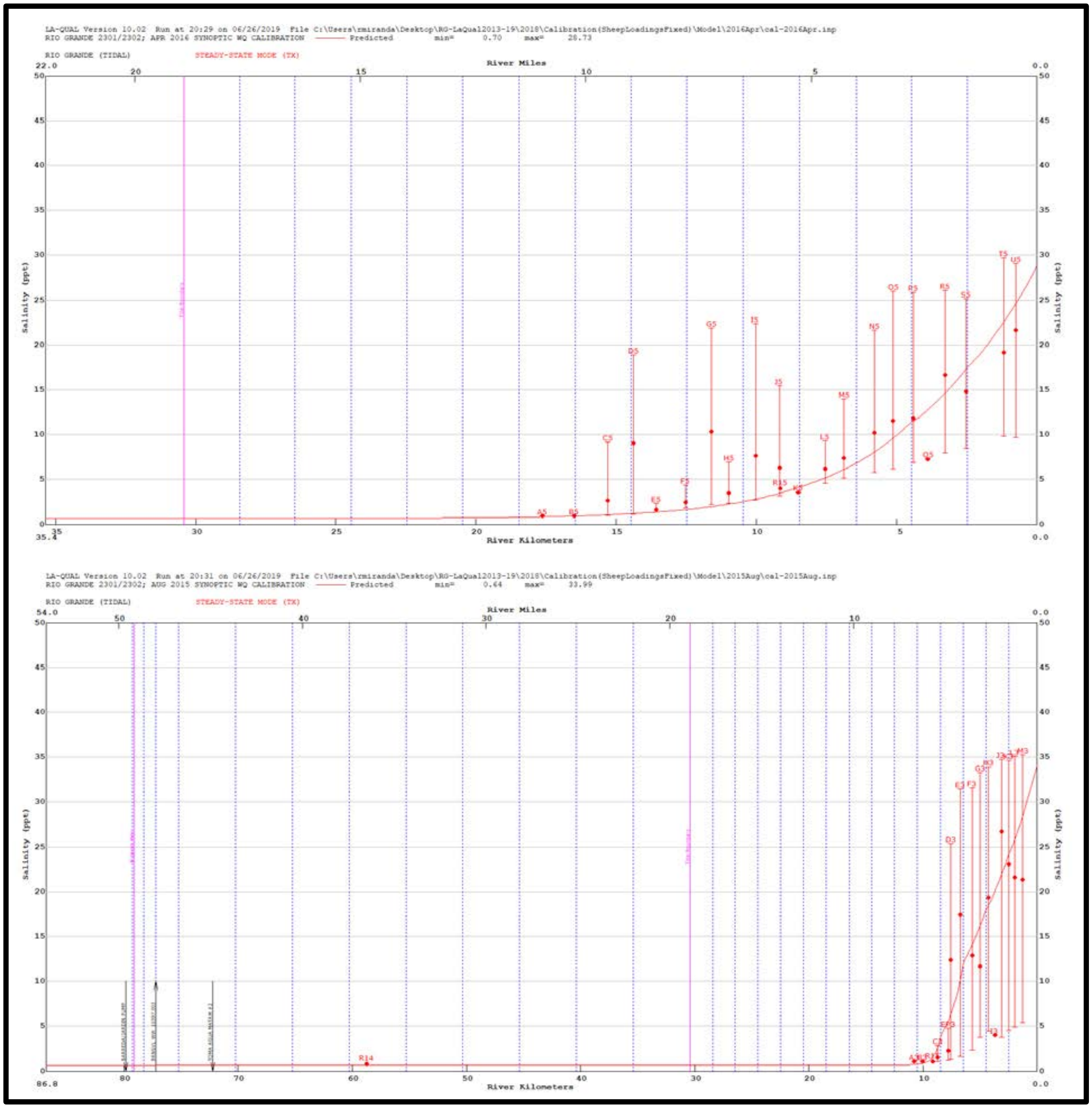


Figure 3-14. Simulation of Salinity at the Tidal Boundary of the Lower Rio Grande/Río Bravo (Synoptic Survey Data from April 2016 [upper] and August 2015 [lower]).

Chlorophyll *a* data for Mexican tributaries and for the main stem of the river in March, August and November of 2015 and April of 2016 was estimated based on the difference between filtered and nonfiltered BOD, organic nitrogen and organic phosphorus values.

Point Source Inputs

The results of the four synoptic surveys, provided values of temperature, salinity, chlorides, TDS, DO, BOD, organic nitrogen, ammonia nitrogen, organic phosphorus, inorganic phosphorus, chlorophyll-a, fecal coliforms, and TSS used to specify the concentrations and values of these parameters in the effluent of the 17 waste water outfalls used in the model. The values are entered in the WSTLD-1, WSTLD-2 and WTSLD-3 blocks (Data Types 24-26) of the LA-QUAL input files. The models include an outfall for the wastewater treatment facility in Gustavo Díaz Ordaz, but it is not used in the models because it is not functional. In addition to the primary outfall, at the Reynosa wastewater treatment facility No. 1, the models include four additional outfalls for this facility. The additional outfalls at the Reynosa wastewater treatment facility No. 1 were not sampled during the LRGWQI synoptic surveys, but information provided by CONAGUA indicated these outfalls were used periodically when influent volumes exceed the facility's treatment capacity. One of these additional outfalls (L4/5) is used in the preliminary calibrations of the July and March synoptic models. The author used a combination of indirect information, such a flow balance in the El Anhelo Drain, and professional judgement to represent the flow and water quality characteristics of outfall L4/5, as no actual monitoring information was available. The July 2014 synoptic survey did not include the sampling of Mexican wastewater outfalls; the values used to represent them in the July synoptic model are the values measured for these inputs in August 2015.

Nonpoint Source Inputs

The methods used to estimate nonpoint source loadings for the LRGWQI were explained in detail Sub-section 1.0.11.2 (Empirical Research Methods and Design) of Chapter 1. The author used the result of geospatial analyses conducted jointly by the TCEQ and IMTA to estimate the number of residents living in a 500 meter riparian buffer around the Rio Grande/Río Bravo or one of its tributaries/ditches to estimate the riparian populations into those served by centralized sanitary sewer systems, those using septic systems and those with no sanitation, each grouped into the subwatersheds associated with each model reach for use in NPS loading estimates.

To estimate human-derived NPS loadings to each modeled reach, the author calculated the human per-capita generated loadings of chlorides, TDS, DO, BOD, organic nitrogen, ammonia nitrogen, organic phosphorus, inorganic phosphorus, fecal coliforms, and TSS using estimates of human wastewater production and composition derived from the technical literature. Differences in loading rates between US and Mexican populations are mainly due to a difference in population and water usage rates across the border with a commensurate difference in per-capita wastewater production.

Sub-section 1.0.11.2 (Empirical Research Methods and Design) of Chapter 1 details the methods used to estimate domestic and wild animal-derived NPS loading from the US side of the watershed to each modeled reach. The values of animal populations are also the results of geospatial analyses conducted jointly by the TCEQ and IMTA to estimate the number of domestic animals potentially contributing to NPS loadings to each reach. To estimate animal-derived NPS loadings to each modeled reach, the author calculated the per-animal generated loadings of chlorides, TDS, DO, BOD, organic nitrogen, ammonia nitrogen, organic phosphorus, inorganic phosphorus, fecal coliforms, and TSS using values of animal waste production and waste composition derived from the technical literature. The NPS loading values estimated for humans and animals are combined and entered in the NONPOINT block of the LA-QUAL input file (Data Type 19).

Loadings from irrigated agriculture are simulated using incremental flows in the INCR-1, INCR-2, and INCR-3 blocks of LA-QUAL (Data Types 16, 17 and 18, respectively). The estimates of the return flows entered in INCR-1 are the product of the sub-basin yield rates estimated during the hydrologic calibration effort and the area of irrigated agricultural land in the sub-basins corresponding to each LA-QUAL reach. The author assigned concentrations of pollutants in the irrigation return flows, deriving them originally from Enciso (2012). The author adjusted the literature-derived concentrations when warranted during the water quality calibration effort.

Water Quality Calibration Data

To calibrate the LA-QUAL simulations of water quality in the LRGWQI models, the author used the values measured during the binational synoptic surveys at 16 main stem sites, in July of 2014, and 15 main stem and 7 tributary sites in March, August, November of 2015 and April of 2016. The synoptic survey conducted in July 2014 did not include the sampling of

Mexican tributaries. For the LA-QUAL simulation of water quality during that survey, the author used values of water quality parameters measured during the August 2015 synoptic survey to compare to the simulation output values. All calibration data are entered into LA-QUAL overlay files, which are used by the LA-QUAL input file to display over simulation output curves and to estimate model performance.

Water Quality Calibration Process

Model calibration for water quality is performed through the adjustment of state variables in the deterministic equations that govern the various processes affecting water quality constituents in the water column of the modeled water body and by adjusting inputs within the range of uncertainty associated with each of the water quality constituent sources. Following hydrologic and hydraulic calibration, the author followed a standard water quality calibration sequence, first calibrating conservative water quality constituents (i.e., chlorides, TDS and salinity) then calibrating nonconservative constituents, such as nutrients, BOD, DO, chlorophyll *a* and finally TSS.

Water Quality Calibration Results

Calibration results varied depending on the water quality constituent and the synoptic period simulated. Table 3-2 shows the ranges in average absolute percent errors for simulations of water quality constituents in the LRGWQI model calibration effort. In general, the models performed better when simulating conservative water quality constituents than when simulating non-conservative constituents. Model performance was least effective with organic phosphorus and coliforms.

Table 3-2. LRGWQI Model Performance Results

Water Quality Constituent	Average Absolute Percent Error Range (%)
Salinity	24.7 – 60.6
Chloride	12.2 – 49.1
TDS	6.7 – 52.1
DO	13.1 – 24.2
Ammonia Nitrogen	59.2 – 76.6
Inorganic Nitrogen	28.1 – 53.6
Dissolved Inorganic Phosphorus	45.6 – 89.9
Chlorophyll *a*	8.8 – NA*
Coliforms	103.9 – 152.7
Effective CBOD	16.8 – 64.5
Effective Organic Nitrogen	23.9 – 54.2
Effective Organic Phosphorus	71.4 – 103.6
Effective TSS	19.6 – 81.5

NA signifies not applicable
* Chlorophyll data a were only collected during the July 2014 Synoptic Survey

The average absolute difference between simulated and observed values of organic phosphorus in the model that yielded the highest absolute percent difference for this constituent (i.e., November 2015 Synoptic Survey) was only 0.06 mg/l, which is a very small value. The value is approximately equal to the average observed value of organic phosphorus measured during the November 2015 Synoptic Survey (Figure 3-15).

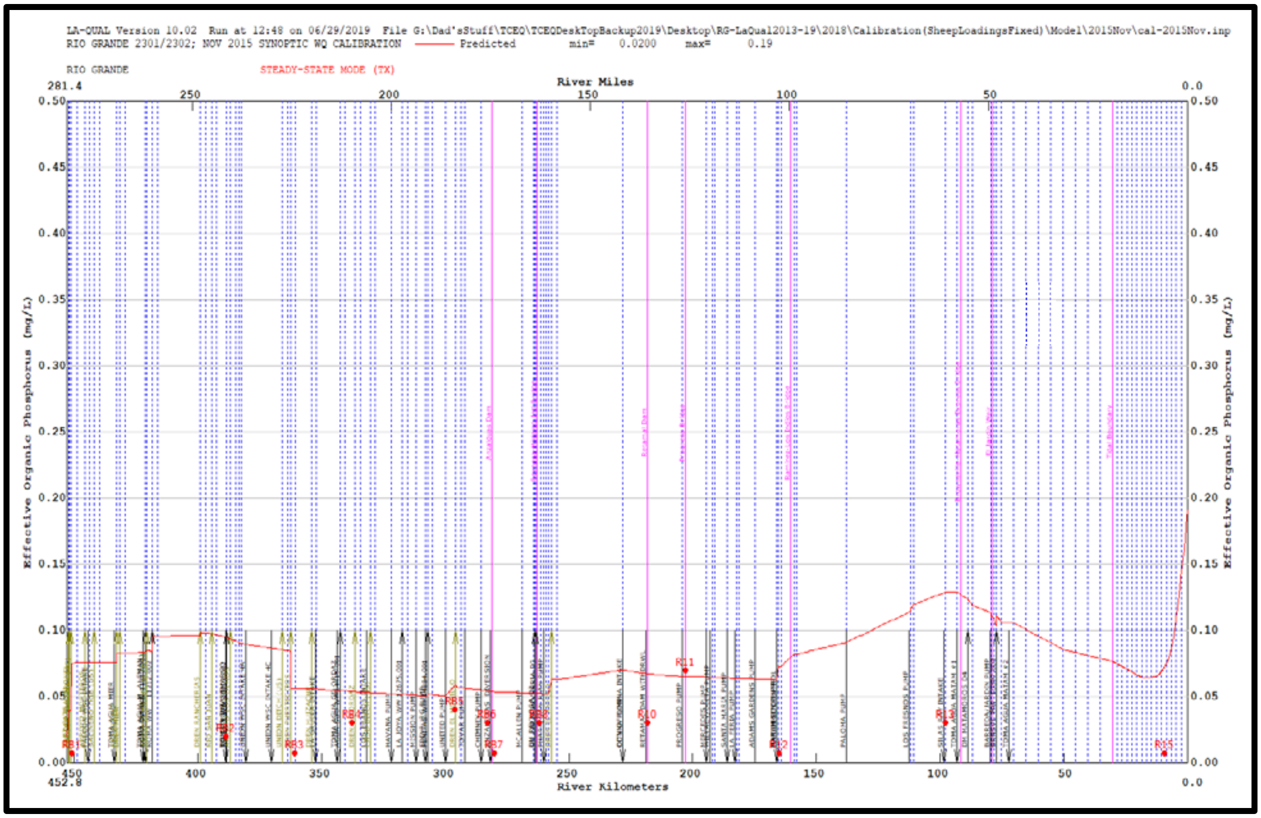


Figure 3-15. Calibration Curve for Effective Organic Phosphorus in the Lower Rio Grande/Río Bravo (Synoptic Survey Data from November 2015).

Model performance is the least robust with regard to the simulation of coliforms. The dataset used to calibrate the models for bacteria contained a number of disproportionately high values for to which no known sources could be linked (Figure 3-16). Faced with the choice of simulating a suspected source of bacteria for which no information was available or of simply ignoring the outlier data, the author, with advice of Bruce Wiland, opted for the latter choice. The author also decided to use all data, including outliers, in the model performance measures partly to call attention to the fact that there are suspected sources of bacteria needing further investigation, a point that was brought to the attention of the Mexican LRGWQI partners during technical discussions within the BTWG.

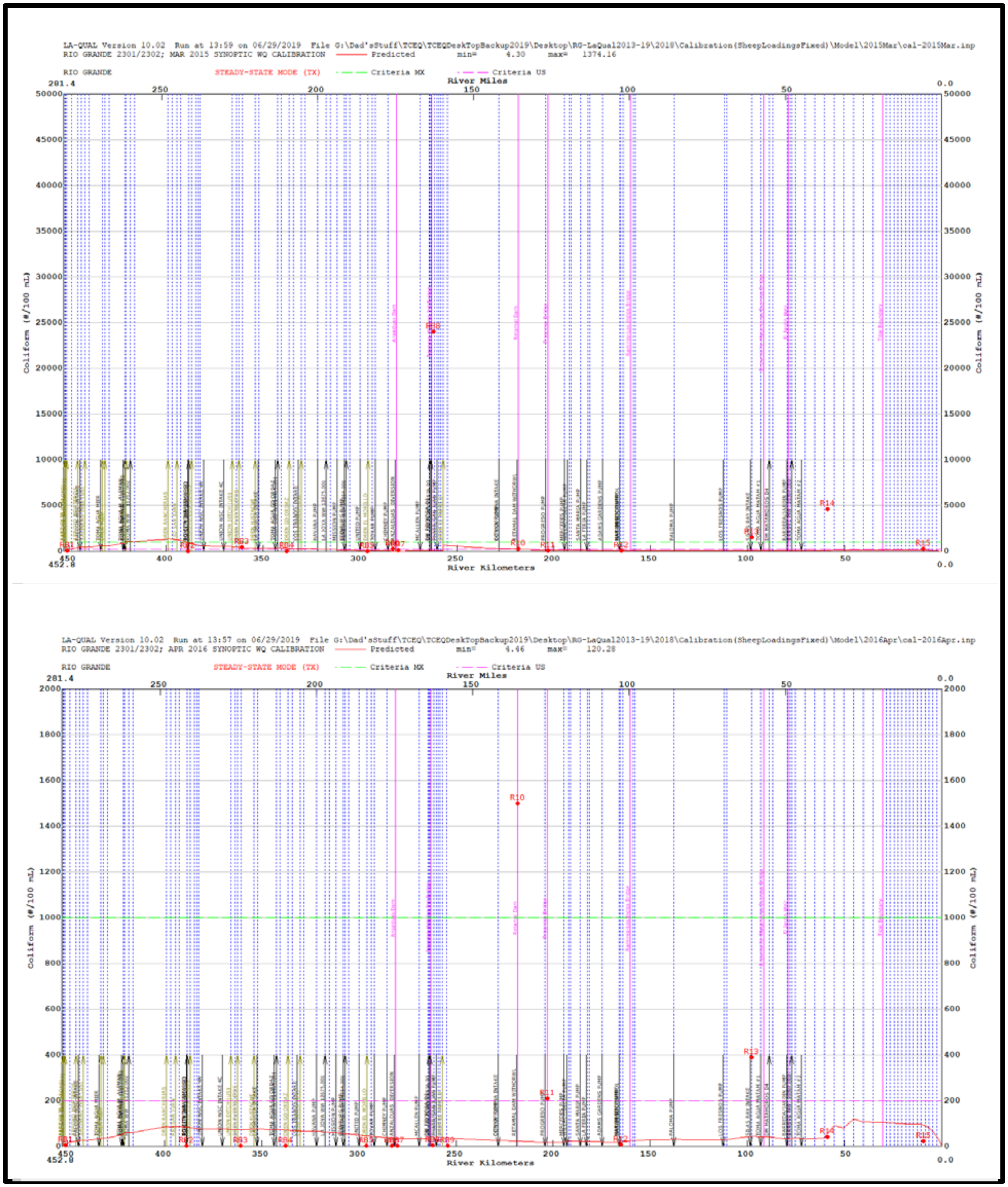


Figure 3-16. Calibration Curves for Coliforms in the Lower Rio Grande/Río Bravo (Synoptic Survey Data from March 2015 and April 2016).

The LRGWQI model parameterization and calibration efforts were an important part of the development of LRGWQIDSS and involved a prolonged technical effort, as well as significant binational interaction between members of the BTWG. In July 2016, after review and approval by the USEPA and USIBWC representatives in the BTWG, the author sent the LA-QUAL input files that represented the final calibrated LRGWQI models to the Mexican representatives in the BTWG along with all raw and processed input and calibration data and model documentation for final Mexican review. In March 2018, the official CONAGUA representative in the BTWG, Jose Alfredo Rojas, approved the models for use in the Declaratoria effort on the Lower Río Bravo and, by extension also, the LRGWQI. Mr. Rojas stated via email "We have reviewed the submitted models and we believe they are satisfactory to progress to the next phase." The official approval, by all members of the of the BTWG, of the calibrated LRGWQI model(s), marked a critical step in the development of the LRGWQIDSS because it legitimized one of the main analytical tools used for decision making in the LRGWQI action arena. While differences in the interpretation of model results are still a possible source of binational disagreement, approval of the LRGWQI models by members of the BTWG allows participants of the work group, and ostensibly also participants in the LRGWQI's national Core Groups and Binational Core Group, to leave behind technical disputes over the analysis tools used for water quality-based decision making.

Binational approval of the LRGWQI models by members of the BTWG signifies two important accomplishments. Although each nation's view of acceptable water quality remains based on its own legal standards, the decision-making processes used by the actors to determine compliance with their standards is, to a greater extent harmonized, in that the participants have agreed on a common model. This is a condition that brings the LRGWQI action arena closer to resembling an archetypical IRC action arena, and CONAGUA's commitment to use the LRGWQI models(s) to develop the Declaratoria for the Lower Río Bravo makes the models part of CONAGUA's regulatory process, effectively institutionalizing the model's use within the Mexican legal/regulatory framework.

3.1.1.5 LRGWQIDSS System Design Description

The components of hardware and software, which represent the top-level architecture of the LRGWQIDSS, are specified in the system's Design Description (Appendix E) along with the manual operations for which the system is designed. The System Design Description also identifies system-wide design decisions, concept of execution, interface design, and requirements-traceability-to-design components.

FILE MANAGEMENT DESIGN

The scope of the LRGWQIDSS, as described in the System Design Description, included three major functions: (1) development of point and nonpoint source loading scenarios; (2) Performing water quality simulations of these scenarios; and (3) visualizing modeling outputs for each scenario. The emphasis on pollutant loading scenarios induced a need for a file management system which creates, stores and retrieves DSS files that are based on pollutant loading scenarios. However, there is also a need to group pollutant loading scenarios linked by common attributes. For example, scenarios simulated under the same [or different] ambient conditions, such as those of a specific binational synoptic event. For this reason, the LRGWQIDSS was designed to create and store files at two levels of attribution, individual scenarios and groups of scenarios called "projects." A LRGWQIDSS project is designed to be composed of all individual scenarios created and saved under that project. The file management design is such that when a project is retrieved, all scenarios created under that project are displayed with all the user-defined values associated with that project.

GEOSPATIAL VISUALIZATION OF MODEL INPUTS AND OUTPUTS

From the start of the design phase for the LRGWQIDSS, the primary role of the system's GUI was described as facilitating and streamlining the preparation of LA-QUAL input files and visually displaying LA-QUAL output. While assumed to be somewhat familiar with the functions of steady state water quality models, the user was not expected to be versed in the use of LA-QUAL nor was the user expected to be skilled in water quality modeling. Conceptually, the look and feel of the GUI was intended, early on in the design phase, to resemble that of GIS software, with interactive features that obviate the need for any significant knowledge of LA-QUAL. Nevertheless, direct access to the LA-QUAL input files is essential to facilitate trouble shooting and mitigate unforeseen difficulties arising from the LRGWQIDSS' creation of input files. Visualization of LRGWQIDSS output was originally limited to enhanced plotting capabilities for

LA-QUAL model output, but was later expanded to include report-style output to accommodate the addition of economics modules.

MODULAR DESIGN

The advantages of modular DSS design were described in Sub-section 2.2.1.9 (Best Practices in DSS Design). The design of the LRGWQIDSS incorporates modularity in two ways, the inherent modularity of GIS is incorporated into the visualization choices of geographic features in the LRGWQIDSS and the functional modularity incorporated in the design of the LRGWQIDSS. Aside from the water quality simulation function, the construction of loading scenarios is segregated into modules that are commensurate with the pollutant source type (i.e., point sources and nonpoint sources) or other factors affecting water quality, such as reductions in instream flow (e.g., headwaters and diversions).

3.1.1.6 Economics Module

The System Design Description document for the LRGWQIDSS does not include a design consideration for estimating scenario costs. While considerations of scenario costs were not explicitly included in the deliberations of the BTWG, the need for incorporating this function into the LRGWQIDSS became apparent, as the transboundary agreement case studies and the results of the institutional analysis indicated the importance of cost as a critical element of decision making. Costs are a concern in both the national Core groups and Binational Core group of the LRGWQI action arena and costs are particularly important in the Mexican and US wastewater treatment action arenas. The author worked with the UT-BEG development team to design a DSS module capable of assessing costs of implementing different loading scenarios simulated using the other modules in the LRGWQIDSS.

3.1.2 DETAILED ARCHITECTURE OF LRGWQIDSS

The following is a top-level description of the system architecture for the LRGWQIDSS. The system-wide design was developed through iterative modification and was influenced by the feedback received from the target users within the BTWG. The LRGWQIDSS is a package of individual open source software components assembled under a Python-based script. The Python programming language, used to develop the LRGWQIDSS, is platform independent. However, as previously mentioned, the program is designed to be a stand-alone Microsoft Windows-based application, the installation software for which can be downloaded form an ftp site or installed manually from disk or USB storage device.

3.1.2.1 Functional Architectural Design

The principal feature of the LRGWQIDSS is the Graphical User Interface (GUI), which allows the user to create LA-QUAL model input files. This function is subdivided into two principal tasks, which represent the input of pollutants into the river from the two principal sources, point sources and nonpoint sources. Figures 3-17 and 3-18 shows the conceptual LRGWQIDSS GUI designs for point source and nonpoint source pollutant inputs, respectively, into the LA-QUAL input file.

The LA-QUAL modeling software itself was modified by Bruce Wiland of Wiland Consulting Inc., to accommodate the GUI design. The architectural design of the LRGWQIDSS follows an object-oriented approach. Three top-level system functionality groups were identified during the system design conceptualization effort (Figure 3-19). These functionality groups were then differentiated into subsystems and the connection and communication among the subsystems was identified and characterized (Figure 3-20).

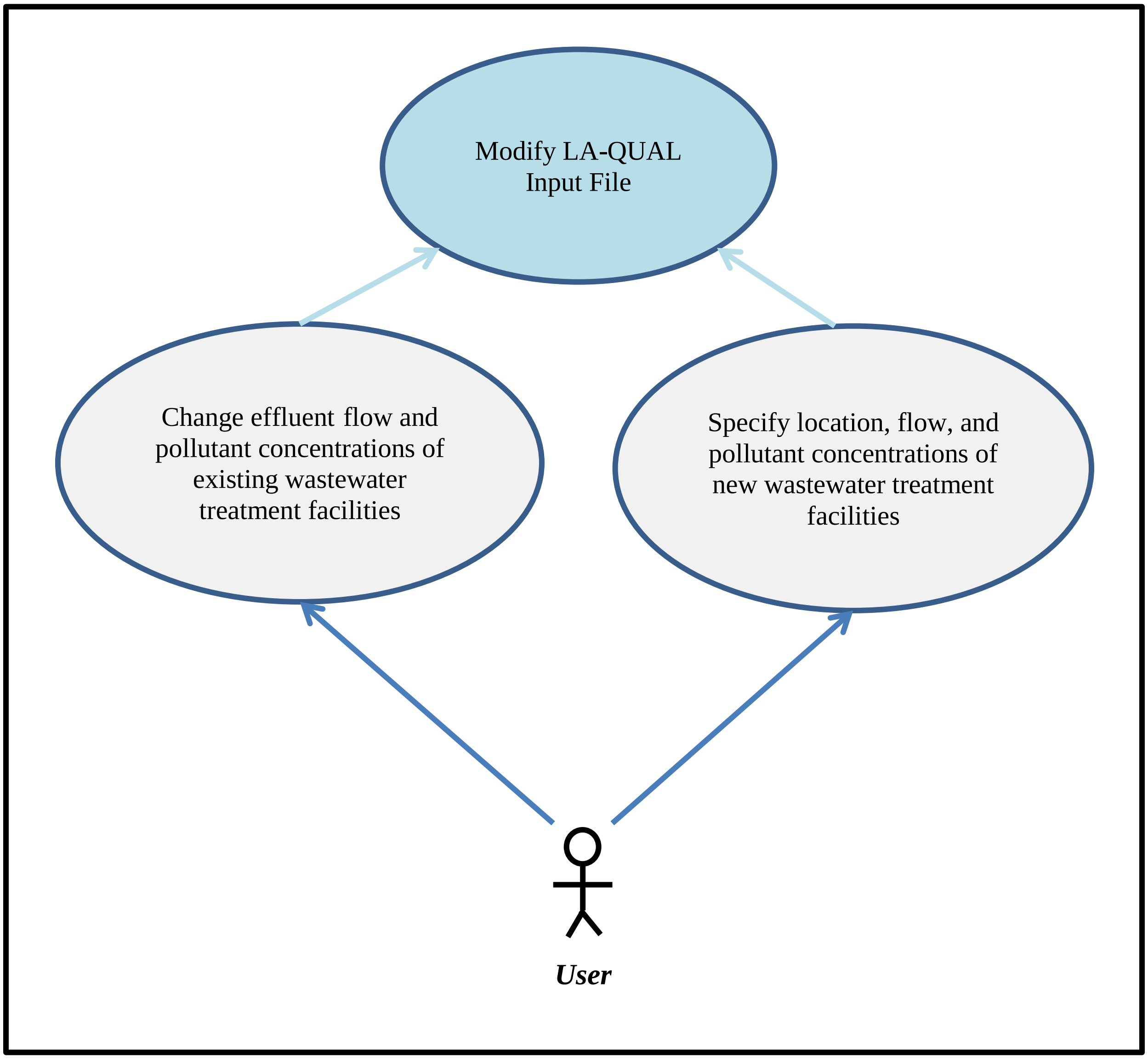


Figure 3-17. Use Case Task for Point Source Pollutant Loading in the LRGWQIDSS GUI.

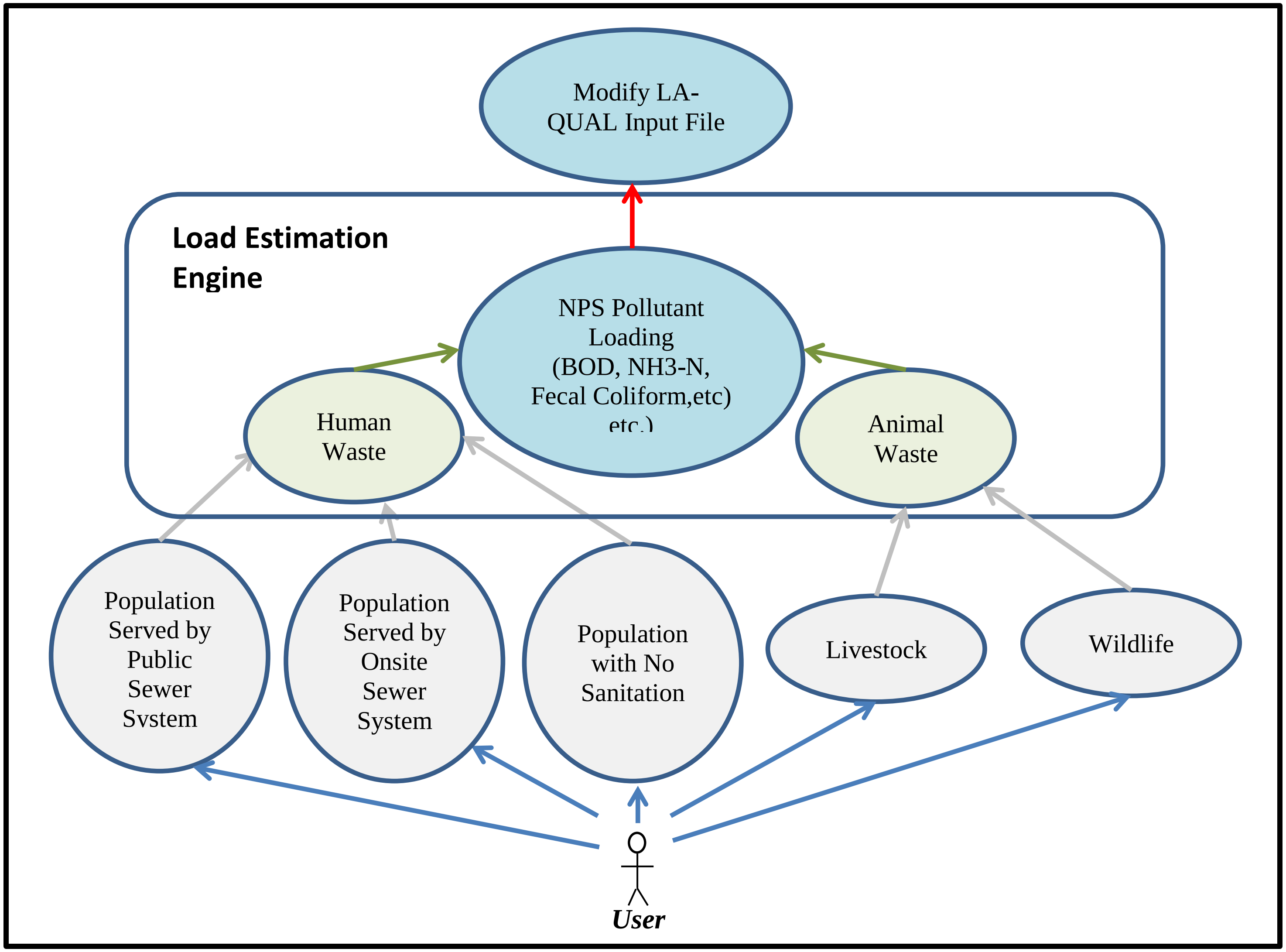


Figure 3-18. Use Case Task for Nonpoint Source Pollutant Loading in the LRGWQIDSS GUI.

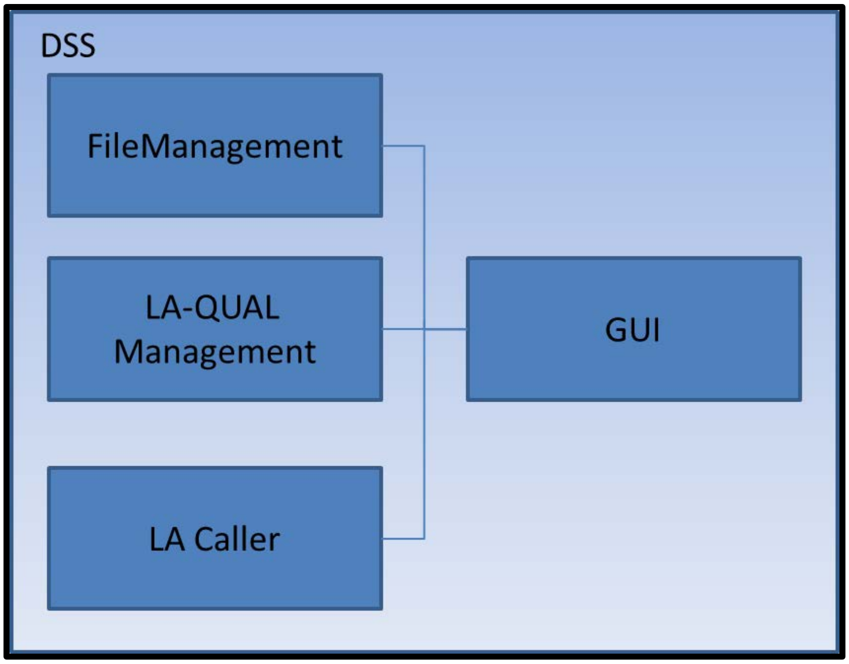


Figure 3-19. Overall System Architecture for the LRGWQIDSS. Source: LRGWQIDSS System Design Description, 2013 (Appendix E).

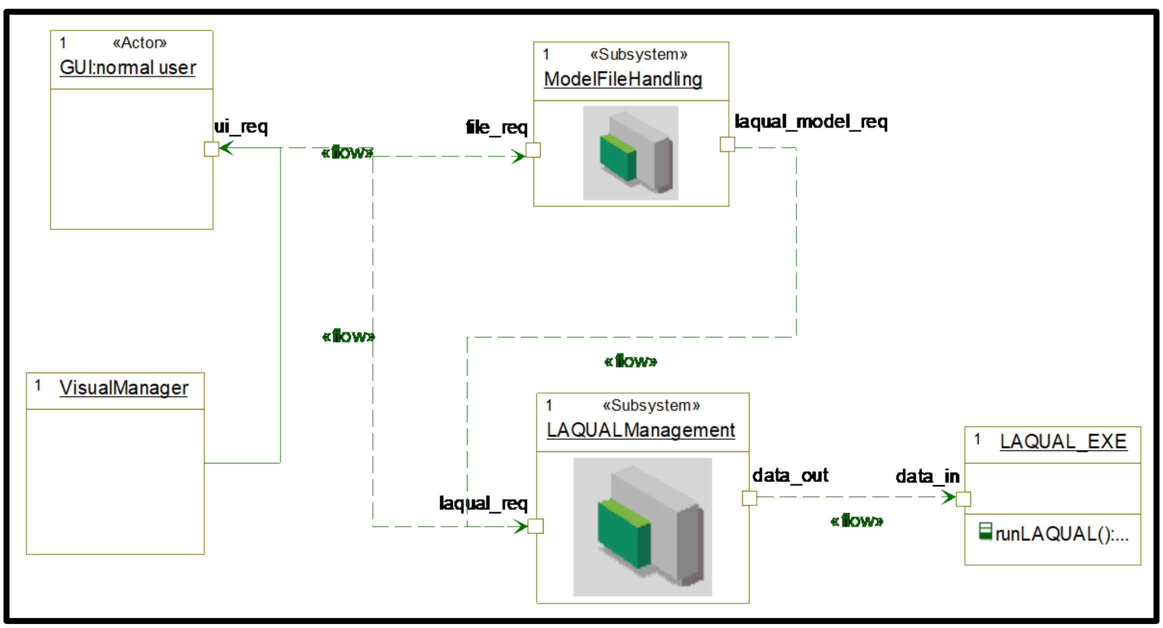


Figure 3-20. Structural Design Diagram of the LRGWQIDSS. Source: LRGWQIDSS System Design Description, 2013 (Appendix E).

The LRGWQIDSS GUI is composed of four main internal functions (Figure 3-20):

1. Model File Handling - provides the input-output support needed to manipulate LA-QUAL input files
2. LA-QUAL Management - provides support to generate valid LA-QUAL input files
3. LA-QUAL Exe - is the external LA-QUAL program executable
4. Visual Manager - loads map files and enables simple GIS operations (e.g., displays coordinates)

The flow of data and information between functions is routed through five main "data ports" associated with each functional component (Figure 3-20):

1. UI_req - provides event handler for GUI inputs
2. File_req - provides file handler for loading and parsing the LA-QUAL input files
3. LA-QUAL_model_req - populates the DSS GUI with information persisted in LA-QUAL model
4. Data_out - generates a valid LA-QUAL input file
5. Data_in - reads the LA-QUAL input file and executes LA-QUAL

Of the components shown in Figure 3-20, the Visual Manager is perhaps the most important component for enhancing visualization. The Visual Manager is GIS-based, allowing the user to build scenarios visually, selecting point- or polygon-based control and management actions from a menu and specifying where those management actions are to be simulated simply by pointing and clicking on a zoomable map of the study area. The LA-QUAL Management component transforms the user-supplied information into commands supplied to the Model File Handling tool, which in turn, generates or modifies an LA-QUAL input file. Options for running the LA-QUAL executable file are available in the Visual Manager, which also displays graphs of in-stream concentrations of water quality constituents resulting from the user-specified simulations for each planning scenario.

The GUI Sequence Diagram (Figure 3-21) depicts the navigation hierarchy and sequence of events and operations that emanate from the GUI. The user functions addressed by the GUI include four functional categories:

1. Model File Handlers - This category of functions supports the save/create/load activities related to the LA-QUAL model
2. Map Handlers - This category of functions supports map displays
3. Scenario Handlers - This category of functions supports specification of point and nonpoint sources in a scenario
4. Run Handlers - This category of functions supports the launch of the LA-QUAL executable

As mentioned previously, the LRGWQIDSS was developed using only open source software. The LRGWQIDSS GUI was developed by the UT-BEG development team in Python code in the ECLIPSE Integrated Development Environment (IDE) with the PyDev Python code editor and compiler. For version control, UT-BEG used the code repository software Apache Subversion. The LRGWQIDSS uses the open source database engine SQLite for database storage and management and the open source GIS software QGIS for all geospatial functions. To generate plots from the LA-QUAL output, the LRGWQIDSS uses the open source plotting software Matplotlib. To program the LRGWQIDSS GUI, UT-BEG used the open source application programming interphase PyQT.

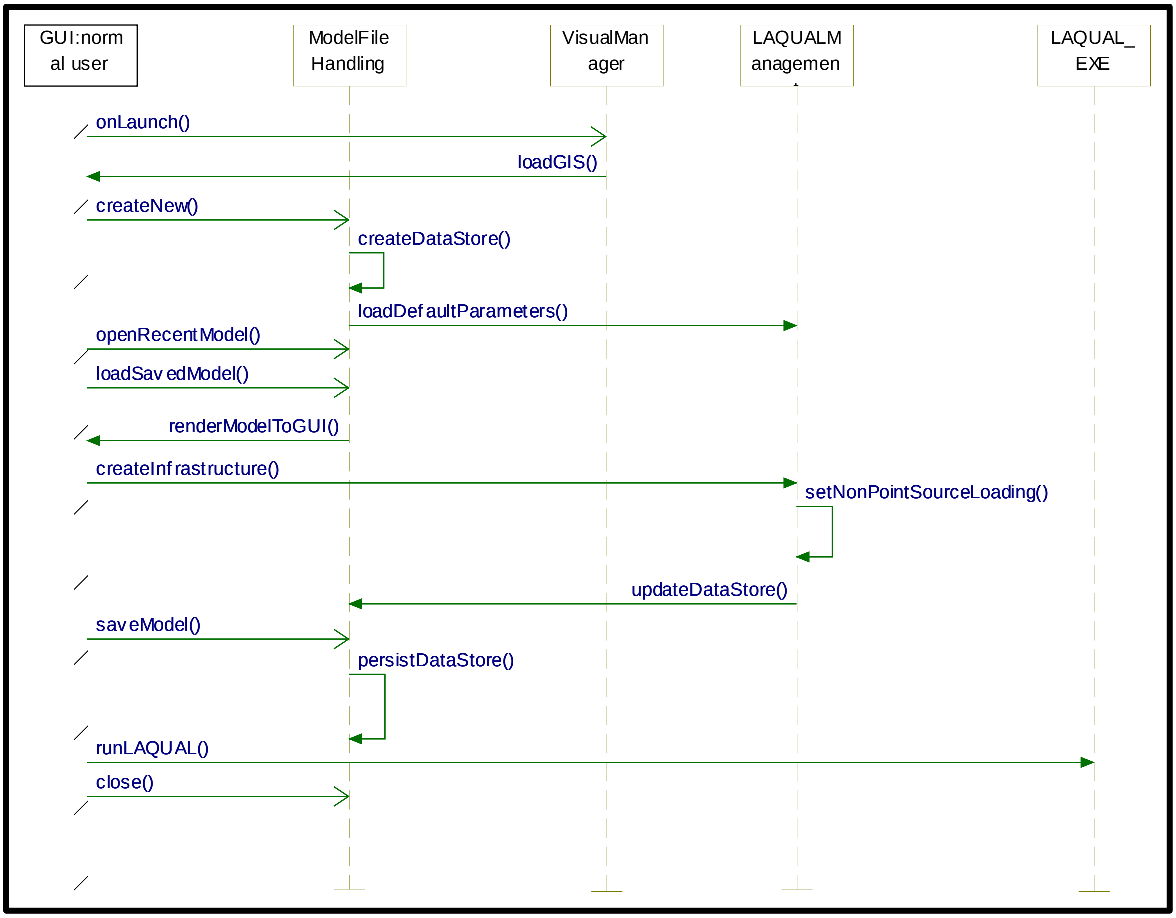


Figure 3-21. Sequence Diagram of the LRGWQIDSS. Source: LRGWQIDSS System Design Description, 2013 (Appendix E).

3.2 The LRGWQIDSS In 2019

From a focus-based classification perspective, the LRGWQIDSS is both an EDSS and a SDSS with a strong focus on decision making associated with water quality. Under the DSS typology classification described by Holsapple (2008), the LRGWQIDSS is best described as a compound DSS, as it incorporates a number of separate tools offered to the user for decision making. Although, the decision-making tools rely on a system of internal databases, the LRGWQIDSS does not fit the classification of a database-oriented DSS because it does not offer the user functions normally associated with relational databases, such as search and data mining/data extraction capabilities. Instead, the LRGWQIDSS provides functions associated mostly with fixed solver-oriented systems. The set of fixed solvers in the LRGWQIDSS are arranged in the form of independent models that carry out functions such as estimation of point source and nonpoint source pollutant loadings, regulation of headwater flows in the river and its tributaries, simulation of flow diversions along the river, simulation of water quality from combined actions included in pollutant loading scenarios, estimation of scenario costs, etc. Although the LRGWQIDSS cannot be classified as a MCDSS, because it does not provide a score based on an index or other alternative ranking algorithm, the system provides the user at least two major criteria for decision making, water quality and cost. The following sub-section provides a description of the features of the LRGWQIDSS as of 2019.

3.2.1 Overview of the LRGWQIDSS Software

Currently the LRGWQIDSS is designed to run on a Windows 7 or 10 operating system. To properly view the graphics output, Windows settings for the display area should be set to a resolution of at least 1024x768 for both screen and desktop.

3.2.1.1 Installation

The LRGWQIDSS software must be installed through the execution of the installer software < LRGWQIDSSsetup.exe> which is a self-extracting executable. During the installation process, the installer must also be able to access (two) separate installation file(s) < LRGWQIDSSsetup-1.bin> and < LRGWQIDSSsetup-2.bin> which are part of the installation package. To mitigate concerns expressed by the Mexican LRGWQI Partners about exposing monitoring data gathered during the LRGWQI synoptic surveys prior to the promulgation of the Río Bravo Declaratoria, the LRGWQIDSS installation process is password-protected. The LRGWQIDSS executable file can be installed in any directory on the user's computer. However, the installer recommends the user install the executable in the root directory of user's computer c:/LRGWQIDSS. The installer will also provide an option to create a shortcut on a Windows® desktop.

Figure 3-22. Image of the LRGWQIDSS Desktop Shortcut.

The shortcut icon can also then be dragged to the Taskbar on the user's Windows desktop. The LRGWQIDSS program icon will also appear in the list of programs in the Start Menu. Total installation time varies depending on the storage capacity and random-access memory (RAM) of the system onto which the program is being installed, but usually ranges between 10 and 12 minutes. When the installation setup program has completed the installation, a final window will appear alerting the user that the installation setup program has finished installing LRGWQIDSS on the computer. Clicking on the "Finish" button exits the installer. However, before exiting the installer, the user is provided the option of launching the LRGWQIDSS program upon exiting the installation setup program. Checking the box next to "Launch LRGWQIDSS" avails the user of this option.

Figure 3-23. Image of the Final LRGWQIDSS Setup Program Window.

The LA-QUAL software imbedded in the LRGWQIDSS uses external programs to edit the input files and view the output files. The default programs that the model uses for editing input files and viewing plain-text output files are the Notepad and WordPad utilities that normally come pre-installed with most Windows operating systems. The default program used for viewing rich-text files is Microsoft Word which may or may not be installed on the user's computer. If Microsoft Word, is not available to the user, the rich-text viewer in the Preferences option of LA-QUAL can be changed to WordPad which will also read rich-text files. In order for these external programs to work, the program directories must be in the system path specified in LA-QUAL. Normally, these directories are already in the system path. If this is not the case, the user can either add them to the system path or provide the full path to the programs in the Preferences options of LA-QUAL.

3.2.1.2 Graphical User Interface (GUI)

Double clicking on the LRGWQIDSS shortcut or selecting the program from the Windows Start menu launches the LRGWQIDSS.

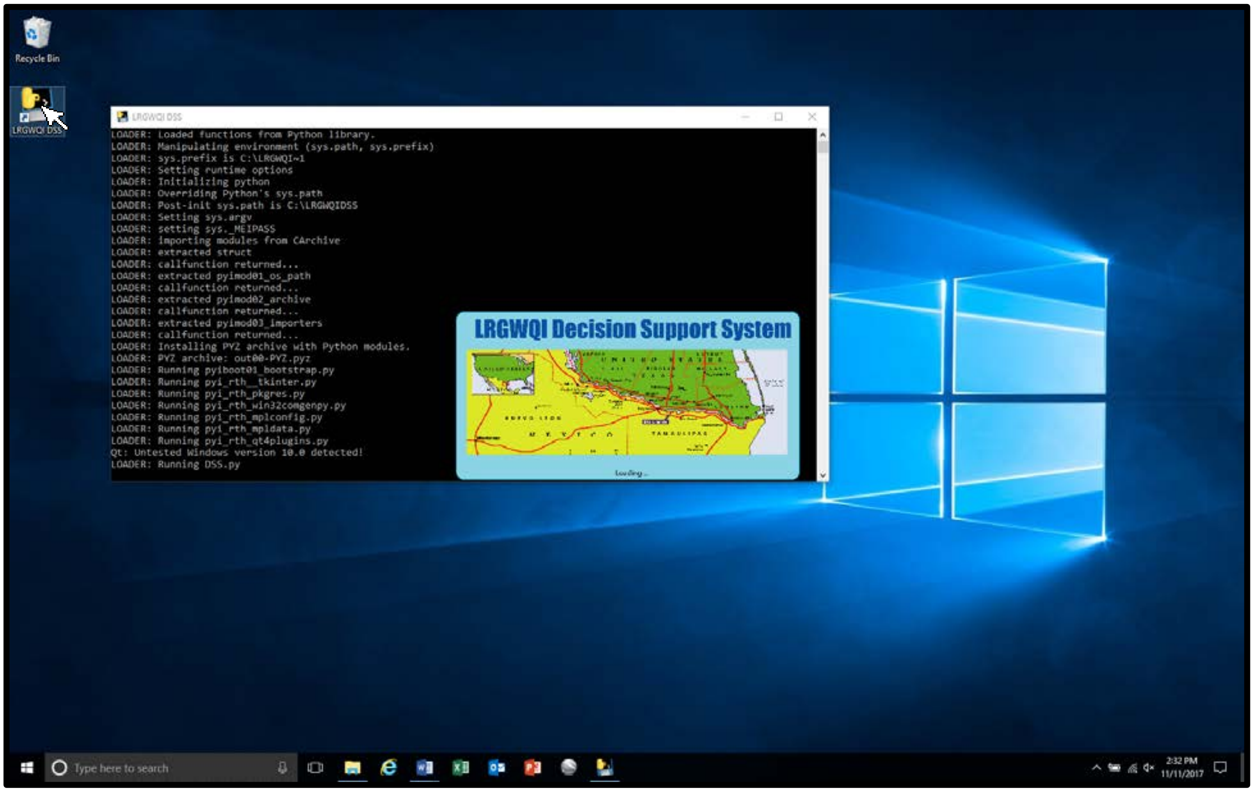


Figure 3-24. Computer Monitor Screenshot of the LRGWQIDSS Splash Screen and Background Loader Command Scroll.

A command prompt window will appear displaying background loader commands followed by the LRGWQIDSS splash screen and the LRGWQIDSS graphical user interface (GUI).

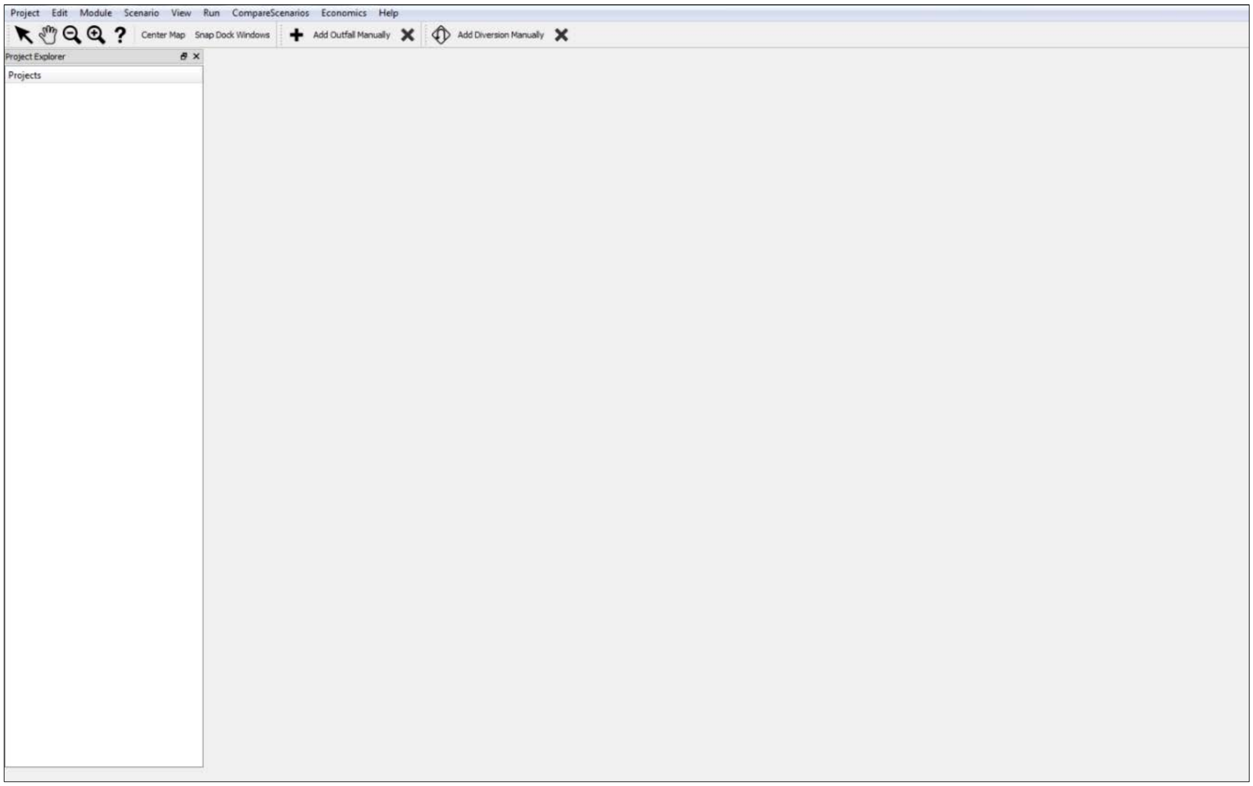


Figure 3-25. Home Window of the LRGWQIDSS Graphical User Interface (GUI).

The main menu bar at the top of the GUI is comprised of nine components, Project, Edit, Module, Scenario, View, Run, CompareScenarios Economics and Help. Clicking on any component of the main menu bar will display a pull down menu containing additional functions specific to each main menu bar component.

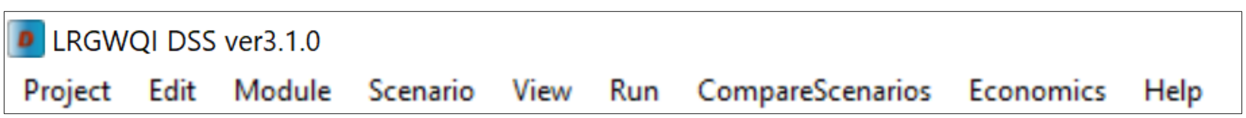


Figure 3-26. Main Menu Bar of the LRGWQIDSS Graphical User Interface (GUI).

3.2.1.3 Creating Projects

In order to access the full capabilities of the LRGWQIDSS the user must create a project. Projects are collections of scenarios created under the same project file name. The map displays will not appear on the Project Explorer window unless a project is created and at least one scenario is created in that project.

PROJECT SETUP WIZARD

To create a new project, the user must click once on the Project component in the main menu bar at the top of the GUI and select “New…”

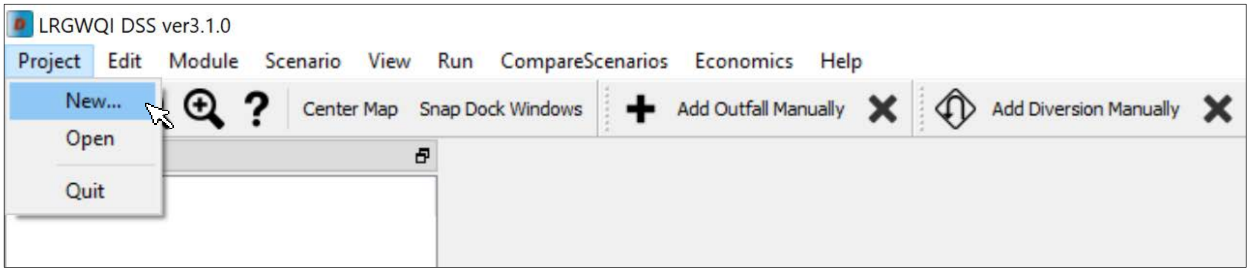


Figure 3-27. Project Component of the Main Menu Bar of the LRGWQIDSS GUI.

A dialogue box will appear with a space in which the user can enter a project name.

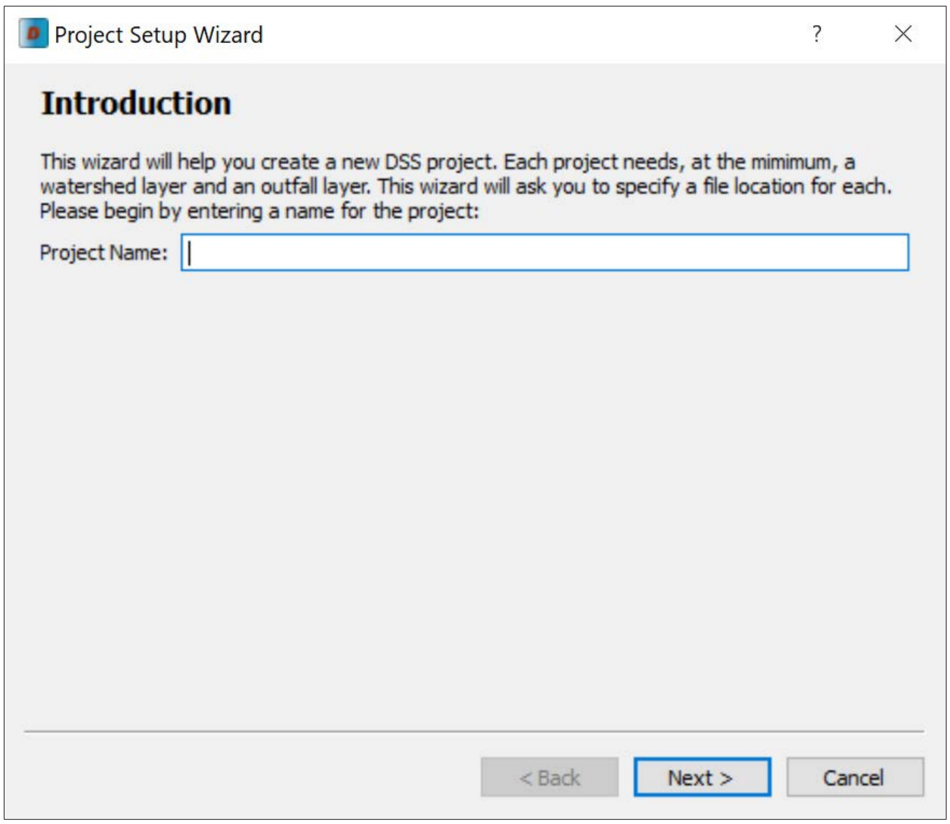


Figure 3-28. Project Setup Wizard of the LRGWQIDSS.

After naming the project, and clicking the “Next” button, subsequent windows in the Project Setup Wizard will ask for geographic information sytem (GIS) layers to load into the project. At a minimum, the user must specify a watershed layer and an outfall layer. The wizard will ask the user to specify a file location for each layer. However, a suggested layer will already appear in the “Add Watershed Layer” dialogue box. Clicking the “Next” button will load the GIS layer suggested by the LRGWQIDSS in the dialogue box (recommended).

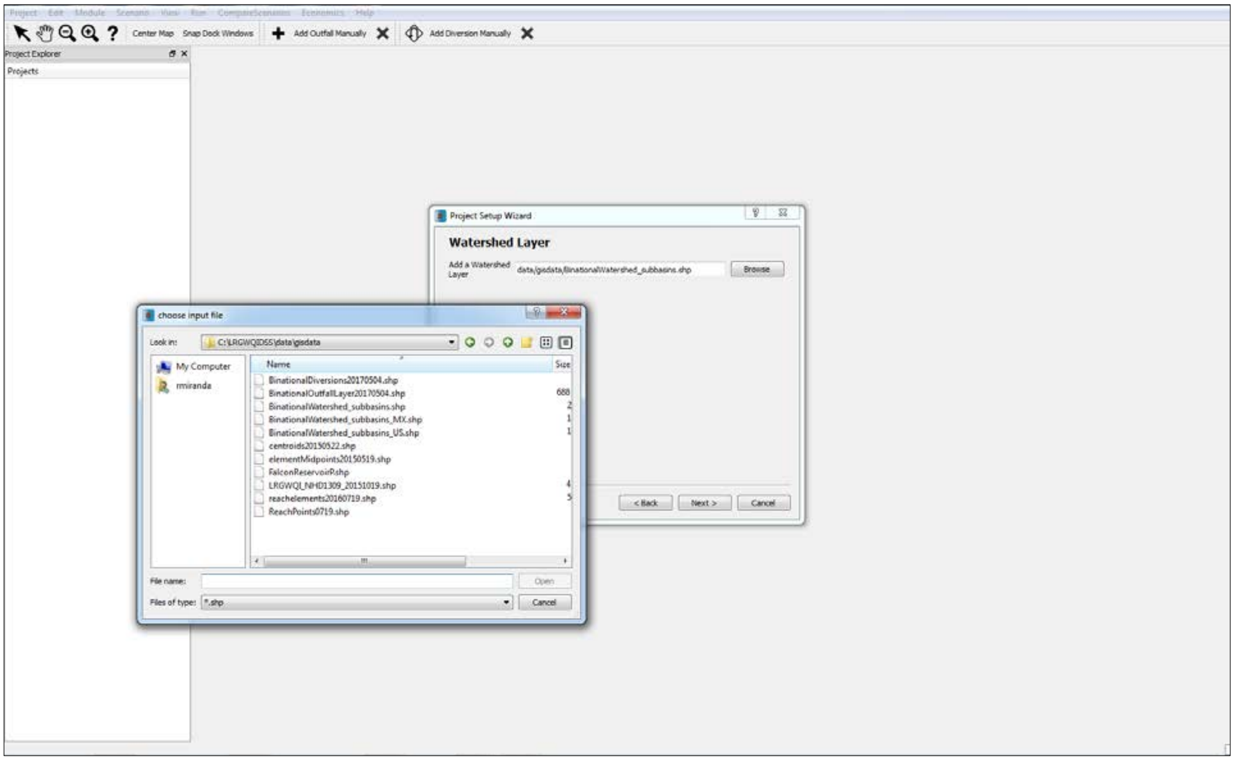


Figure 3-29. The “Add Watershed Layer” Dialogue Box of the Project Setup Wizard of the LRGWQIDSS.

GIS layers come preloaded into the directory ...\LRGWQIDSS\data\gisdata, which is created during the program installation. Clicking on a file in the “choose input file” directory window selects the file that will be used in the project. Clicking the “Open” button in this dialogue box chooses the selected file, which will then appear in the “Add…” line of the Project Setup Wizard window. Clicking the “Next” button will input the file into the project and will move the Project Setup Wizard to the next file selection dialogue box. This process is repeated until all project GIS and input layers are loaded into the new project. Once all GIS layers are loaded into the project, the “Set the Extent” dialogue box will appear.

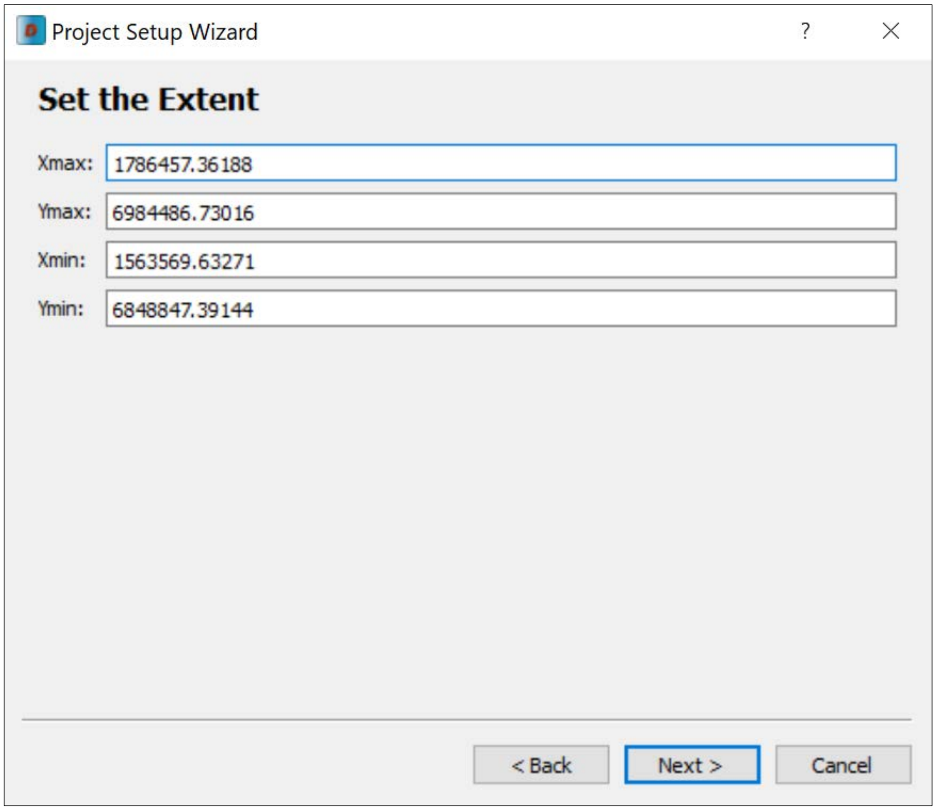


Figure 3-30. The "Set Extent" Window of the Project Setup Wizard of the LRGWQIDSS.

This dialogue box sets the map display area. Unless there is an intense area of focus in mind, the user is urged to simply accept the default Xmax, Xmin, Ymax and Ymin settings prespecified in this dialogue box by clicking the "Next button. The coordinates are specified as cartesian grid coordinates, not latitude and longitude. Reverting to the recommended view will require the specification of the exact coordinates shown above.

The last dialogue box of the Project Setup Wizard is the "LA-QUAL Input" dialogue box.

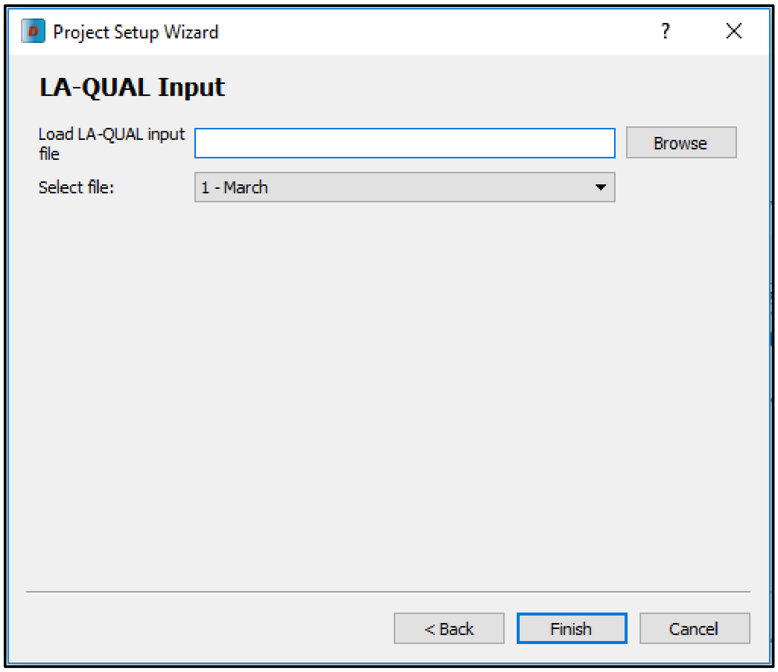


Figure 3-31. The "LA-QUAL Input" Dialogue Box of the Project Setup Wizard of the LRGWQIDSS.

The user can select from one of the LA-QUAL input files currently available in the LRGWQIDSS by clicking on the "Browse" button and selecting it from the pull-down menu.

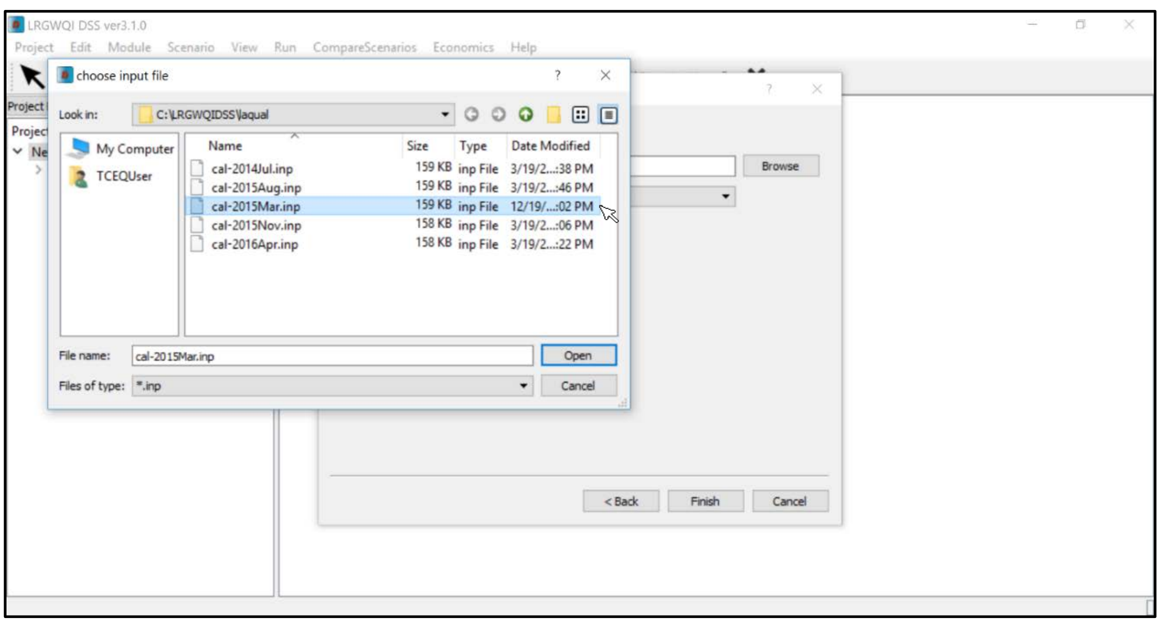


Figure 3-32. Pull-down Menu of the "LA-QUAL Input" Dialogue Box of the Project Setup Wizard of the LRGWQIDSS.

The input files correspond to the models of the synoptic surveys used to calibrate the LRGWQI models. Clicking on the "Open" button loads the input file into the project. The pop-up window will disappear and the selected LA-QUAL input file will display in the "load LA-QUAL input file" line of the "LA-QUAL Input" dialogue box . In addition to selecting an LA-QUAL input file, the user must also select a commensurate nonpoint source file corresponding to the same month as that of the LA-QUAL input file selected. This is done using the pull-down menu next to the "Select file" dialogue in the "LA-QUAL Input" dialogue box.

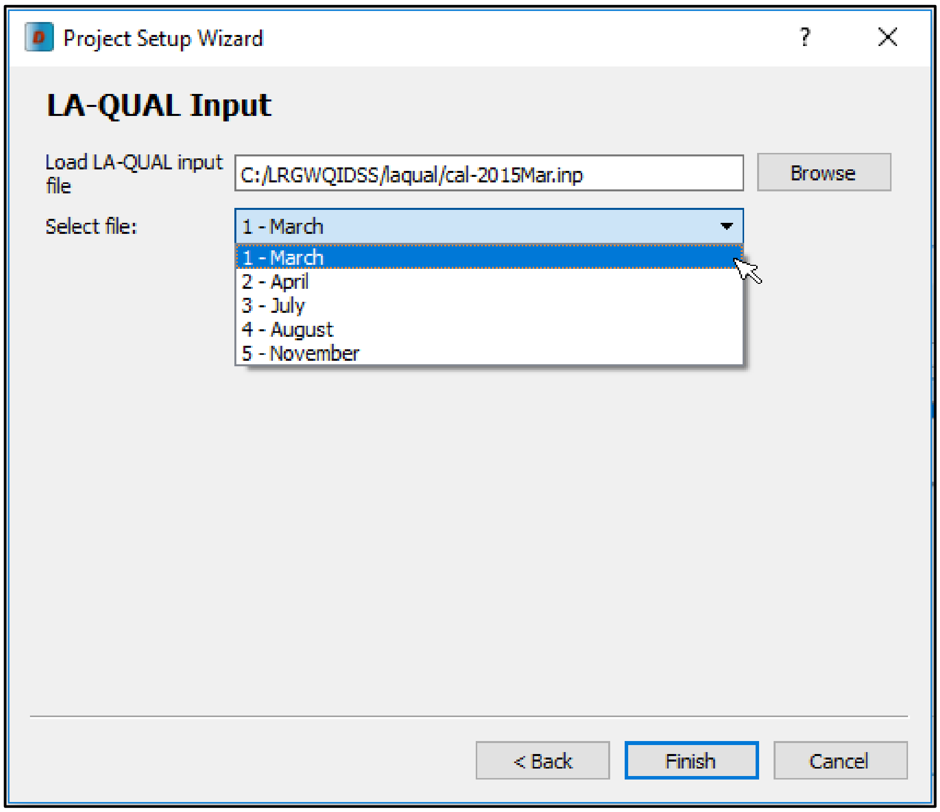


Figure 3-33. Nonpoint Source File Selection in the Project Setup Wizard of the LRGWQIDSS.

Clicking the "Finish" button closes the Project Wizard and loads the Project into the LRGWQIDSS GUI. The newly created Project will appear in the Project Explorer window.

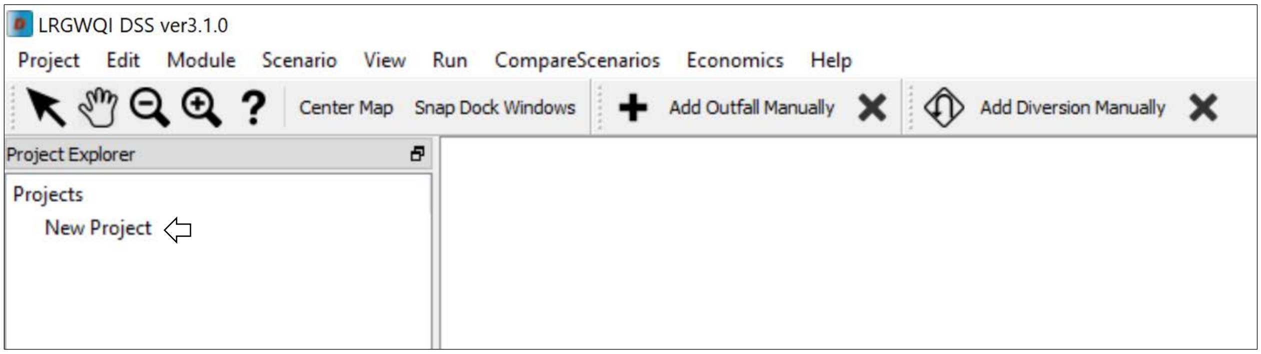


Figure 3-34. New Project Displayed in the Project Explorer Window of the LRGWQIDSS GUI.

Projects can be saved, closed and reopened much like the files in other commercial software programs. To load a saved project, the user must click once on the Project button in the main menu bar at the top of the GUI and select the project from "Load Project" popup window. Clicking the "Open" button in this pop-up window loads the selected Project, which will then appear in the Project Explorer window of the GUI.

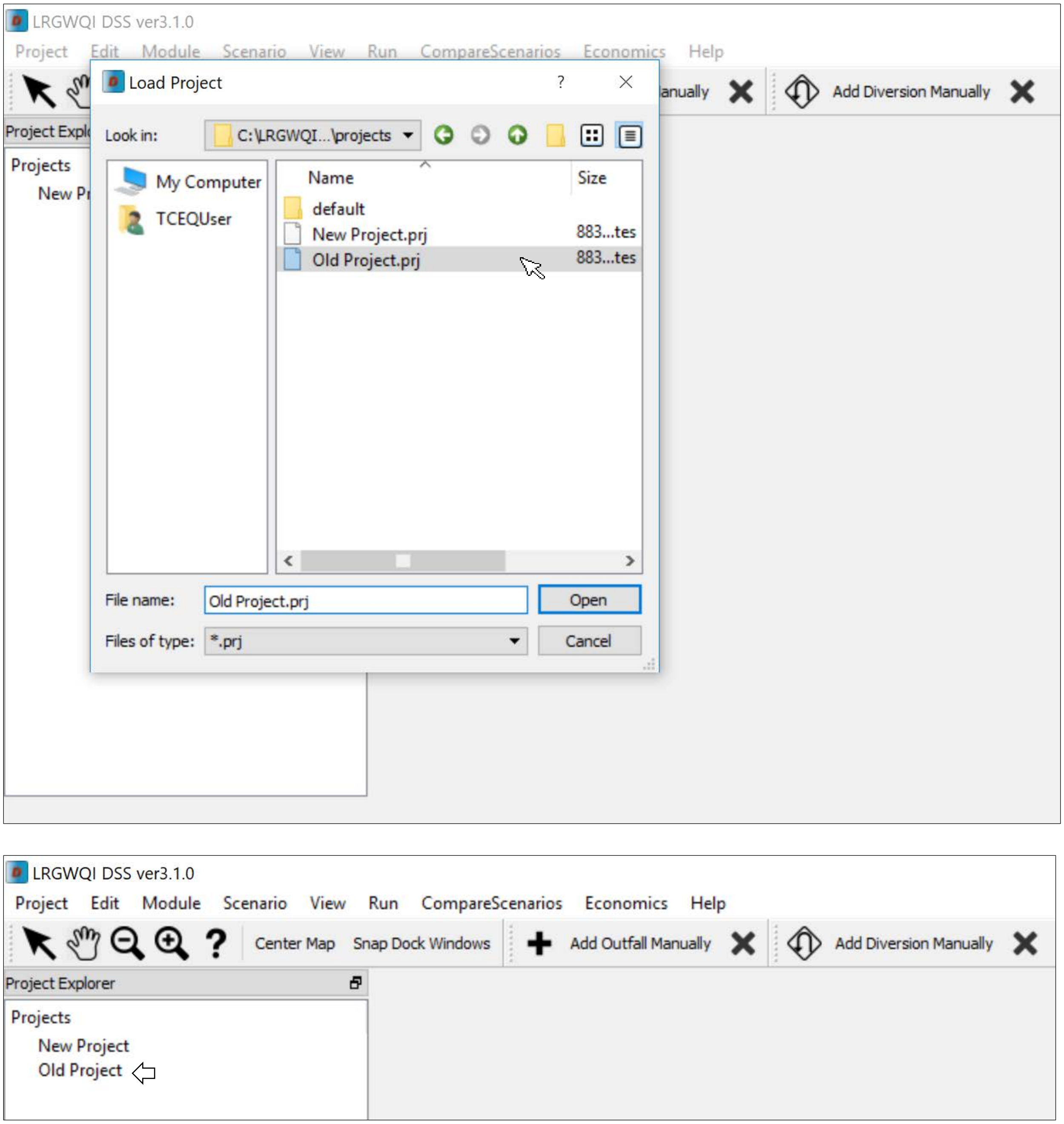


Figure 3-35. The "Load Project" Pull-down Menu of the Project Component of the Main Menu Bar of the LRGWQIDSS GUI.

Creating Scenarios

As previously mentioned, Projects in the LRGWQIDSS are composed of "scenarios." In order to use the full capabilities of the LRGWQIDSS, the user must create at least one scenario under each Project created using the Project Setup Wizard. Scenarios are created using the "Scenario" component of the main menu bar at the top of the LRGWQIDSS GUI.

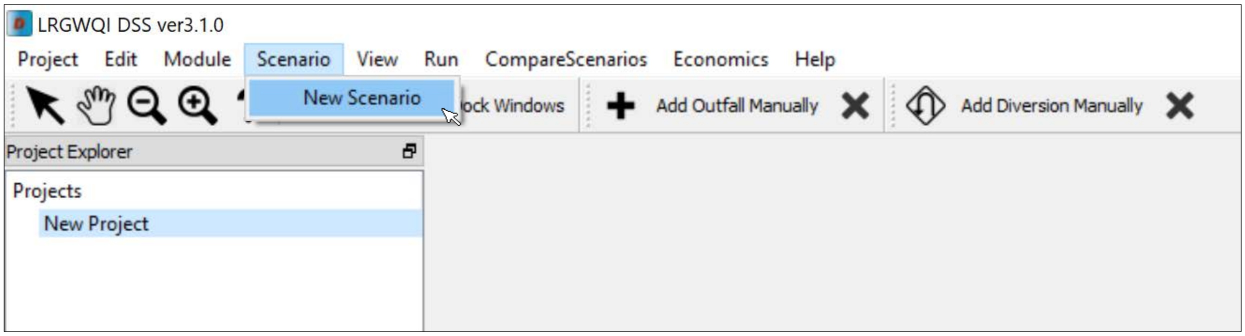


Figure 3-36. Creating a New Scenario in the Scenario Component of the Main Menu of the LRGWQIDSS GUI.

Clicking on "New Scenario" from the pull down menu under the Scenario component of the main menu bar displays the "Create Scenario" dialogue box.

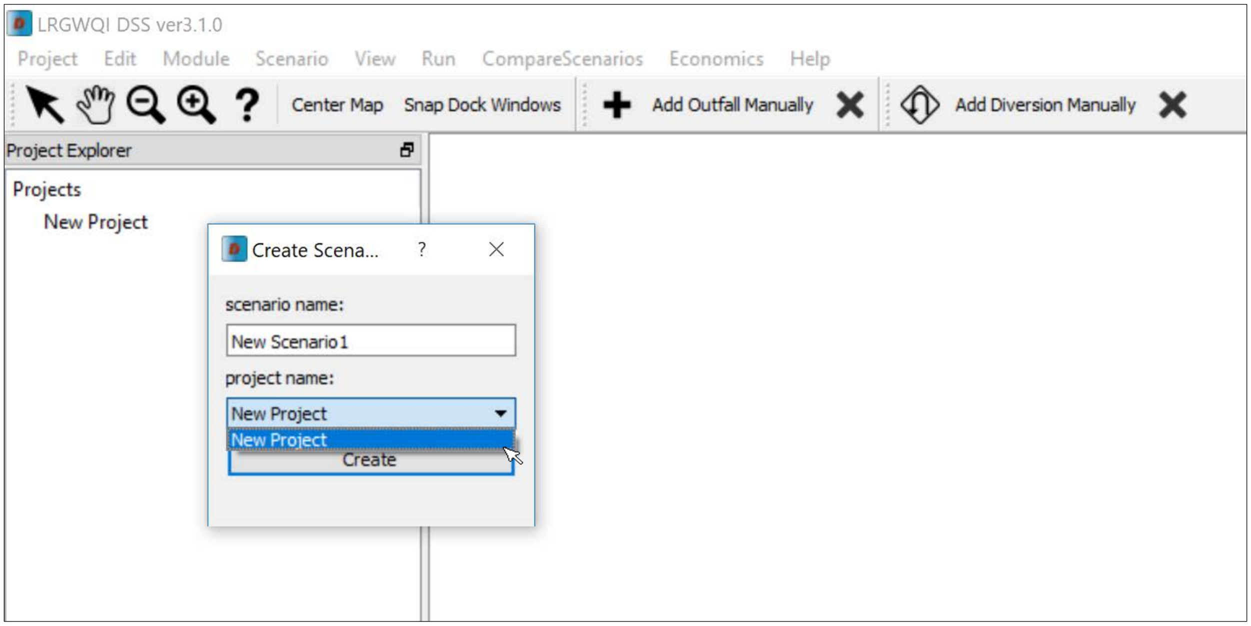


Figure 3-37. The "Create Scenario" Dialogue Box of the Scenario Component of the LRGWQIDSS GUI.

In addition to providing a name for the newly-created scenario, the user must also specify the Project under which the new scenario will be included. This can be done using the pull down menu under the "project name" dialogue. Not making this specification can result in the new scenario being included under the wrong Project. Clicking on the "Create" button in the "Create Scenario" dialogue box creates the scenario in the Project specified under "project name" dialogue. The newly created scenario is displayed automatically in the "Project Explorer" window.

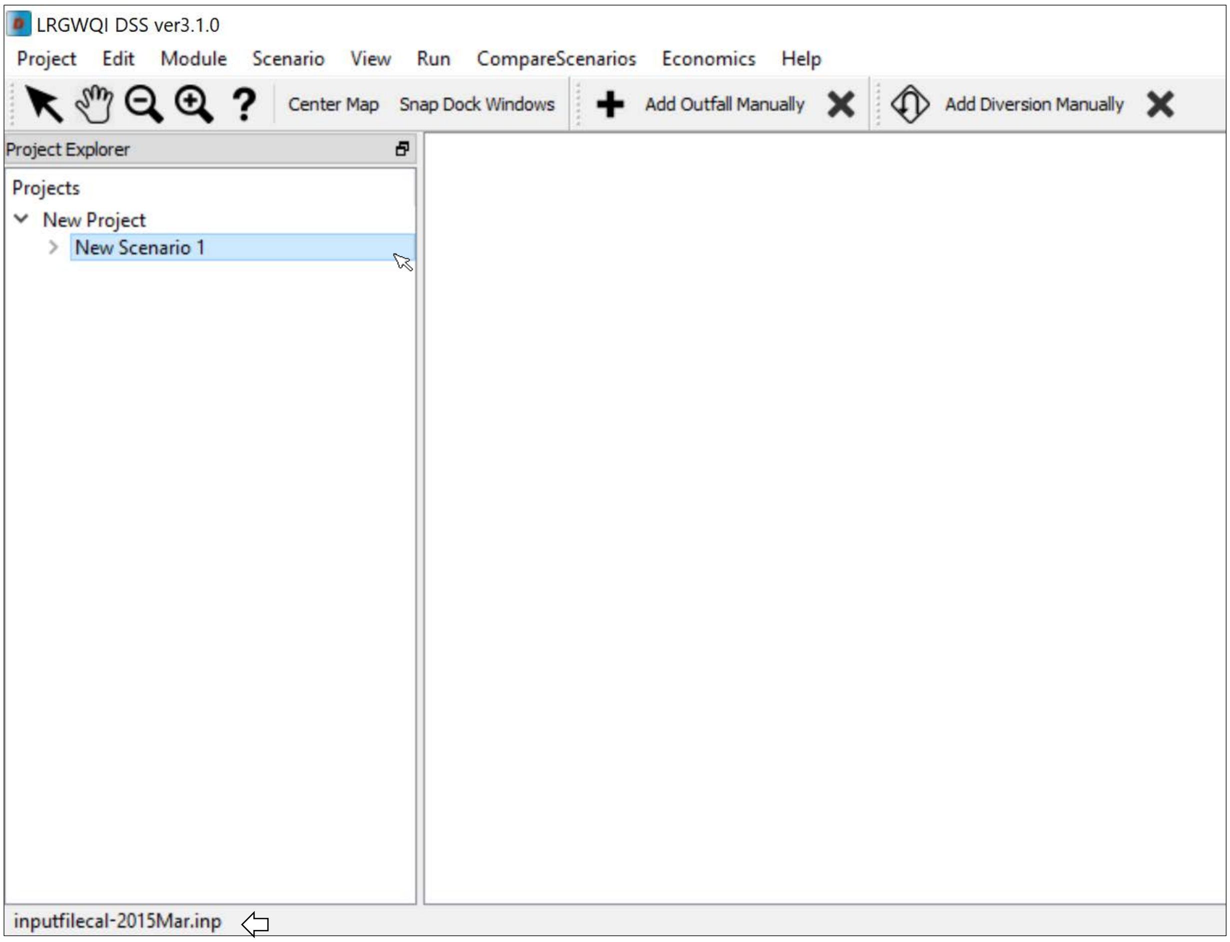


Figure 3-38. New Scenario Displayed in the "Project Explorer" Window of the LRGWQIDSS GUI.

Clicking on the new scenario once makes it active. The "Module," "View" and "Run" components of the main menu bar will not function unless a scenario is selected (made active). The name of the LA-QUAL input file associated with the Project under which the scenario was created is displayed at the bottom left corner of the LRGWQIDSS GUI.

3.2.1.4 Selecting and Viewing Project Scenario GIS Layers

To display the GIS layers selected during the Project setup, the user must select the "Settings" option in the pulldown menu under the "View" component of the main menu bar; a check mark will be placed on that option following its selection.

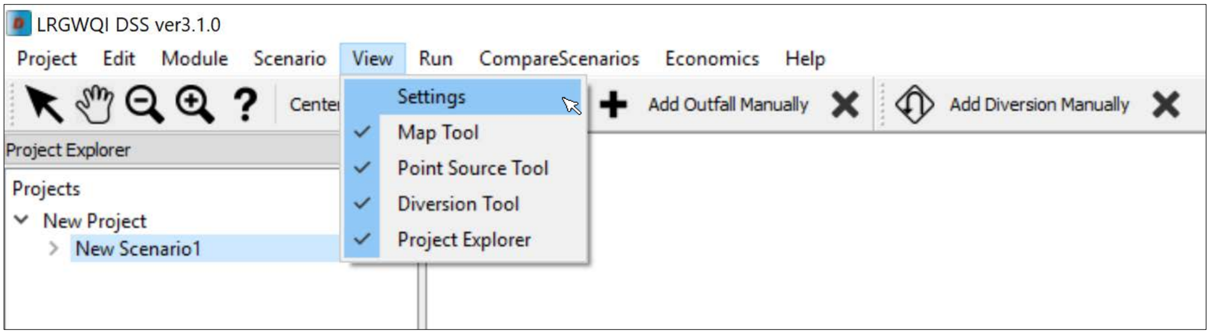


Figure 3-39. The "Settings" Option of the View Component of the Main Menu Bar of the LRGWQIDSS GUI.

The "View" component of the main menu bar also controls the display of the tools in the LRGWQIDSS tool bar (discussed later in the following sub-section).

Figure 3-40. The LRGWQIDSS Tool Bar in the LRGWQIDSS GUI.

Checking the "Settings" option in the "View" component of the main menu bar will display the "Visibility Settings" window beneath the "Project Explorer" window.

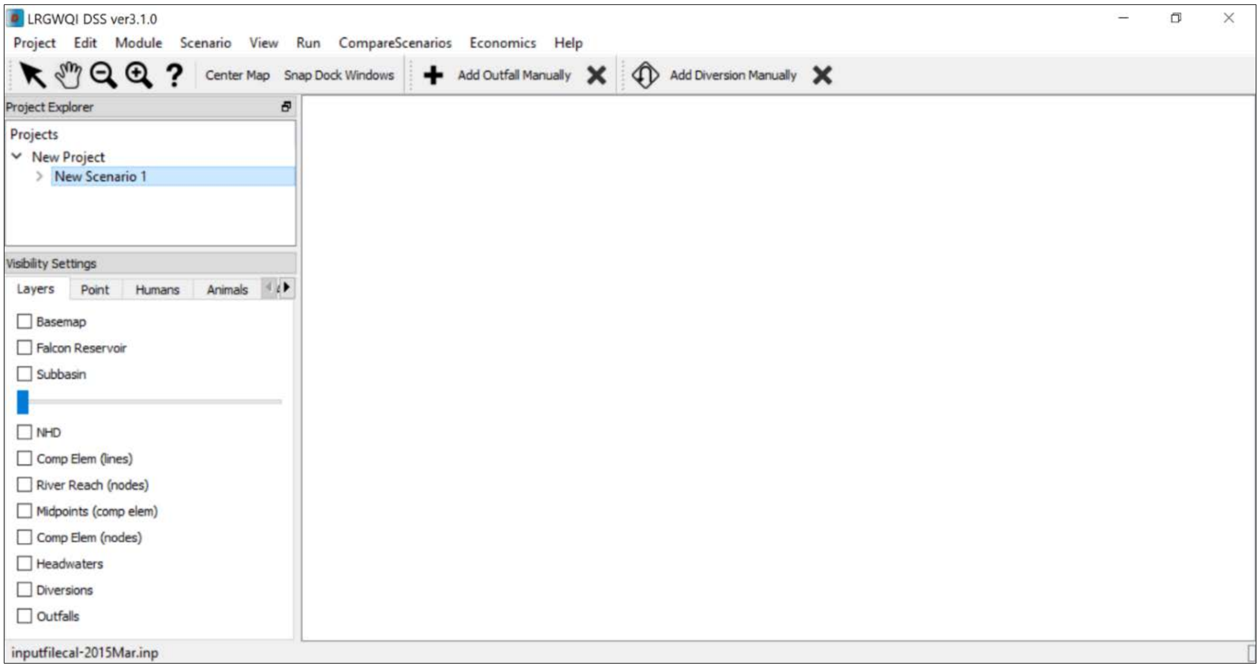


Figure 3-41. The "Visibility Settings" Window in the LRGWQIDSS GUI.

The "Visibility Settings" window consists of seven tabs, "Layers," "Point," "Humans," "Animals," "Ag," "Headwaters," and "Diversion." The "Layers" tab controls the display of layers in the map window. The rest of the tabs in the "Visibility Settings" window control the information displayed in the Module tables which are discussed in the following sub-section. The user can select from a menu of GIS layers offered in the "Layers" tab of the "Visibility Settings" window. The menu of GIS layers in this tab reflects the choices made by the user during the Project Setup Wizard.

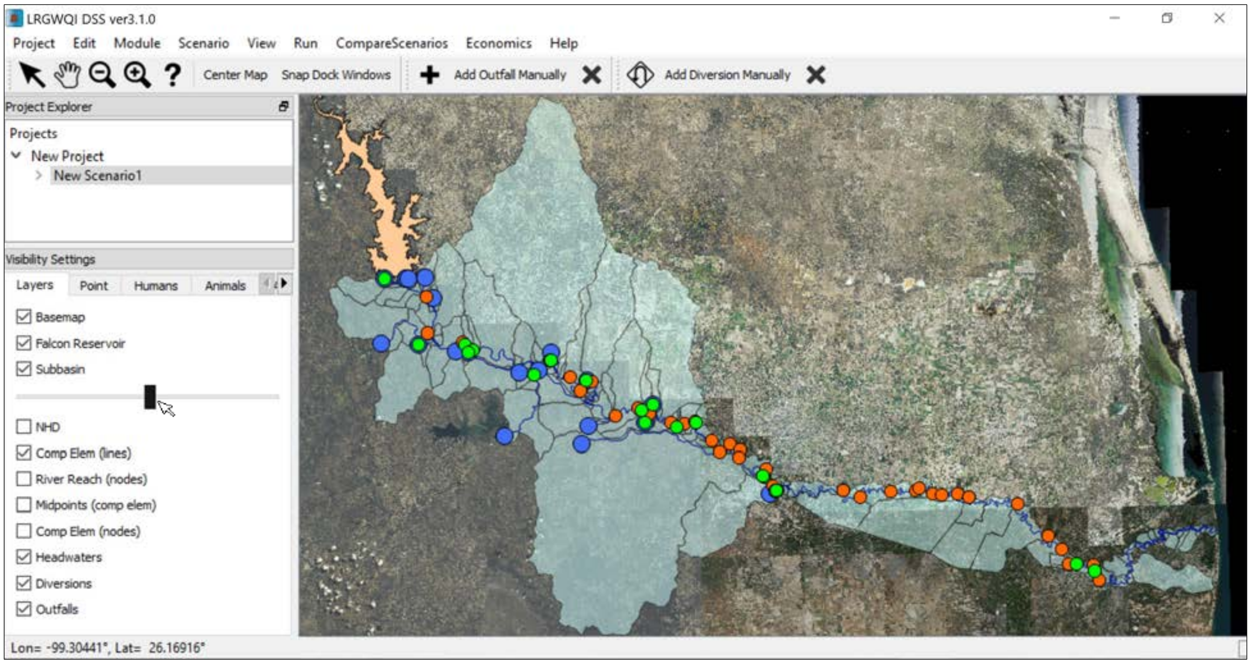


Figure 3-42. The “Layers” Tab of the “Visibility Settings” Window in the LRGWQIDSS GUI.

Clicking on the box next to a GIS layer in the “Layers” tab of the “Visibility Settings” window displays the GIS layer in the “Map” window. The slide bar controls the transparency of the sub-basins that form the Lower Rio Grande/Río Bravo watershed. By checking or unchecking the boxes next to the various layers in the “Layers” tab of the “Visibility Settings” window, a user can turn the layers on or off in the “Map” window. The transparency or opaqueness of the watershed layer is controlled by the slide bar under the “Sub-basin” layer. A user may also wish to display a more detailed hydrographic layer (i.e., the USGS’ National Hydrographic Dataset [NHD]). However, only the hydrography displayed in the layer named “Comp Elem (lines)” is associated the LA-QUAL model. The computational element boundaries and midpoints of the LA-QUAL model can also be displayed by checking the boxes next to the layers named “Comp Elem (nodes)” and “Midpoints (comp elem).”

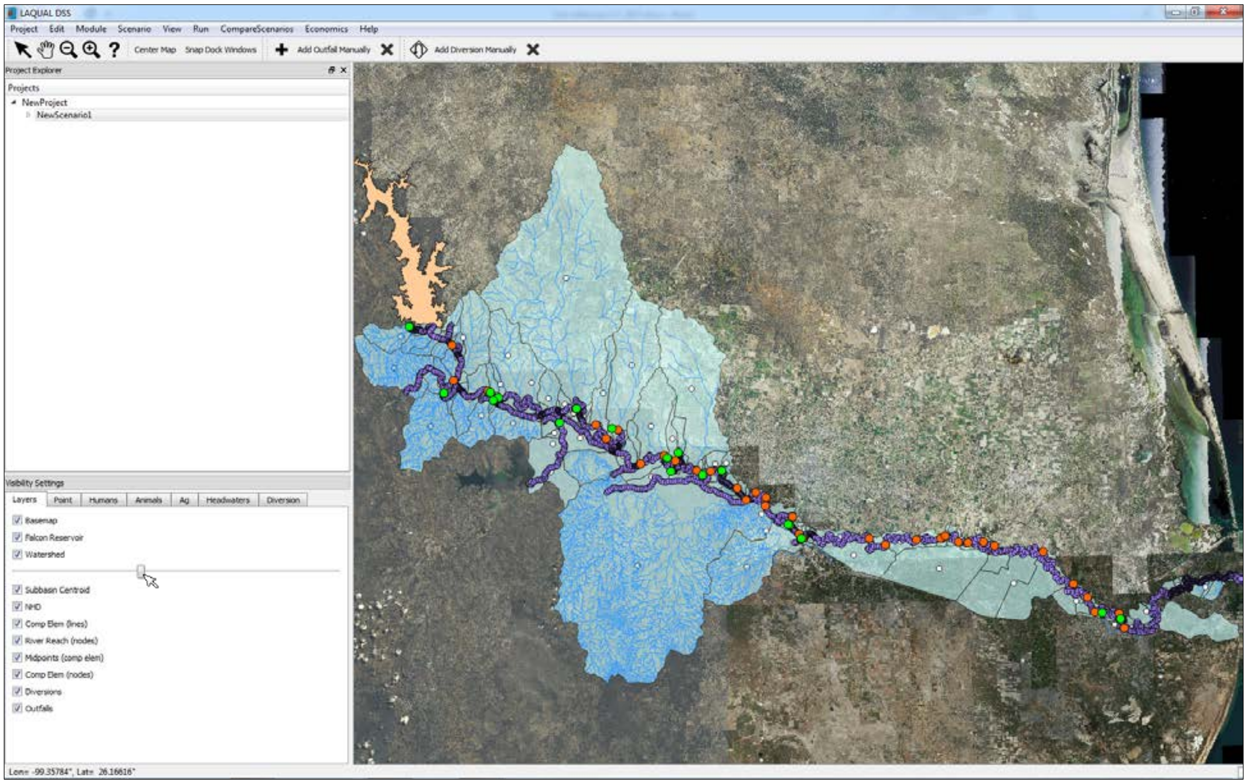


Figure 3-43. GIS Layers Displayed in the "Map" Window of the LRGWQIDSS GUI.

The "Visibility Settings" window can be hidden by unchecking the box next to "Settings" in the pull-down menu of the "View" component of the main menu bar.

COMPUTATIONAL ELEMENTS, REACHES, AND SUB-BASINS

The "Comp Elem (lines)" layer, in the "Layers" tab of the "Visibility Settings" is a visual (geographic) representation of the LA-QUAL model domain. In the LA-QUAL model, computational elements are grouped into 147 separate reaches which are arranged contiguously end-to-end forming a segmented (discretized) hydrography layer; as previously mentioned, each river reach is itself composed of computational elements.

The "Headwaters" point layer shows the nodes that define the upstream boundaries of each of the headwater reaches in the LA-QUAL model. The "River Reach (nodes)" point layer shows the nodes that define the upstream boundaries of all other river reaches in the LA-QUAL model. The nodes of the "River Reach (nodes)" layer also define the pour points (downstream boundaries) of the sub-basins associated with each of the river reaches. All the point and nonpoint sources contributing pollutants of concern to the computational elements of a particular river reach are located within the sub-basin associated with that particular river reach. Therefore, there are 147 sub-basins corresponding to the 147 river reaches. The “Comp Elem (nodes)” point layer shows the nodes that define the upstream boundaries of the computational elements within each of the reaches of the LA-QUAL model. The “Midpoints (comp elem)” point layer defines the midpoint of each of the computational elements of the model.

3.2.1.5 Map Tools

The Map Tools allow the user to visually navigate the Map window, as well as select and display information about the layers shown in the Map. The LRGWQIDSS GUI maps tools afford the user many of the capabilities available in other commercial GIS software.

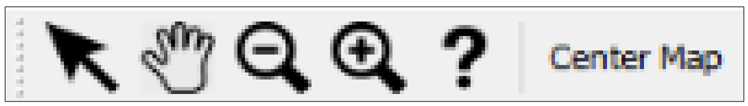


Figure 3-44. The Map Tools in the Tool Bar of the LRGWQIDSS GUI.

POINT TOOL 

The Point Tool displays the coordinates of the location, on the map, where the tip of the arrow of the Point Tool is pointing. The longitude and latitude of the location are displayed, in decimal degrees, at the lower left corner of the GUI window.

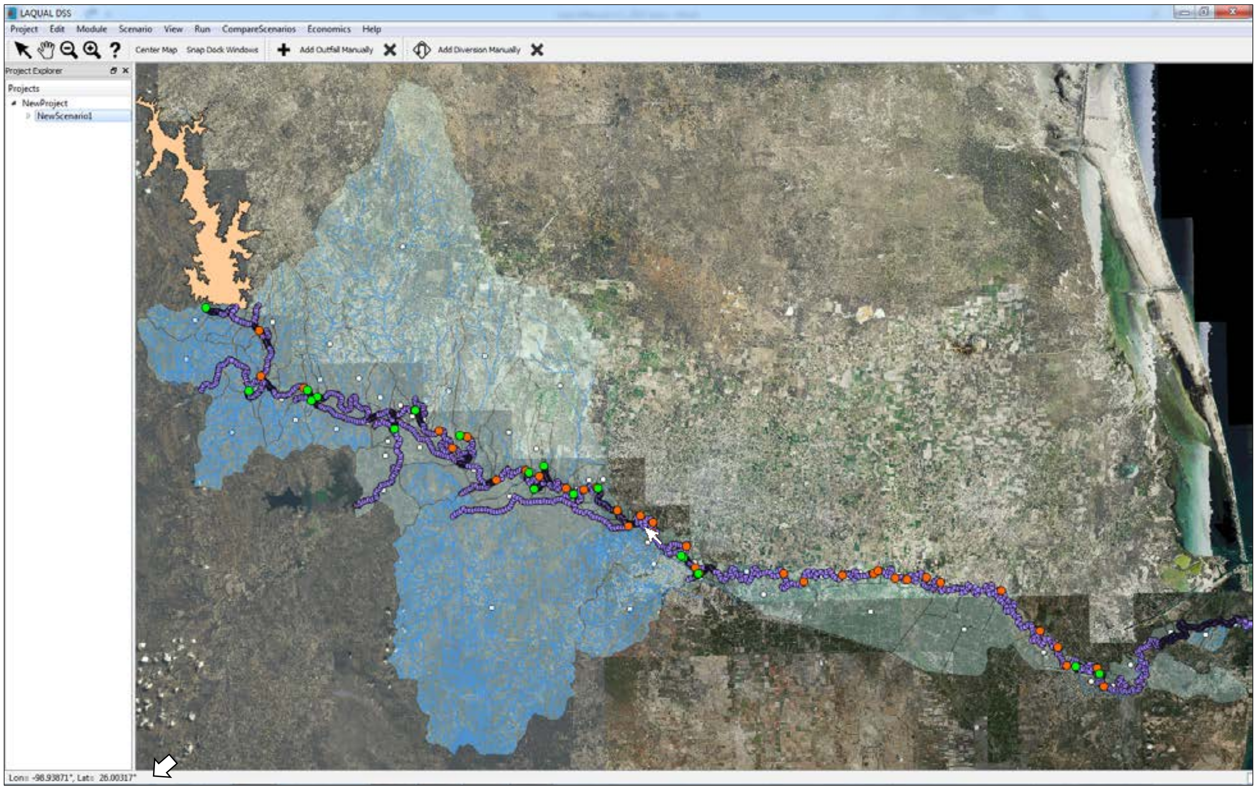


Figure 3-45. Using the Point Tool to Determine Latitude and Longitude.

PAN TOOL 

The Pan Tool allows the user to pan across the map extent. This tool is most useful when used in combination with zoom tools, as the full map extent of the LRGWQI is limited to a 31,725 km^2 quadrant.

ZOOM TOOLS 

The Zoom tools allow the user to zoom in and out of the map view in the “Map” window. Clicking on the “Zoom-In” tool  activates the tool. Once activated, the tool appears in place of the cursor on the “Map” window. Clicking once on the map will zoom to a view extent resulting from a pre-set zoom multiplier (4x). Dragging a box diagonally over the area of interest while pressing and holding the left mouse button zooms into the area defined by the drag box. The “Zoom-out” tool  works the same way, but in reverse.

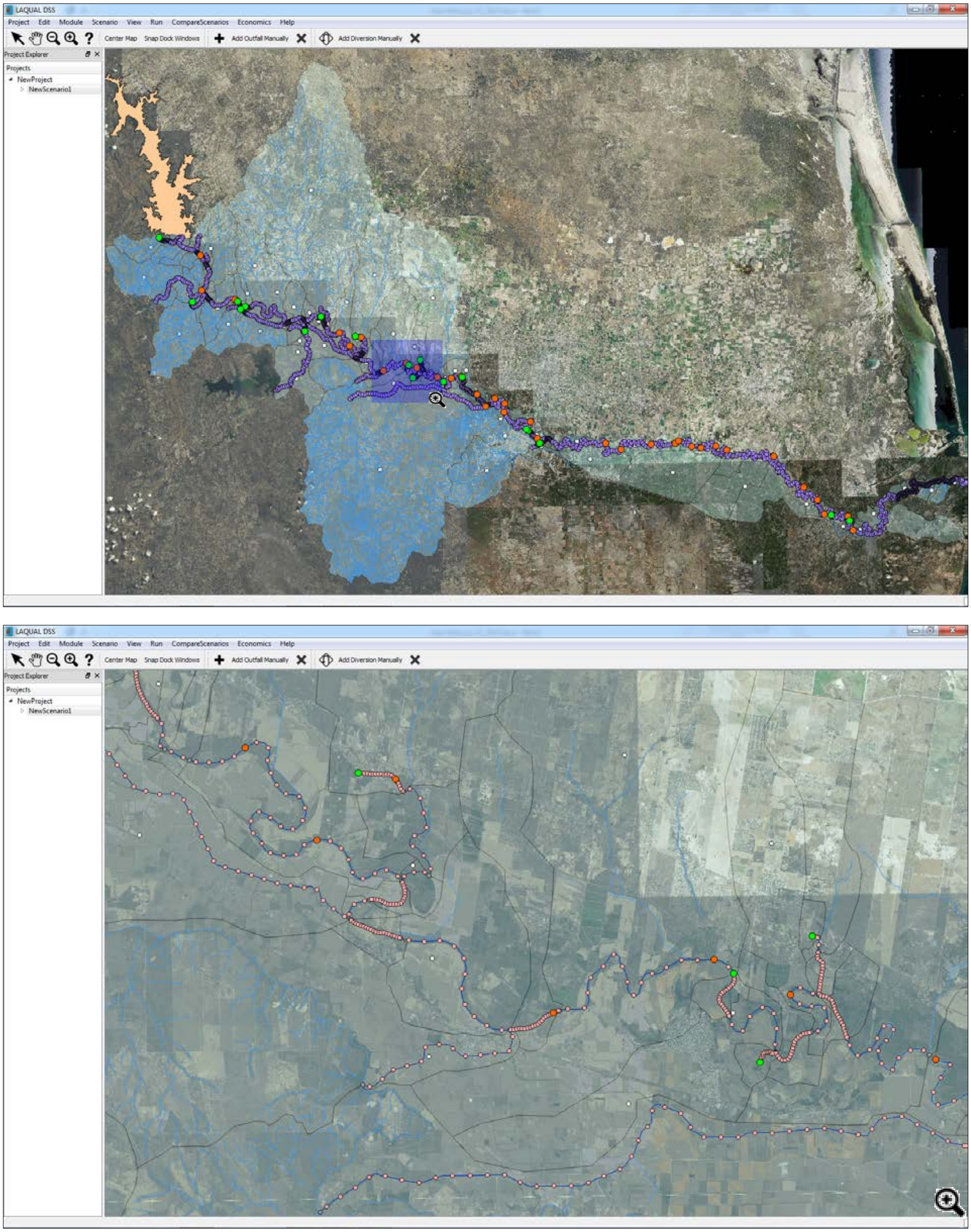
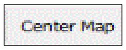


Figure 3-46. Using the Zoom Tool to “Zoom in” on an Area in the “Map” Window.

CENTER MAP 

Clicking on the "Center Map" button in the Map Tool menu returns the map view to the base extent in the Map Window (default 135 km x 235 km).

INFO TOOL 

The Info tool allows the user to display summary information about certain layers displayed in the Map window. The layers for which information is displayed include Diversions, Headwaters, River Reach (nodes), Sub-basin and Outfalls. Of these, only River Reach is common to all projects and scenarios, the rest of the layers for which the Info tool displays information are project- and scenario-specific. Clicking on the Info tool activates the tool. Once activated, the "Active Layer" window appears beneath the "Project Explorer" window and the cursor on the Map window changes to .

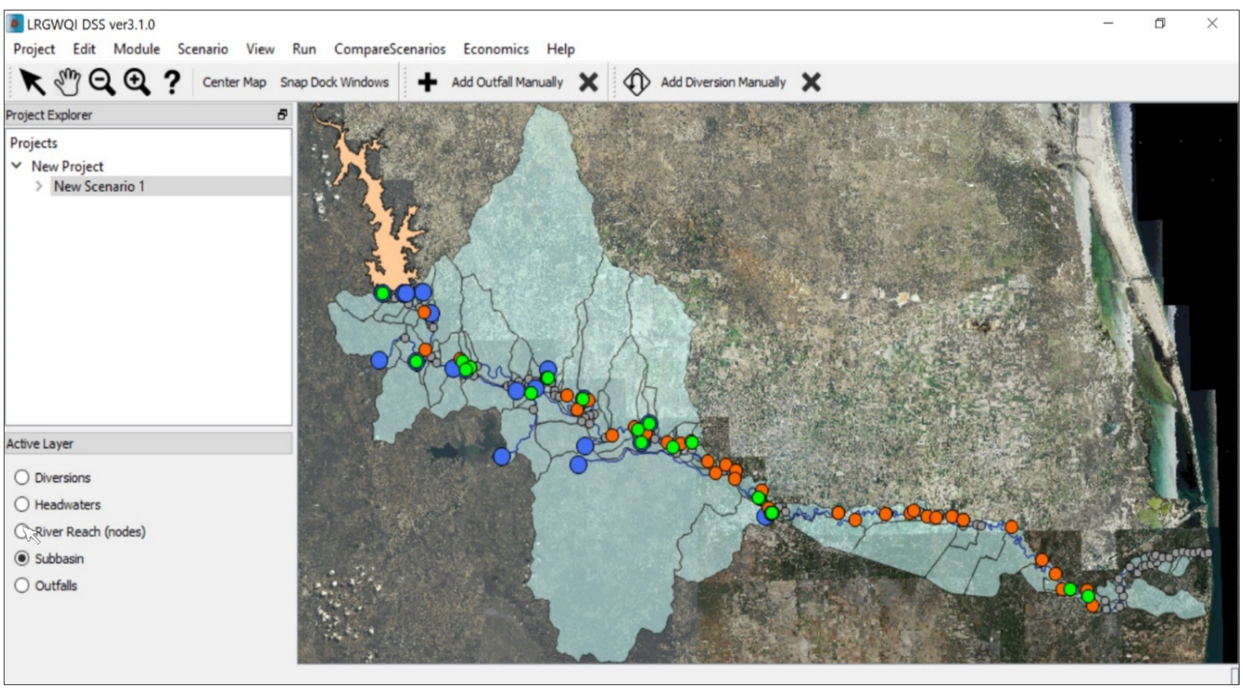


Figure 3-47. Activating a GIS Layer in the "Active Layer" Window of the LRGWQIDSS GUI.

To display an Info window, the user must first select an active layer from the “Active Layer” window by clicking on the radial button next to the desired layer (i.e., Diversions, Headwaters, River Reach, Sub-basin or Outfalls). The layer of interest must already be displayed in the “Map” window. Clicking once on the desired feature on the map will highlight the feature and display the “Info” window containing summary information associated with the highlighted feature.

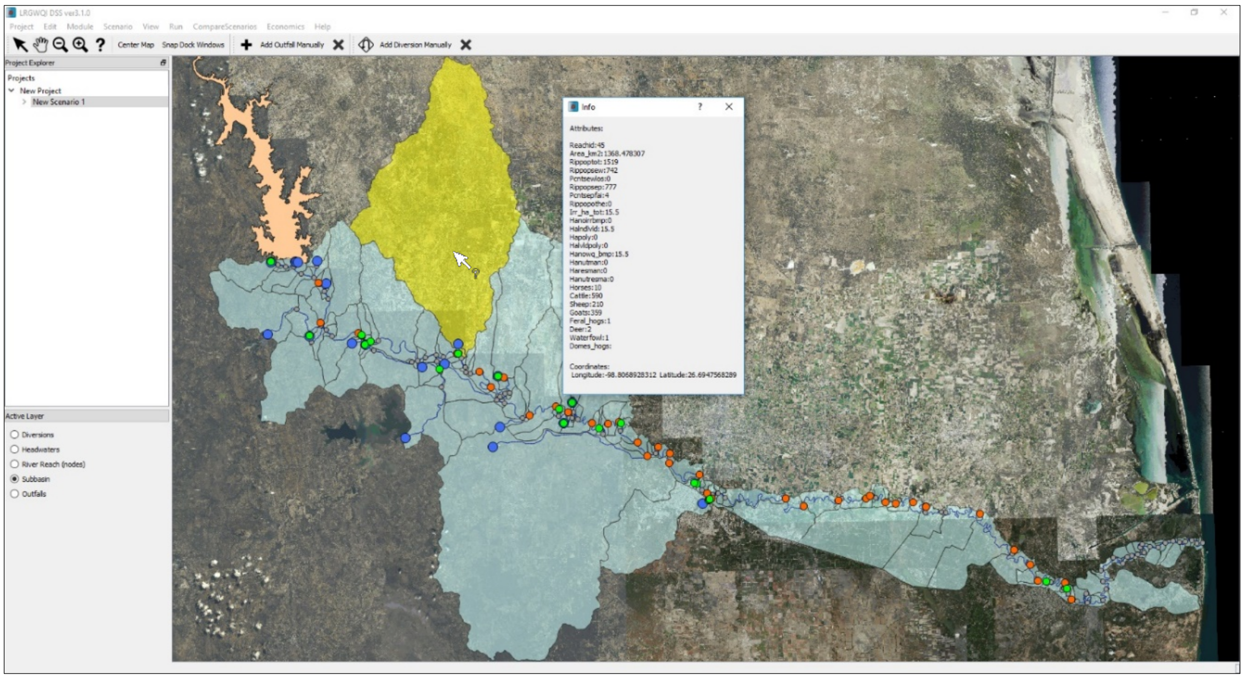


Figure 3-48. Using the Info Tool to Display Information About Features in the “Map” Window of the LRGWQIDSS GUI.

3.2.1.6 Pollutant Loading Modules

The LRGWQIDSS pollutant loading modules allow the user to build and modify water quality simulation scenarios based on the point and nonpoint source inputs specified by the user. The inputs can include changes in effluent flow and/or pollutant concentrations from existing point source outfalls, such as existing wastewater treatment facilities or other known wastewater outfalls. A user can also create new point sources of water borne pollution, such as proposed or suggested new wastewater treatment facility outfalls or predicted untreated wastewater outfalls. In addition to point sources, the user can include in the simulation scenarios a number of situations involving changes in nonpoint sources of pollutants, such as suggested or predicted changes in riparian populations, new urban and rural sanitation service areas, changes in wild or domesticated animal populations and/or implementation of agricultural management practices.

The modules also allow users to simulate the effects, on water quality in the Lower Rio Grande/Río Bravo, of water diversions or of changes in in-stream flows and/or pollutant concentrations at the headwaters of the river (i.e., at Falcon Dam) or at the headwaters of tributaries and ditches that contribute flow to the Lower Rio Grande/Río Bravo (e.g., El Morillo Drain).

Overview of Water Quality Modules of the LRGWQIDSS

The pollutant loading modules of the LRGWQIDSS list the various point and nonpoint sources of pollutants of concern in each sub-basin along with the properties of these pollutant sources. In the case of point sources, these properties can include the river reach and element number to which each facility discharges, the measured effluent flow, effluent pollutant concentrations and the populations served by each facility. In the case of nonpoint sources, the properties can include sub-basin ID, country, total riparian population in the sub-basin, estimated sewer conveyance losses, riparian population in the sub-basin on septic systems, septic failure rate in the sub-basin, and total riparian population in the sub-basin using some other means of sanitation (other).

The Point Sources module and Humans Loadings Sub-module (of the Nonpoint Sources Module) of LRGWQIDSS, are interconnected and the changes made in one module may affect the other, depending on the change made. For example, if the user creates a new wastewater treatment facility serving a user-specified number of people living in the riparian area of the river (i.e., people living with 500 meters of a computational element, including tributaries and ditches), this action will increase the loading of point source pollutants to the river from the new outfall at a specific reach and computational element, while at the same time reducing the nonpoint source pollutant load emanating from the same riparian population served by the new wastewater treatment facility, as the sewage from this population is now collected and treated.

User-defined changes made in the Animal Loadings sub-module of the Nonpoint Sources Module are limited to the number of animals of a certain species found in each of the sub-basins. User-defined changes made in the Agriculture Loadings Sub-module of the Nonpoint Sources Module can include the implementation of up to six agricultural BMPs, 3 irrigation BMPs (i.e., land leveling, use of polypipe, and both of these BMPs together) and 3 water quality BMPs (i.e., post-harvest crop residue management, nutrient management, and both of these BMPs together). Therefore the changes specified by the user in the Nonpoint Sources Module include total irrigated area within a sub-basin, total irrigated area within a sub-basin lacking any recognized irrigation best management practices (NoIrrBMP), total irrigated area within a sub-basin that is land-leveled, total irrigated area within a sub-basin that is irrigated using polypipe, total irrigated area within a sub-basin that is land-leveled and is irrigated using polypipe, total irrigated area within a sub-basin with no recognized water quality best management practices (NoWQBMPs), total irrigated area within a sub-basin that is managed for nutrients, total irrigated area within a sub-basin that is managed for post-harvest crop residue, and total irrigated area within a sub-basin that is managed for both nutrients and post-harvest residue.

The user can access the LRGWQIDSS modules by selecting them from the pull-down menu of the Modules component of the main menu bar. A more detailed explanation of each LRGWQIDSS module is provided in the following sub-sections.

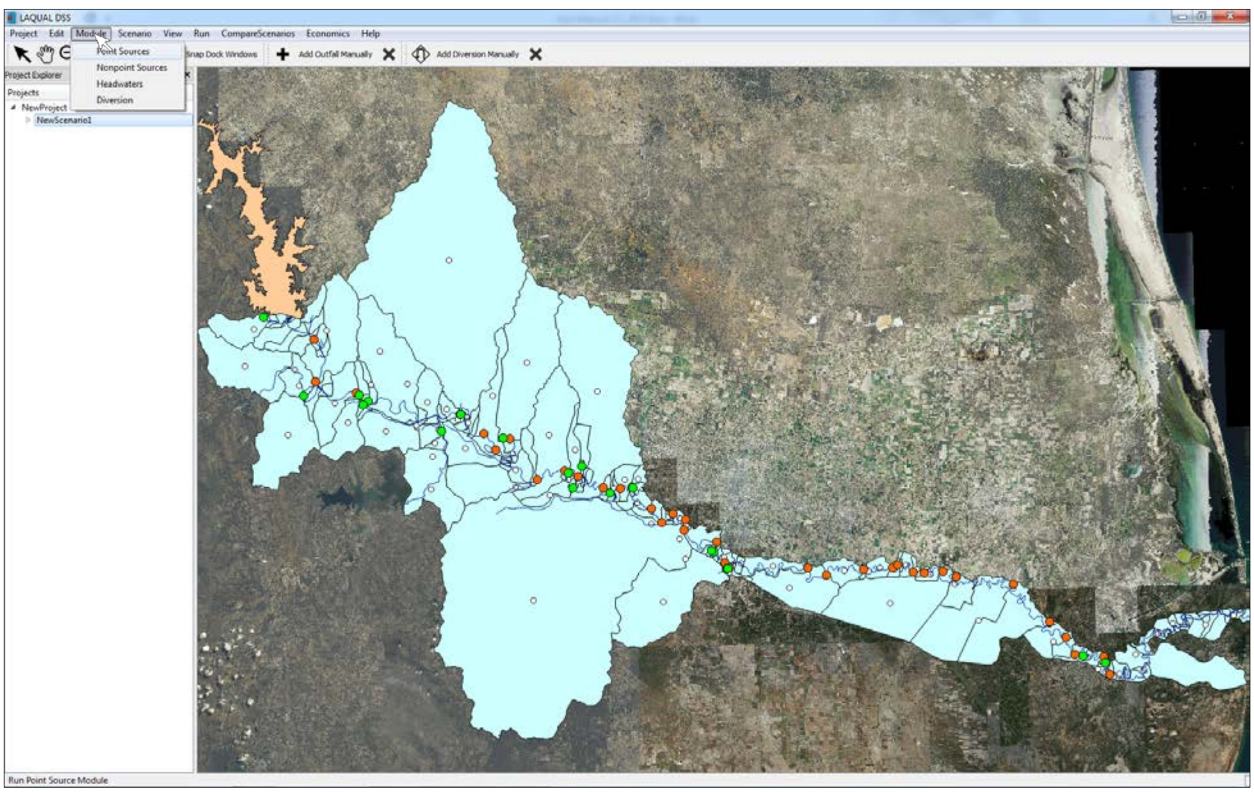


Figure 3-49. The Modules Component of the Main Menu Bar of the LRGWQIDSS GUI.

Point Sources Module

The "Point Sources" Module of the LRGWQIDSS allows the user to build scenarios involving changes in sanitation and wastewater treatment. Clicking on the "Point Sources" option of the pull-down menu of the Module component in the main menu bar places a check mark beside it and opens the "Point Sources Table" window beneath the "Map" window. The existing point sources and associated wastewater outfalls are preloaded with the flows and pollutant concentrations measured during the synoptic surveys conducted as part of the LRGWQI.

The various columns shown in the "Point Sources Table" can be hidden or displayed by checking or unchecking the boxes next to the names of the column headers in the "Point" tab of the "Visibility Settings" window (displayed by clicking the "Settings" option of the "View" component in the main menu bar). The value in the "Reach" column is the reach number, in the LA-QUAL model, into which the outfall flows. The numbers used to describe river reaches in the LA-QUAL model also correspond to the numbers of the sub-basins associated those LA-QUAL reaches.

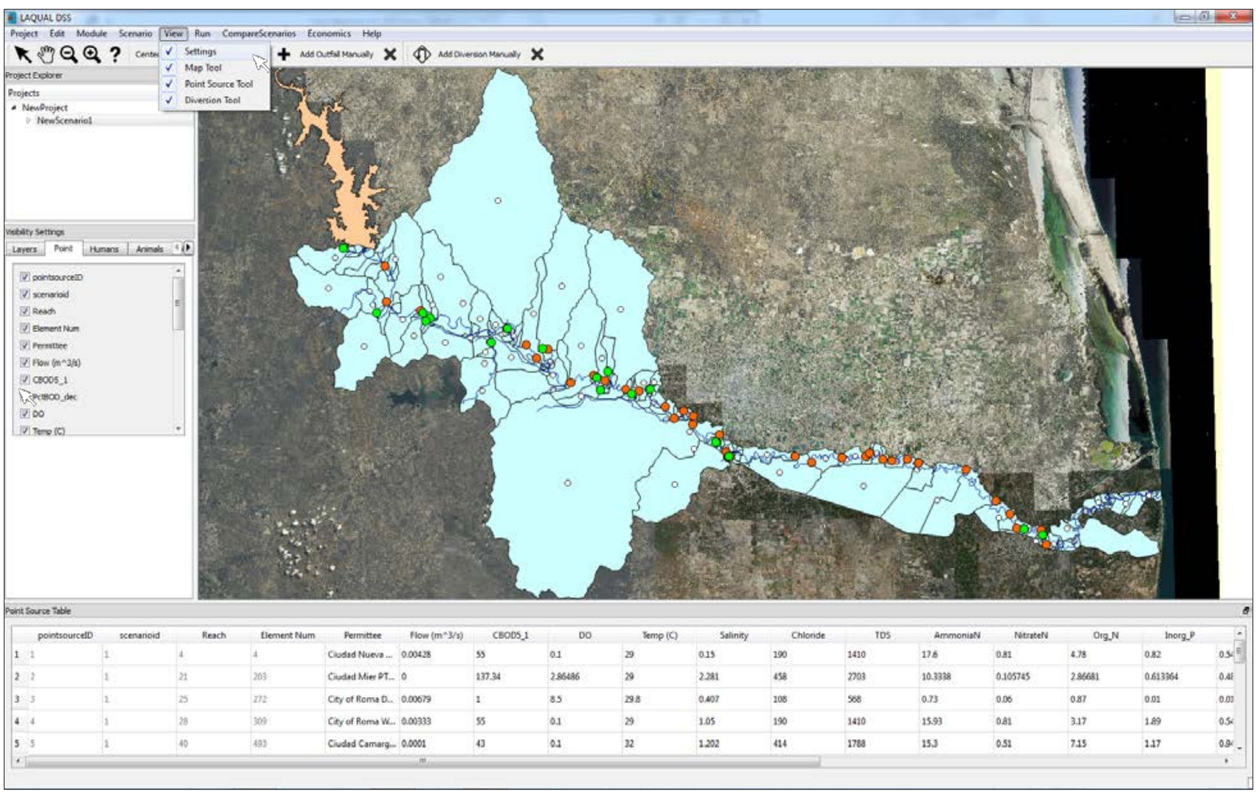


Figure 3-50. The "Point" Tab in the "Visibility Settings" Window of the LRGWQIDSS GUI.

Modifying Existing Point Source Outfalls

The user can change any of the values in the columns of the Point Sources Table. However, in order to effect any change in the simulation of water quality, the user must run the LA-QUAL model. Running the LA-QUAL model is explained in more detail in the Sub-section 3.1.2.8 (Running Scenario Simulations). Sometimes the design of wastewater treatment systems is focused on a particular parameter, but the design often has an effect on other pollutants. For example, a treatment process targeting reductions in biochemical oxygen demand (BOD) or ammonia may also change the concentration of organic nitrogen or nitrates in the effluent and the user may not know exactly how a particular treatment system may affect all pollutants of concern. The LRGWQIDSS includes an option for allowing the DSS to automatically fill in the effluent concentrations of certain pollutants based on a change in the BOD concentrations specified by the user, ostensibly resulting from a change in an existing treatment process, or from a change in the efficiency of the existing treatment process, or resulting from a new treatment system altogether. The user can opt to allow the LRGWQIDSS to make these changes in the effluent concentrations of inorganic phosphorus, organic phosphorus, ammonia nitrogen, nitrate plus nitrate nitrogen and organic nitrogen or the user can decline the option and fill in the concentrations manually.

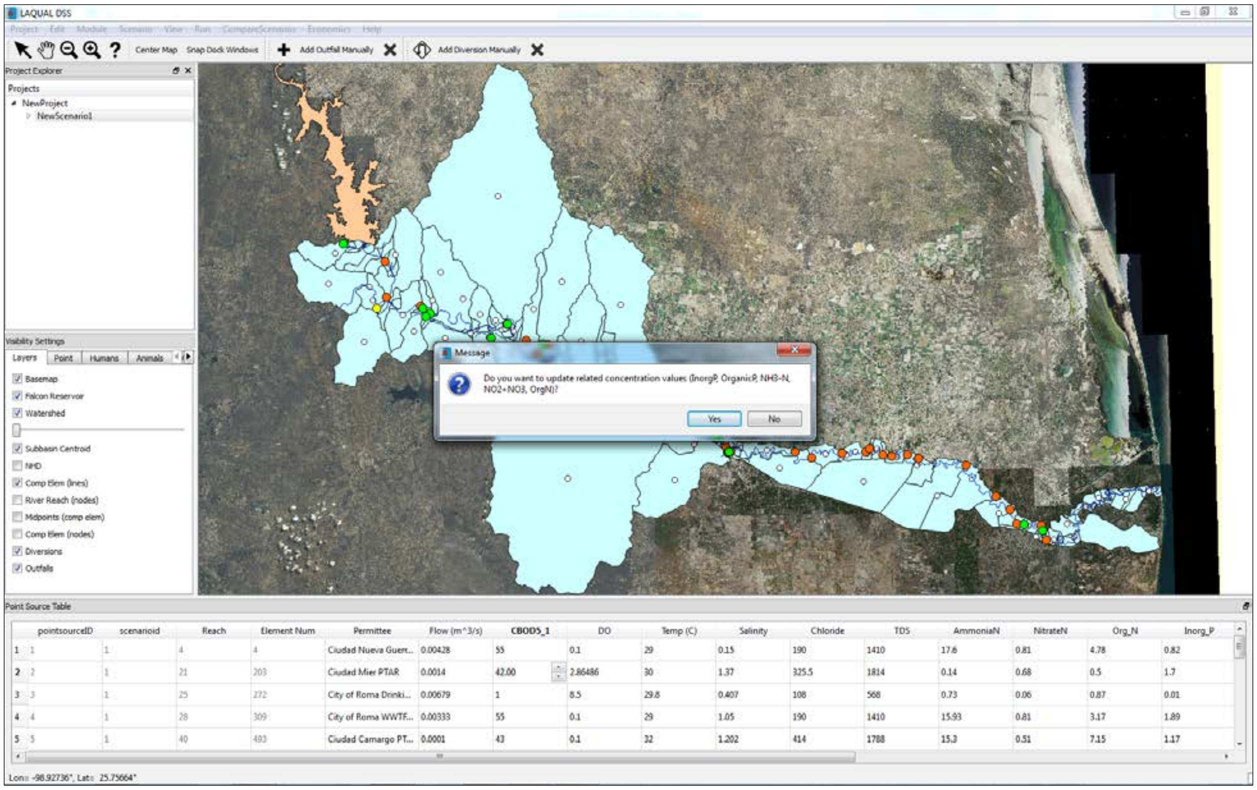


Figure 3-51. Automatic Nutrient Effluent Concentration Estimation Option Dialogue Box in the "Point Sources Table" of the LRGWQIDSS GUI.

If the user wishes to make a change in the riparian population served by a particular wastewater treatment facility or wastewater outfall ("TotalRipPopServed" column), the user must specify where the change in the sanitation services is to take place. Changing the value in the "TotalRipPopServe" column automatically opens the "Link Riparian Population Served" Window. The "Link Riparian Population Served" window can also be opened by right-clicking the record of interest in the "TotalRipPopServe" column and selecting "Set Population." The current riparian population served by the wastewater treatment facility or wastewater outfall for which the change in population served is being made will be displayed in the "Set population served" box on the right side of the "Link Riparian Population Served" window.

In the "Link Riparian Population Served" window, the user must enter the new value for the riparian population served (RipPopOnSewer) in the box next to the appropriate sub-basin. The values entered into this box will also be automatically entered into the "RipPopOnSewer" column of the "Human Loadings Table" in the "Nonpoint Sources" Module. A complete description of the Nonpoint Sources Module is included in later sub-sections.

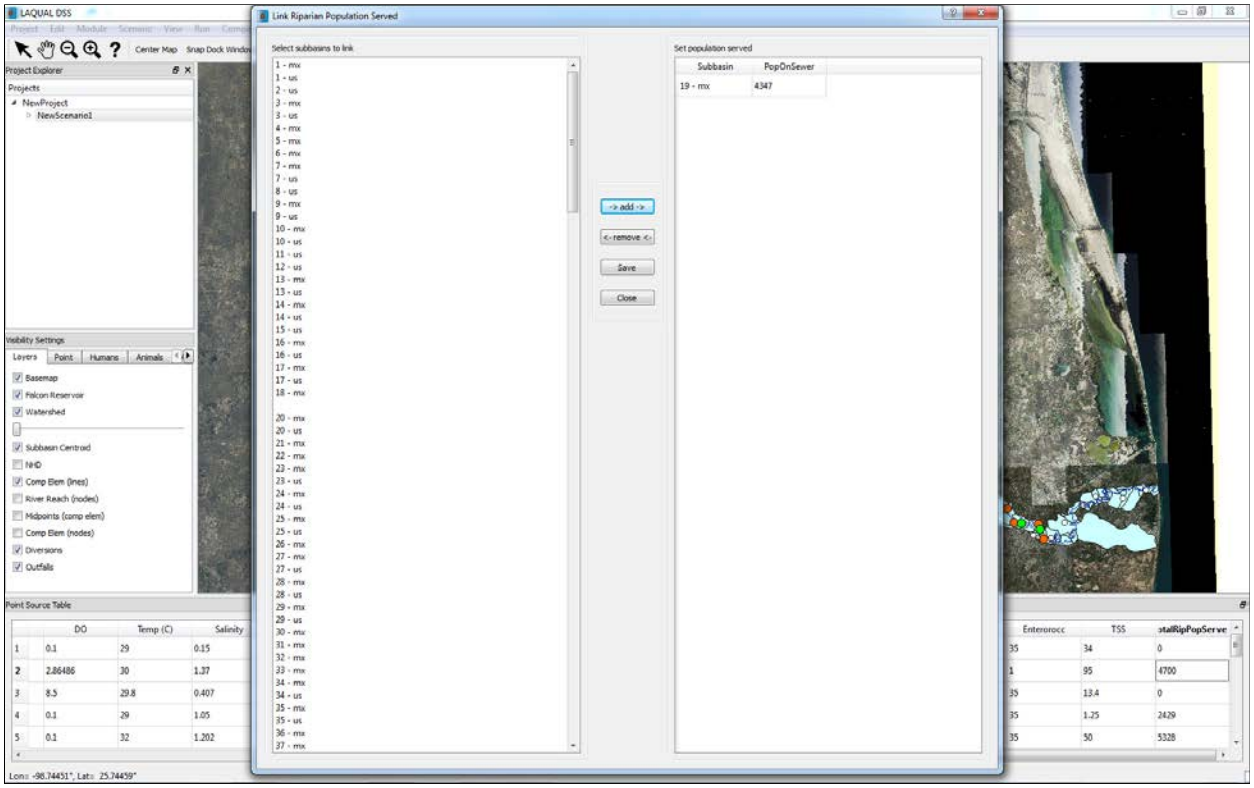


Figure 3-52. The "Link Riparian Population Served" Window in the "Point Sources Table" of the LRGWQIDSS GUI.

If the new riparian population served is located in more than one sub-basin, the user must specify the value of the population served in each sub-basin by adding or removing the appropriate sub-basin from the "select sub-basins to link" box located on the left side of the "Link Riparian Population Served" window and the user must specify a population served value in the RipPopOnSewer box next to the sub-basin added to the "Set Population Served" box.

To save the changes, the user must click on the "Save" button before closing the "Link Riparian Population Served" Window. However, if the sum of the values in the "Set population served" box of the "Link Riparian Population Served" window do not equal the value specified by the user in the "TotalRipPopServed" column of the "Point Sources Table," an error message will display alerting the user. The changes will not be saved until the sum of values in the "Set population served" box of the "Link Riparian Population Served" window equal the value specified by the user in the "TotalRipPopServed" column of the" Point Sources Table.

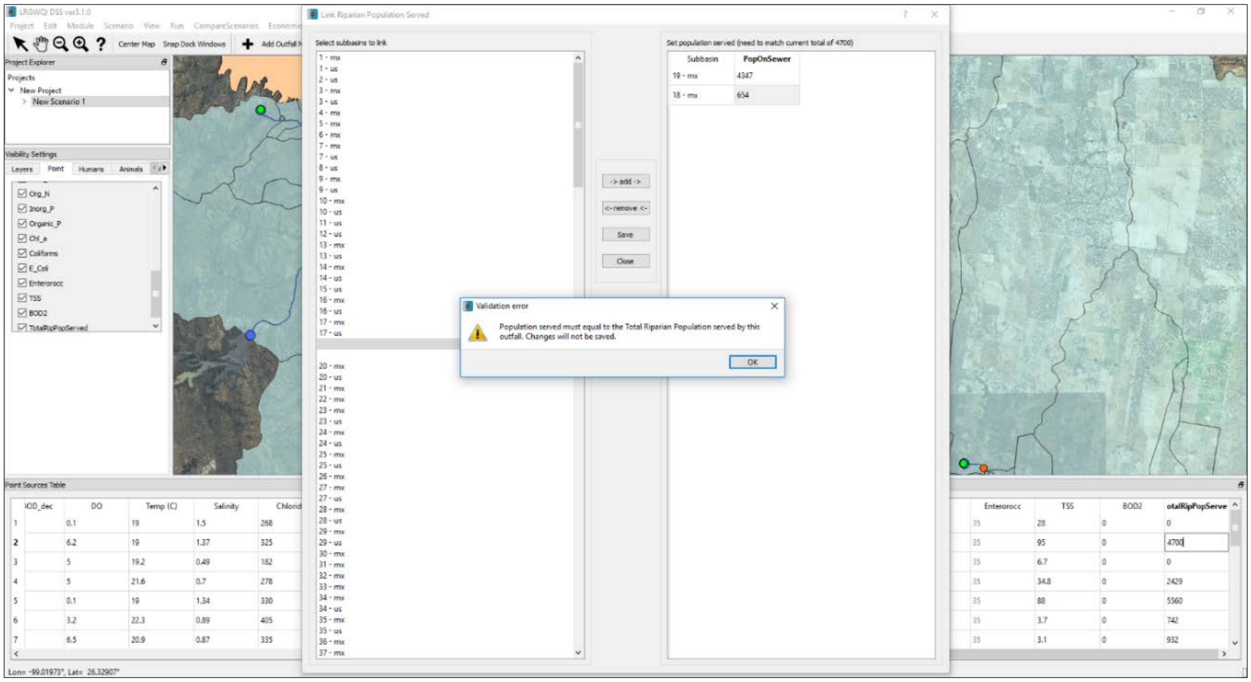
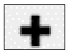


Figure 3-53. Validation Error Message in the "Link Riparian Population Served" Window in the "Point Sources Table" of the LRGWQIDSS GUI.

After the changes made by the user in the "Link Riparian Population Served" window the values are saved (using the "Save" button) and the window is closed (using the "Close" button), the LRGWQIDSS displays a message alerting the user to specify commensurate changes in the "Human Loadings" tab of the "Nonpoint Sources Tables." That is, the user must specify the riparian populations using septic systems, "other" means of sanitation (or lacking sanitation), as well as sewer conveyance losses, in the sub-basins where the modifications in the "PopOnSewer" were made in the "Link Riparian Population Served" window of the "Point Sources Table." A more detailed description of the Nonpoint Sources Module is provided in subsequent sub-sections.

Creating New Point Source Outfalls

There are two ways a user can create a wastewater outfall and add it to a scenario. The user can create an outfall manually or through point-and-click. In either case, the user must enter information about the new outfall in the “Point Sources Table” after the outfall is created. To create an outfall using the point-and-click method, the user must use the “Add Outfall” button  located in the “Outfall Tools” in the LRGWQIDSS tool bar beneath the main menu bar. Clicking on this tool converts the cursor to a hand with a pointing finger ; clicking again once on the “Map” window creates a wastewater outfall in the location on the map where the tip of the pointing finger is pointing.

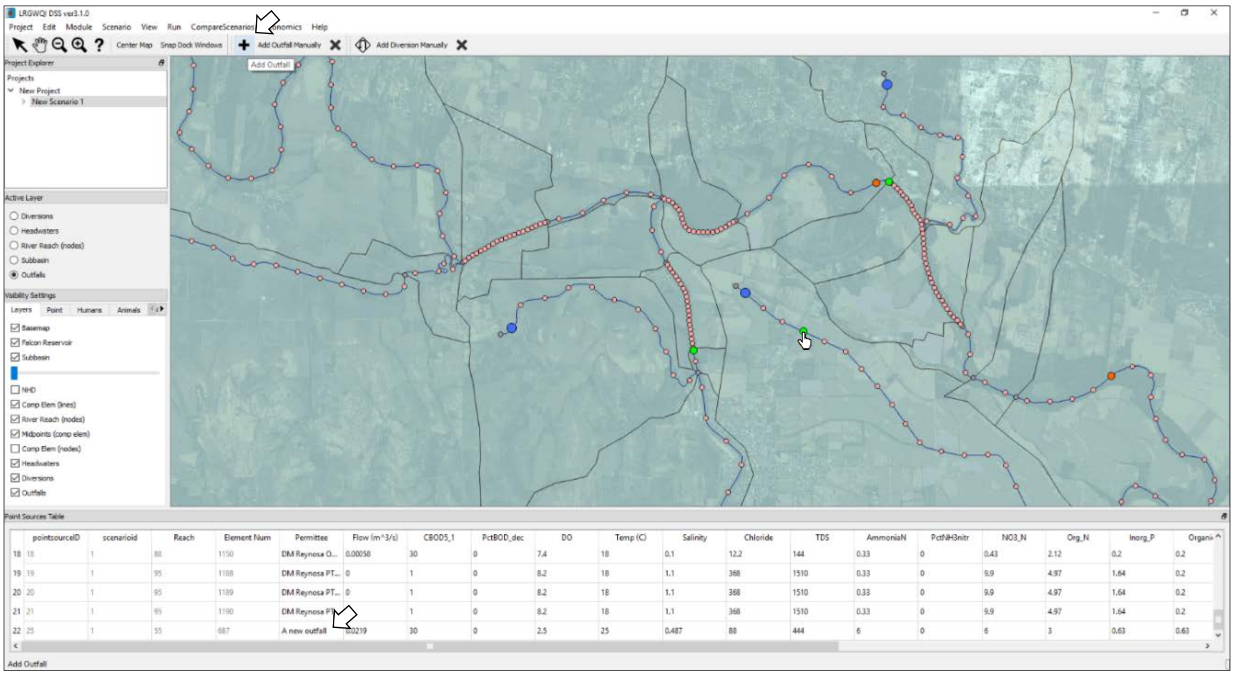
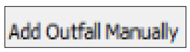


Figure 3-54. Adding a New Point Source Outfall Using the “Add Outfall” Button in the Tool Bar of the LRGWQIDSS GUI.

To increase precision in the placement of new wastewater outfalls created using the point-and-click method, it is advisable to first use the zoom tool to zoom in on the location of interest prior to clicking on the “Add Outfall” button. The “Add Outfall” function will only create an outfall in one of the computational elements of the LA-QUAL model (i.e., Comp Elem [lines]). It does so by snapping the newly created outfall point to the nearest computational element midpoint. To increase the precision of placement further, the user may choose to display the “Midpoints (comp elem)” layer in the “Visibility Settings” (displayed by clicking on the “Settings” option in the “View” component of the main menu bar).

Upon the creation of a new wastewater outfall, a new row is added to the bottom of the "Point Source Table." The LRGWQIDSS places the name "A new outfall" in the new record under the "Permittee" column and automatically fills the records under the effluent flow and pollutant concentration columns with default values (flow = 0.5 MGD = 0.0219 m^3/s). The value in "TotalRipPopServed" is assigned a default value of zero, which the user is expected to change with the value of the proposed population served using the "Link Riparian Population Served" window.

An alternative method for creating a new wastewater outfall is to use the "Add Outfall Manually" tool 

. Using this method, the user can specify the exact location where a new wastewater outfall is to be created. When the user clicks the "Add Outfall Manually" button, a dialogue box opens requesting the latitude and longitude of the new outfall.

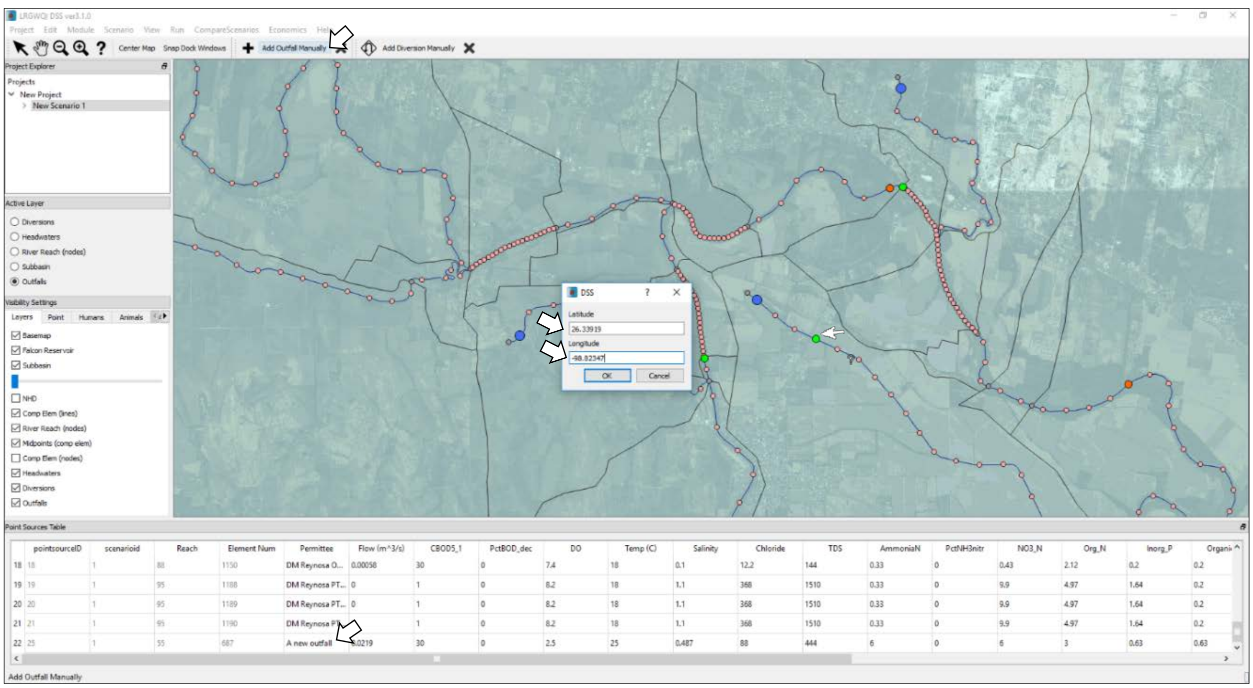
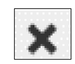


Figure 3-55. Adding a New Point Source Outfall Using the "Add Outfall Manually" Tool in the Tool Bar of the LRGWQIDSS GUI.

The user must then enter the coordinates of the new outfall in decimal degrees in the appropriate slots in the "DSS" dialogue box. As with the point-and-click method, the LRGWQIDSS will snap the location of the newly created wastewater outfall to the nearest LA-QUAL computational element midpoint. Like the "point-and-click" method, creation of a new wastewater outfall using the "manual" method will also add a row to the bottom of the "Point Source" Table. Again, the LRGWQIDSS will place the name "A new outfall" in the new record under the "Permittee" column and will automatically fill the records under the effluent flow and pollutant concentration columns with default values. The user must then enter specific information, as necessary, about the new outfall in the "Point Source Table" after the outfall is created.

Deleting Wastewater Outfalls

A new or existing outfall can be deleted by right-clicking on the row in the "Point Source Table" where the deletion is to occur. Another way to delete a newly created wastewater outfall, or any wastewater outfall, for that matter, is to use the "Delete Feature" button  of the "Outfall Tools." Deleting an outfall removes it completely from the LA-QUAL model (in the active Scenario). The point disappears from the "Map" window and the row containing the information associated with the deleted outfall is removed from the "Point Source Table." Like many other actions in the LRGWQIDSS, the action of deleting wastewater outfalls can be reversed and the deleted outfalls restored using the "Undo" option in the "Edit" component of the main menu bar.

Nonpoint Sources Module

The Nonpoint Sources Module (NPS Module) of the LRGWQIDSS is designed to incorporate, into simulation scenarios, a number of practices, control actions and management measures that affect pollutant loadings emanating from diffuse sources, such as unsewered riparian communities, animal sources and agricultural activities. The user can access the NPS module by clicking on the "Nonpoint Point Sources" option of the pull-down menu of the "Module" component in the main menu bar. Doing so places a check mark beside the "Nonpoint Sources" option and opens the "Nonpoint Sources Tables" window beneath the "Map" window. The NPS Module consists of three submodules represented as three separate tabs in the "Nonpoint Sources Table:" Human Loadings, Animal Loadings and Agricultural loadings.

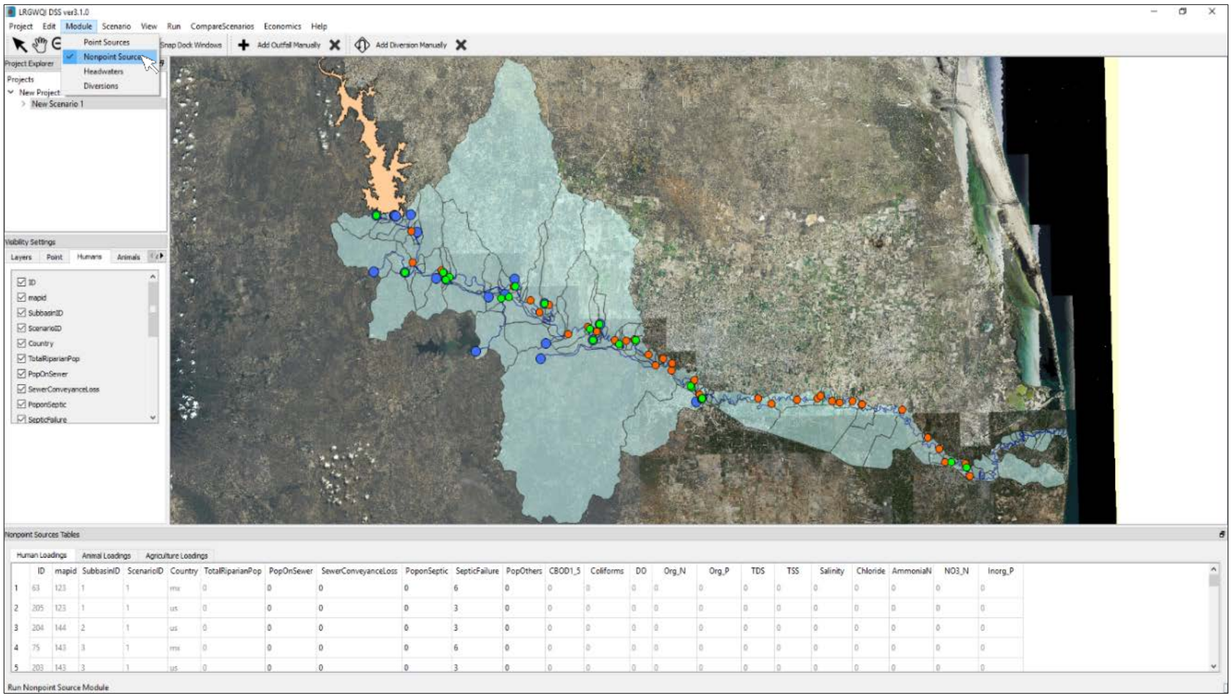


Figure 3-56. The "Nonpoint Point Sources" Option of the Pull-down Menu of the Module Component in the Main Menu Bar of the LRGWQIDSS GUI.

The Human Loadings Submodule

The "Human Loadings" sub-module of the LRGWQIDSS' NPS module works in combination with the "Point Sources" module to help the user set up simulation scenarios involving changes in sanitation to residents living in the riparian areas of the 147 sub-basins represented in the "Sub-basin" GIS layer. In addition to the reduction in pollutant loadings resulting from the connection of previously unsewered residents to new or improved treatment facilities, the "Human Loadings" sub-module allows the user set up simulation scenarios involving improvements in sewage conveyance (i.e., reducing "SewerConveyanceLoss" values in the "Human Loadings" table) and improvements in onsite sewage treatment (i.e., reduction in "SepticFailure" rates in the "Human Loadings" table).

The "Human Loadings Table" is preloaded with the information collected during the LRGWQI study (see Chapter 1). As with the "Point Sources" table, the user can choose to display or hide any of the seventeen columns of the "Human Loadings Table" by checking or unchecking the various column headings in the "Humans" tab in the "Visibility Settings" window (displayed by checking the "Settings" option in the "View" component of the main menu bar of the LRGWQIDSS GUI). The column labeled “Sub-basin ID” shows the number of the sub-basins represented by each row in the table. The Sub-basin ID number reflects the river reach, in the LA-QUAL model input, that is associated with the particular sub-basin (i.e., the model reach into which the nonpoint source pollutant loadings emanating from that sub-basin are contributed).

The existing number of residents living in the riparian zones of each of the 147 sub-basins is represented under the column labeled “TotalRiparianPop.” These populations are further subdivided into subcategories according to the type of sanitation used by the residents living in the riparian zones of each sub-basin. Residents in the column labeled “PopOnSewer” are those that are currently receiving centralized wastewater collection and treatment services. Residents in the column labeled “PopOnSeptic” are those that use onsite sewage treatment facilities for sanitation. Residents in the column labeled “PopOthers” are those that use other means of sanitation. Residents under the “PopOthers” column are deemed by the LRGWQIDSS to use inadequate or non-existent sanitation.

The column labeled “SewerConveyanceLoss” contains values between 0 and 1. These values represent the fraction (i.e., percentage) of the sewage collected in the riparian zone that is lost to the environment in the particular sub-basin represented by each row in the table. The column labeled “SepticFailure” also contains values between 0 and 1 and represents the fraction of the onsite treatment systems, in the riparian zones in the particular sub-basin, that are failing. The user can only change the values in the columns labeled “PopOnSewer,” “SewerConveyanceLoss,” “PopOnSeptic,” “SepticFailure” and “PopOthers.” The values in the “TotalRiparianPop” column are always the sum of the values in the adjacent “PopOnSewer,” “PopOnSeptic” and “PopOthers” columns. Although the user cannot change the total riparian population living in each sub-basin directly, the value in the “TotalRiparianPop” column can be increased or decreased by specifying the number of residents entered under the “PopOnSewer,” “PopOnSeptic” and “PopOthers” columns, as “TotalRiparianPop” is the sum of these.

If the user changes a value in a record under the “PopOnSewer” column, the “Link Riparian Population Served Window” will automatically open and the user must specify the number of the outfall linked to the change made in the value entered into the record under the “PopOnSewer” column. The outfall number corresponds to the “pointsource ID” number in the “Point Sources Table” (“Point Sources” module).

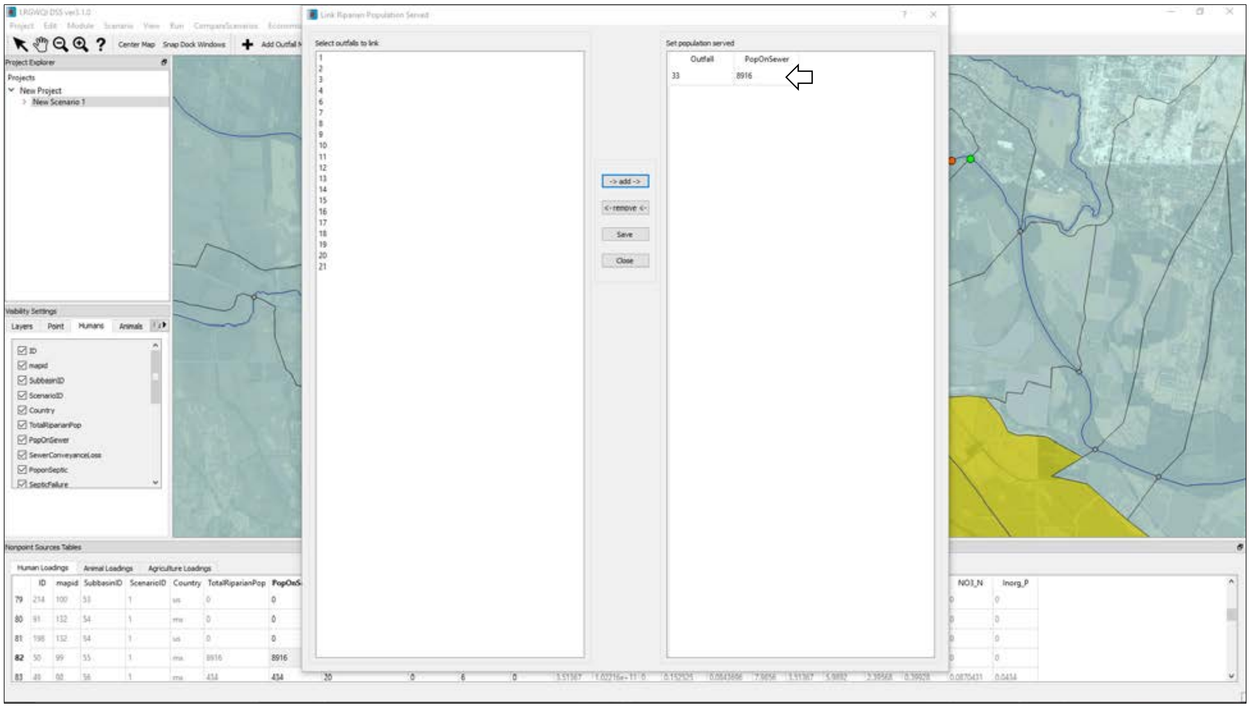


Figure 3-57. The "Link Riparian Population Served" Window in the "Human Loadings Table" in the "Nonpoint Sources Tables" of the LRGWQIDSS GUI.

The user is responsible for making any changes to the outfall in the "Point Sources Table" that are necessary due to the changes made in the "Human Loadings" Table (Nonpoint Sources module). For example, if the delivery of centralized wastewater services to riparian residents previously using septic systems or without sanitation services is expected to result in an increase in the amount of treated wastewater effluent flow from an existing wastewater treatment facility outfall, the user is responsible for modifying the flow value of that outfall in the "Point Sources Table" ("Point Sources" module). The "Link Riparian Population Served Window" will only show existing outfalls, so if the delivery of centralized wastewater services to riparian residents that were previously using septic systems or were without sanitation services is expected to be provided by a new facility, that facility must have already been created in the "Point Sources Table" ("Point Sources" module). The "Link Riparian Population Served" window can also be opened by right-clicking the record of interest in the "PopOnSewer" column and selecting "Set Population."

Relationship Between Point Source and Nonpoint Source Tables

The "PopOnSewer" column of the "Nonpoint Source Table" is directly related to the "TotalRipPopServed" column of the "Point Source Table." As previously explained in the description of the "Point Sources" module, any changes specified by the user in the RipPopOnSewer box(s) associated with specific sub-basins in the "Set population served" box of the "Link Riparian Population Served" window will automatically change the values of the commensurate record in the "PopOnSewer" column of the "Human Loadings Table." Accordingly, any changes specified by the user in the "PopOnSewer" column of the "Human Loadings Table" will also be reflected in the values in the "Set population served" box of the "Link Riparian Population Served" window and in the "TotalRipPopServed" column of the "Point Source Table."

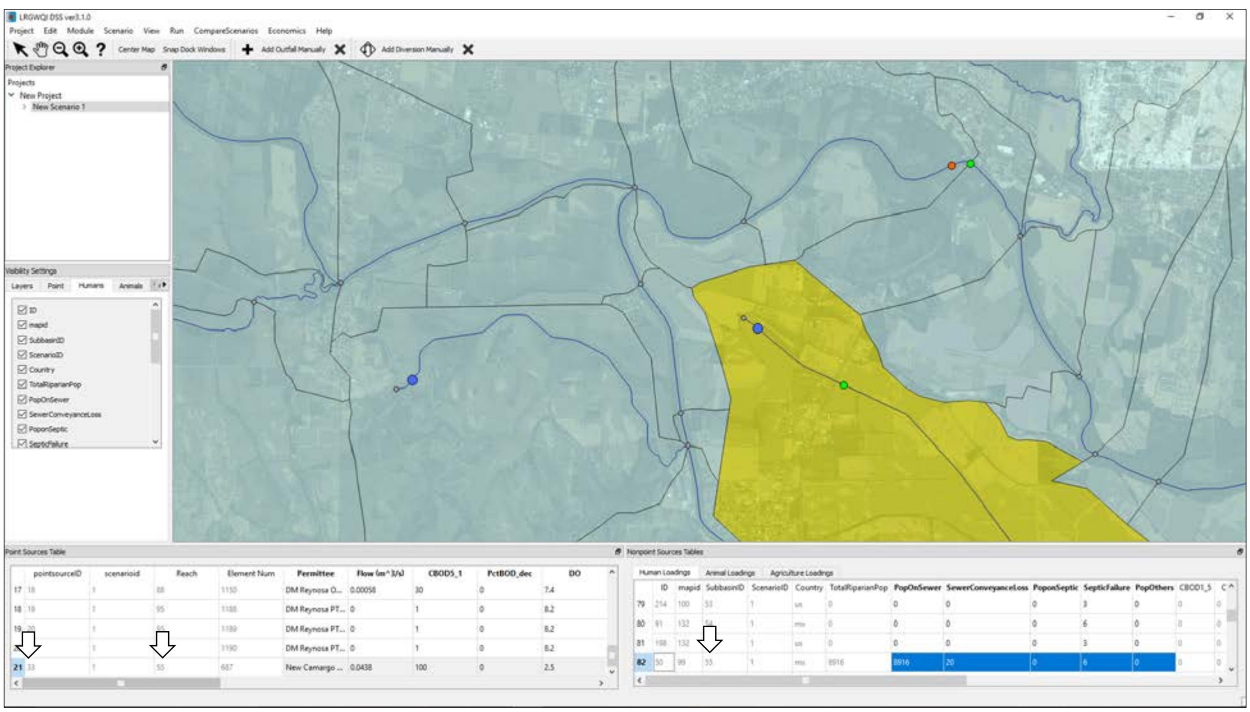


Figure 3-58. Linkage Between Reach ID in the "Point Sources Table" and Subbasin ID in the "Human Loadings Table" of the "Nonpoint Sources Tables" in the LRGWQIDSS GUI.

The Animal Loadings Submodule

The "Animal Loadings" submodule allows the user to build scenarios involving changes in pollutant loading, to the Lower Rio Grande/Río Bravo and/or one of its tributaries or contributing ditches, resulting from changes in animal populations within each of the Lower Rio Grande/Río Bravo watershed sub-basins. The user can access the "Animal Loadings" submodule by clicking on the "Animal Loadings" tab in the "Nonpoint Sources Tables." The "Animal Loadings Table" is preloaded with the animal population information derived from geospatial analyses conducted as part of the LRGWQI study (See Chapter 1).

Estimates of the average populations of four domestic animal species (cattle, horses, goats and sheep) found in each sub-basin and three wild (or feral) animal species found in the riparian zones and wetland habitats in each sub-basins (deer, feral hogs and waterfowl) are preloaded under the column headings bearing the name of each animal species. The user can modify the nonpoint source pollutant loadings generated by each of these animal species in each of the sub-basins by changing the population value in the appropriate record in the "Animal Loadings Table."

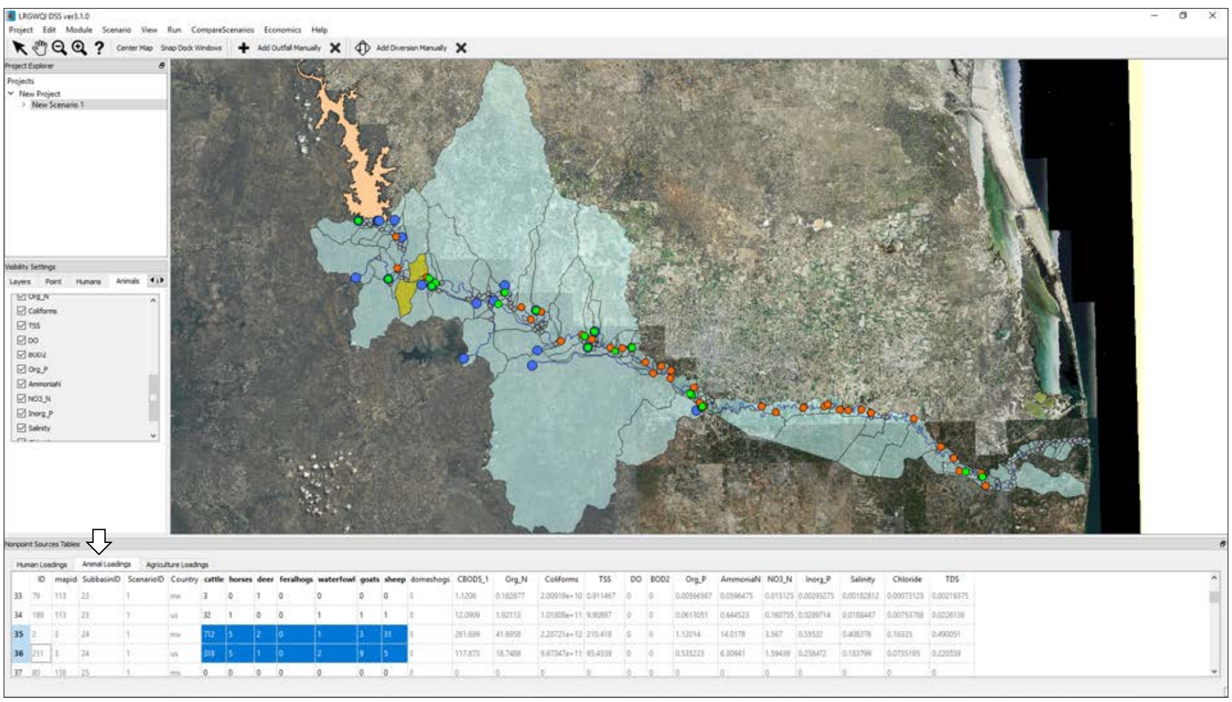


Figure 3-59. The "Animal Loadings Table" of the "Nonpoint Sources Tables" of the LRGWQIDSS GUI.

The total loading, by pollutant, generated by all animals in each sub-basin, is shown in the last eleven columns on the right side of the table. Additional pollutants are available for display, but the parameter must be checked in the "Visibility Settings" window (displayed by checking the "Settings" option in the "View" component of the main menu bar of the LRGWQIDSS GUI).

Agricultural Loadings Submodule

The Agricultural Loadings Submodule allows the user to set up simulation scenarios involving the implementation of agricultural BMPs, including irrigation methods that minimize irrigation return flow to surface water bodies and agronomic practices that reduce pollutant loadings to these water bodies. The user can access the "Agricultural Loadings" submodule by clicking on the "Agricultural Loadings" tab in the "Nonpoint Sources Tables," which activates the "Agricultural Loadings Table."

The "Agricultural Loadings Table" is preloaded with the information gathered during the LRGWQI study (see Chapter 1). As is the case with all module tables, the user can choose to display or hide any of the twenty-seven columns of the "Agricultural Loadings Table" by checking or unchecking the various column headings in the "Ag" tab of the "Visibility Settings" (displayed by checking the "Settings" option in the "View" component of the main menu bar).

For each of the 147 Lower Rio Grande/Río Bravo watershed sub-basins, the total amount of irrigated land, in hectares, is shown under the column labeled "TotalIrrArea." The column labeled "LndLvldBMP (Ha)" shows the total amount of irrigated land area that has been leveled in each sub-basin. The column labeled "PolyBMP (Ha)" shows the total hectares of irrigated land in which polypipe is used for irrigation in each sub-basin. The hectares of irrigated land in which both of these irrigation practices are used together is entered under the column named "LvldPoly (Ha)" for each sub-basin. The hectares of irrigated land in which neither of these two irrigation practices are used (i.e., not leveled and not using polypipe) is entered under the column named "NoIrrBMP (Ha)" for each sub-basin. The estimated total irrigation return flow, in cubic meters per second, generated by all irrigated land in each sub-basin (TotalIrrArea) is shown in the column labeled "Returnflow."

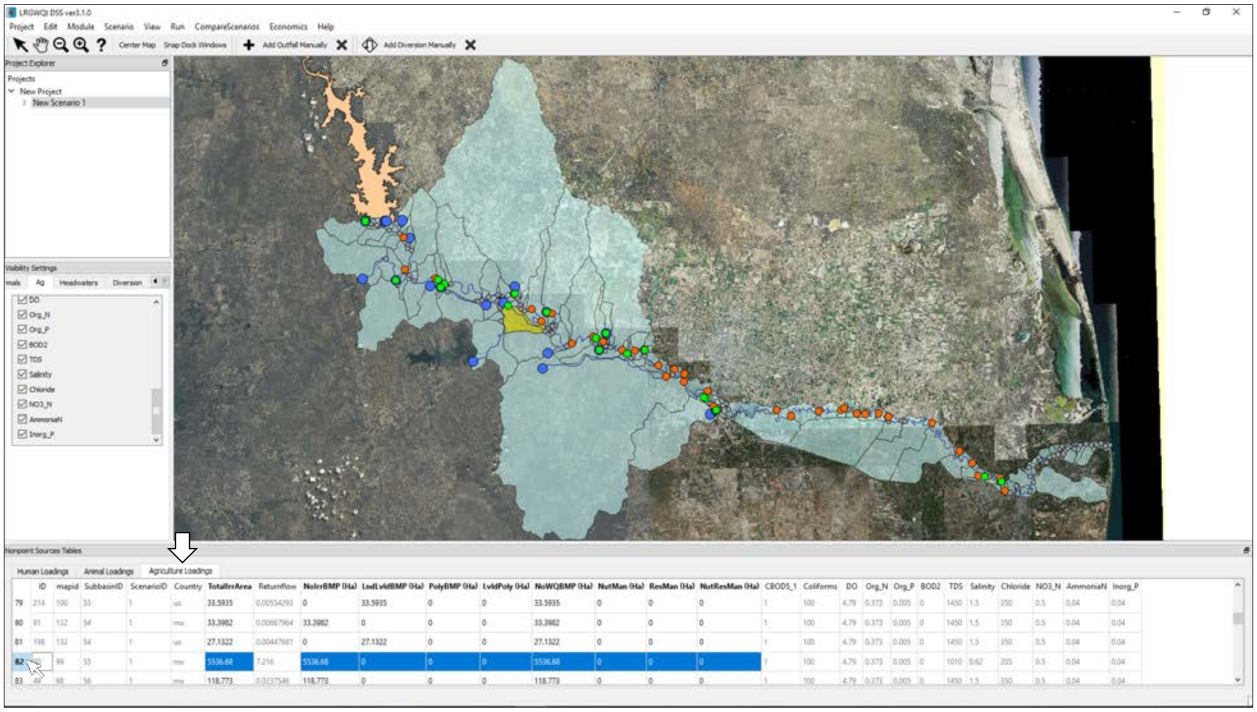


Figure 3-60. The "Agriculture Loadings Table" of the "Nonpoint Sources Tables" of the LRGWQIDSS GUI.

For each sub-basin, the user can increase or decrease the values in the columns labeled "LndLvldBMP (Ha)," "PolyBMP (Ha)," and/or "LvldPoly (Ha)" to simulate the individual effect, on irrigation return flows and pollutant loadings, of land leveling or the use of polypipe for irrigation. But, it is important to remember that the hectares of land in which both of these irrigation practices are used together must be entered under the column labeled "LvldPoly (Ha)" and not in either of the two other irrigation BMP columns.

Entering values into the "LndLvldBMP (Ha)," "PolyBMP (Ha)," and/or "LvldPoly (Ha)" columns subtracts hectares of land from the column labeled "NoIrrBMP (Ha)." If the value in the column labeled "LndLvldBMP (Ha)" or "PolyBMP (Ha)" or "LvldPolyBMP (Ha)" exceeds the value in the column labeled "TotalIrrArea," the LRGWQIDSS will display a message alerting the user that the area of an irrigated BMP must be smaller than or equal to the total irrigated area. The user must either decrease the BMP area or increase the amount of irrigated land in the sub-basin.

The column labeled "NutMan (Ha)" shows the total amount of irrigated agricultural land that is subjected to nutrient management in each sub-basin. The column labeled "ResMan (Ha)" shows the total amount of irrigated agricultural land that has been subjected to residue management in each sub-basin. The hectares of irrigated land in which both of these water quality protective agricultural best management practices are used together (i.e., nutrient management and residue management together) is entered under the column named "NutResMan (Ha)" for each sub-basin. The hectares of irrigated agricultural land in which neither of these two water quality BMPs are used (i.e., no nutrient management and no residue management) is entered under the column named "NoWQBMP (Ha)."

For each sub-basin, the user can increase or decrease the values in the columns labeled "NutMan (Ha)," "ResMan (Ha)" and/or "NutResMan (Ha)" to simulate the individual effect, on pollutant loadings, of nutrient management or residue management. The hectares of land in which both of these water quality protection practices are used together must be entered under the column labeled "NutResMan (Ha)."

Entering values into the "NutMan (Ha)," "ResMan (Ha)" and/or "NutResMan (Ha)" columns subtracts hectares of land from the column labeled "NoWQBMP (Ha)." If the value in the column labeled "NutMan (Ha)" or "ResMan (Ha)" or "NutResMan (Ha)" exceeds the value in the column labeled "TotalIrrArea," the LRGWQIDSS will display a message alerting the user that the area of a water quality protection BMP must be smaller than or equal to the total irrigated area. The user must either decrease the BMP area or increase the amount of land under the water quality protection BMP exceeding the "TotalIrrArea" in the sub-basin.

Headwaters Module

The "Headwaters" module of the LRGWQIDSS allows the user to build scenarios involving changes in flow and water quality occurring at the headwaters of the Lower Rio Grande/Río Bravo or in one of its two major tributaries (Río Álamo and Río San Juan) or in the seventeen drains and major ditches that contribute flow and pollutant loads to the river. Clicking on the "Headwaters" option of the pull-down menu of the "Module" component of the main menu bar places a check mark beside it and opens the "Headwater Table" window beneath the "Map" window.

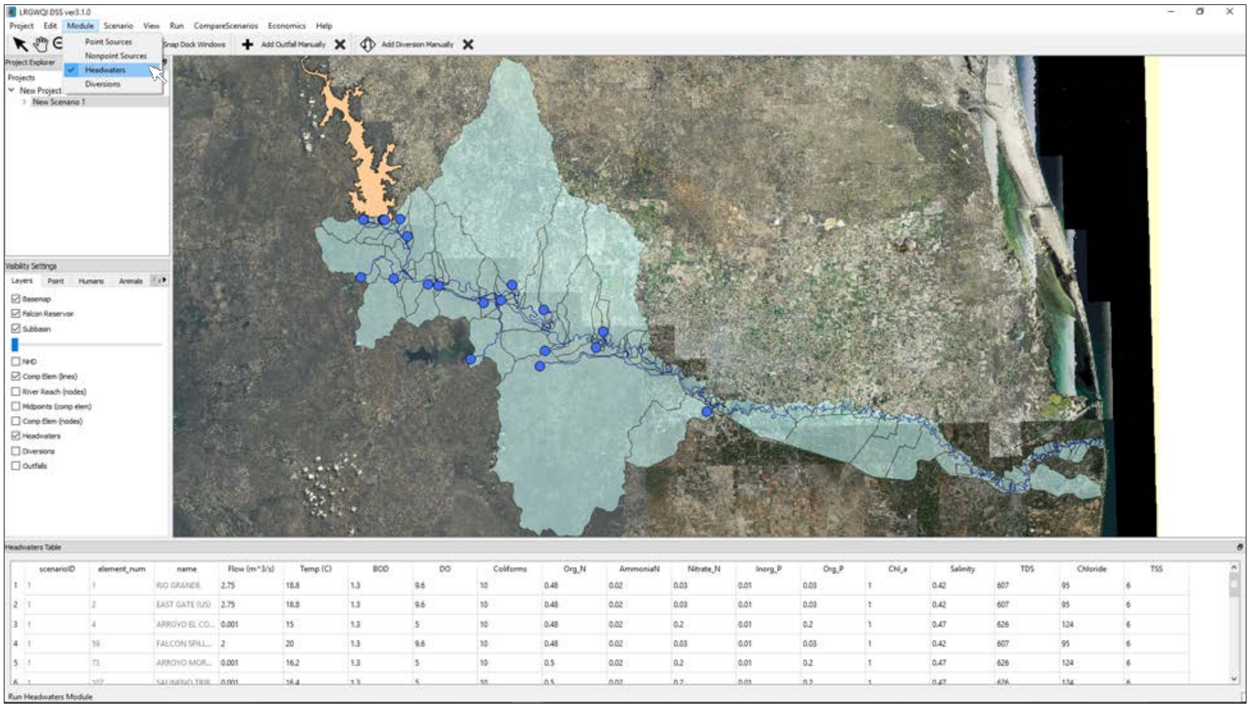


Figure 3-61. The "Headwater Table" in the "Headwaters" Module of the LRGWQIDSS GUI.

The twenty headwaters featured in the LA-QUAL models of the Lower Rio Grande/Río Bravo along with the pertinent flow and water quality information associated with each (for the five synoptic surveys conducted as part of the LRGWQI) are displayed in the "Headwater Table." The various columns shown in the "Headwater Table" can be hidden or displayed by checking or unchecking the various column headings in the "Headwaters" tab of the "Visibility Settings" (displayed by checking the "Settings" option in the "View" component of the main menu bar). The user can change the flow and pollutant concentrations in any of the twenty headwaters by entering new values in the appropriate columns. However, new headwaters cannot be created, and existing headwaters cannot be deleted.

Headwater nodes are depicted, in the "Map" window of the LRGWQIDSS GUI, at the midpoint of the first computational element of their corresponding LA-QUAL reach. Consequently, the "Comp Elem (lines)" GIS layer will show a small portion of the LA-QUAL reach upstream of the associated headwater point.

Diversions Module

The “Diversions Module” of the LRGWQIDSS allows the user to build scenarios involving changes in flow diverted, pumped, or otherwise extracted, from the Lower Rio Grande/Río Bravo or one of its tributaries, or from a contributing drain or ditch. Clicking on the “Diversions” option of the pull-down menu of the “Module” component in the main menu bar places a check mark beside it and opens the “Diversions Table” window beneath the “Map” window.

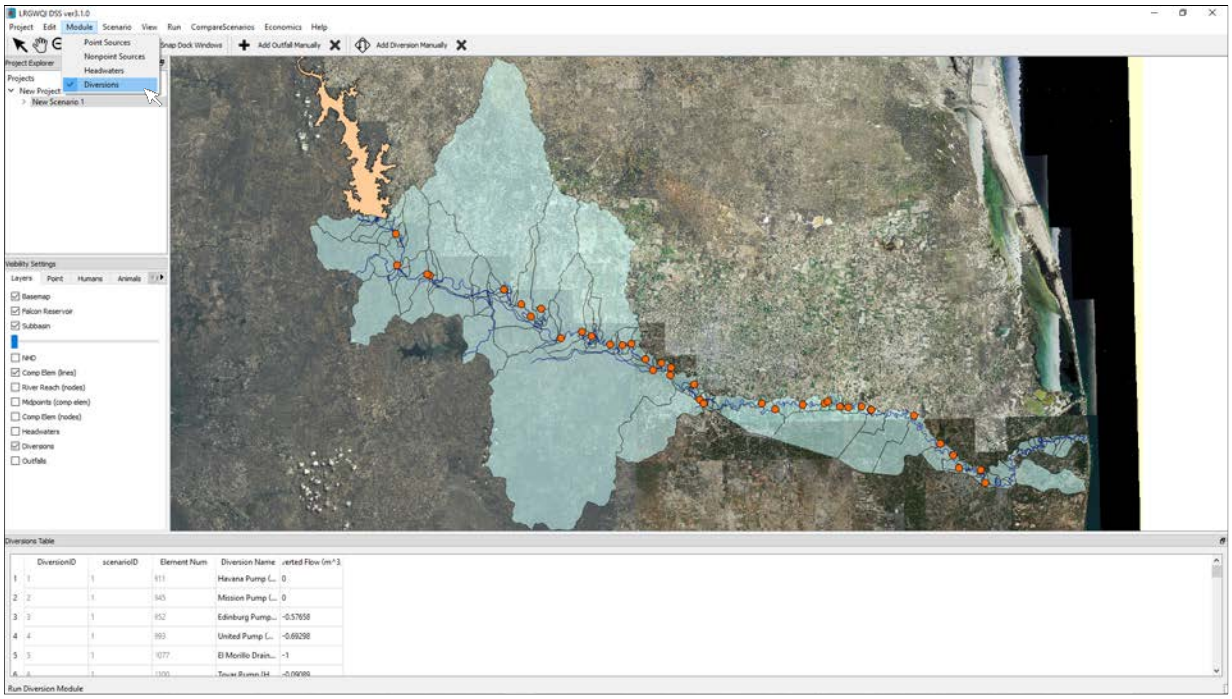
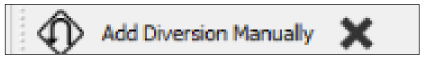


Figure 3-62. The “Diversions Table” in the “Diversions” Module of the LRGWQIDSS GUI.

The forty-one flow diversions and extractions featured in the LA-QUAL models of the Lower Rio Grande/Río Bravo are displayed in the “Diversions Table” along with the flow diverted at each diversion point/pumping location. The various columns shown in the “Diversions Table” can be hidden or displayed by checking or unchecking the various column headings in the “Diversion” tab of the “Visibility Settings” (displayed by checking the “Settings” option in the “View” component of the main menu bar). The user can change the flow, in cubic meters per second, diverted or pumped in any of the existing diversion points/pumps by entering new values in the column labeled “Diverted Flow (m^3/s).” It is important to note that diverted flows/extraction pumpage must be entered as negative values. The user can also add or remove diversions in any of the LA-QUAL model elements using the "Diversion Tools" located beneath the main menu bar 

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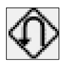
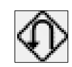
Creating a New Diversion

Like the outfalls in the "Point Sources Module," there are two ways a user can create a new diversion and add it to a scenario. The user can create a diversion/extraction from the Lower Rio Grande/Río Bravo, a tributary or contributing drain or ditch, manually or through the point-and-click method. In either case, the user must enter information about the new diversion in the "Diversion Table" after the diversion is created.

To create a diversion using the point-and-click method, the user must use the "Add Diversion" button . Clicking on this tool converts the cursor to a hand with a pointing finger ; clicking again once on the "Map" window creates a new diversion point in the location on the map where the tip of the pointing finger is pointing. To increase precision in the placement of new diversions created using the point-and-click method, it is advisable to first use the "Zoom" tool to zoom in on the location of interest prior to clicking on the "Add Diversion" button .

The "Add Diversion" function will only create a diversion point on one of the computational elements of the LA-QUAL model (i.e., Comp Elem [lines]). It does so by snapping the newly created diversion point to the nearest computational element midpoint. To increase the precision of placement further, the user may choose to display the "Midpoints (comp elem)" layer in the "Visibility Settings" (displayed by checking the "Settings" option in the "View" component of the main menu bar).

Upon the creation of a new diversion/extraction, a new row is added to the bottom of the "Diversion Table." The LRGWQIDSS places the name "A new diversion" in the new record under the "Diversion Name" column with a default diversion flow rate of zero.

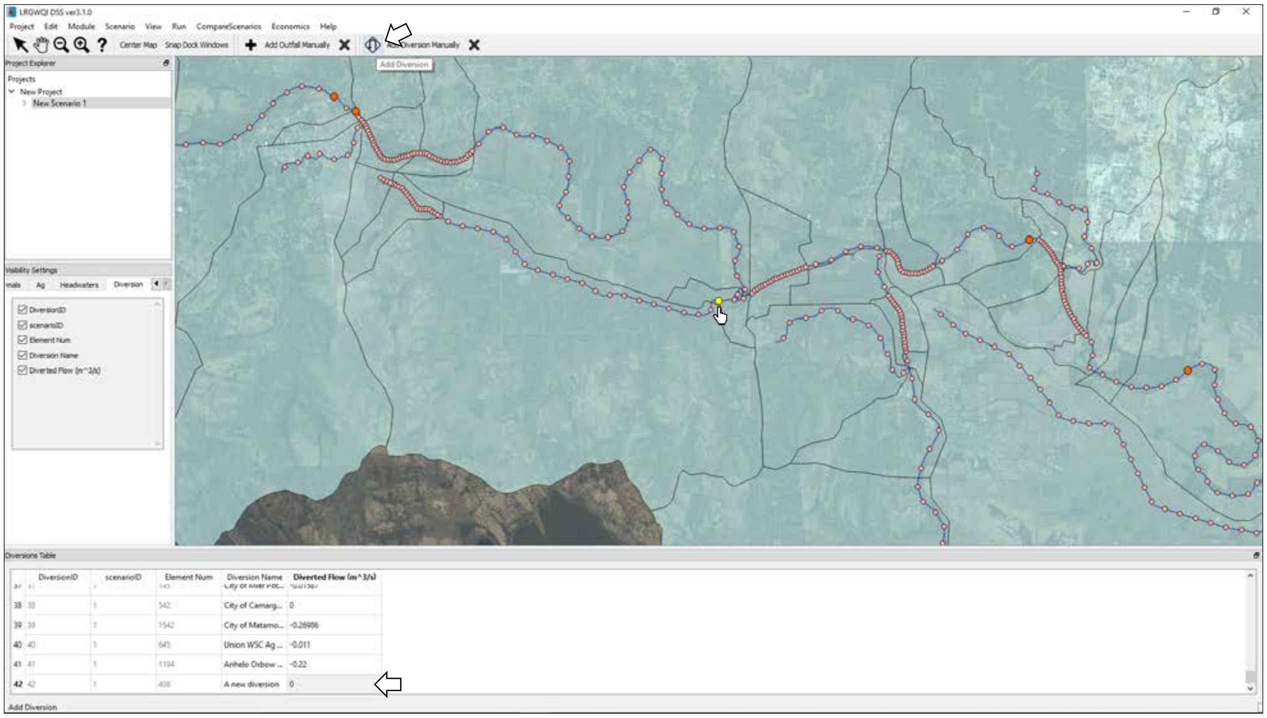
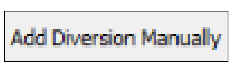


Figure 3-63. Adding a New Diversion Using the "Add Diversion" Button in the Tool Bar of the LRGWQIDSS GUI.

As with the creation of outfalls in the "Point Sources Module," there is also an alternative method for creating a new diversion using the "Add Diversion Manually" function 

. Adding a diversion manually, the user can specify the exact location where a diversion is to be created. When the user clicks the "Add Diversion Manually" button, a dialogue box opens requesting the latitude and longitude of the new diversion point. The user must then enter the coordinates of the new diversion in decimal degrees in the appropriate slots in the "DSS" dialogue box. As with the point-and-click method, the LRGWQIDSS will snap the location of the newly created diversion to the nearest LA-QUAL computational element midpoint. A new diversion point will be added to the bottom of the "Diversion Table" with a default diversion flow rate of zero.

After the creation of a new diversion using either method, the user must then enter the specific information about the new diversion in the Diversion Table, including the desired name and flow rate. The "Undo and "Redo" functions, in the "Edit" component of the main menu bar, can be used with the "Diversions Module" in the same manner as all other actions in the LRGWQIDSS GUI.

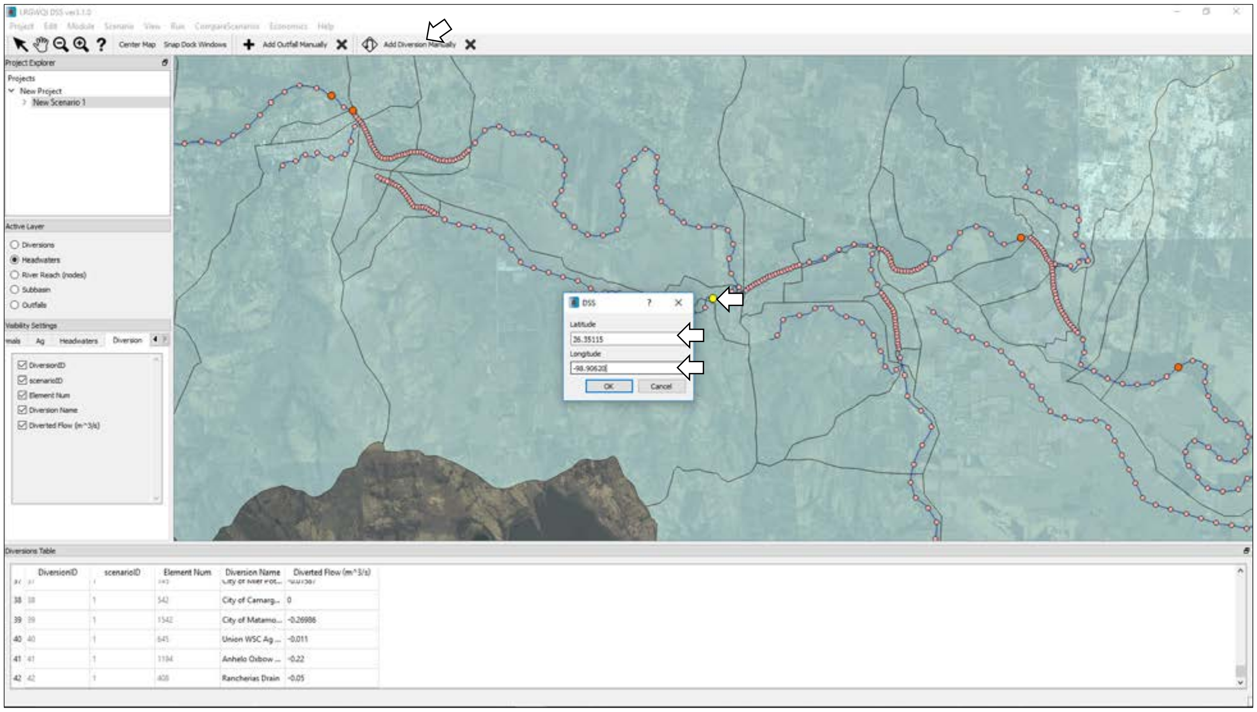
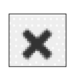


Figure 3-64. Adding a New Diversion Using the "Add Diversion Manually" Tool in the Tool Bar of the LRGWQIDSS GUI.

Deleting Diversions

Deleting new or existing diversion points is accomplished in the same manner as deleting wastewater outfalls in the "Point Sources Module." A new or existing diversion can be deleted by right-clicking on the row that is to be deleted in the "Diversion Table" and clicking on the "Delete Row" box that appears.

Another way to delete a newly created diversion, or any diversion for that matter, is to use the "Delete Feature" button of the "Diversions" tool . Deleting a diversion removes it completely from the LA-QUAL model; the diversion point disappears from the "Map" window and the row containing the information associated with the deleted diversion is removed from the "Diversion Table."

3.2.1.7 Running Water Quality Simulation Scenarios

After setting up a scenario using the various LRGWQIDSS modules and associated tools, the user can run the LA-QUAL model to simulate the effects of the scenario on water quality. The simulations can be run in "standard LA-QUAL mode," using the standard LA-QUAL GUI or the simulations can be run in "silent" mode. An explanation of these two options is provided in the subsequent Sub-sections.

SIMULATING POLLUTANT LOADING SCENARIOS IN STANDARD LA-QUAL MODE

Clicking on the Run Component of the Main Manu Bar displays two options, "LA-QUAL" and "LA-QUAL (silent)." Selecting the "LA-QUAL" option will launch the internal (standard) LA-QUAL GUI, which gives the user complete access to all the functions and capabilities of the LA-QUAL for Windows water quality simulation software. LRGWQIDSS Project scenarios can only be simulated sequentially (i.e., only one at a time).

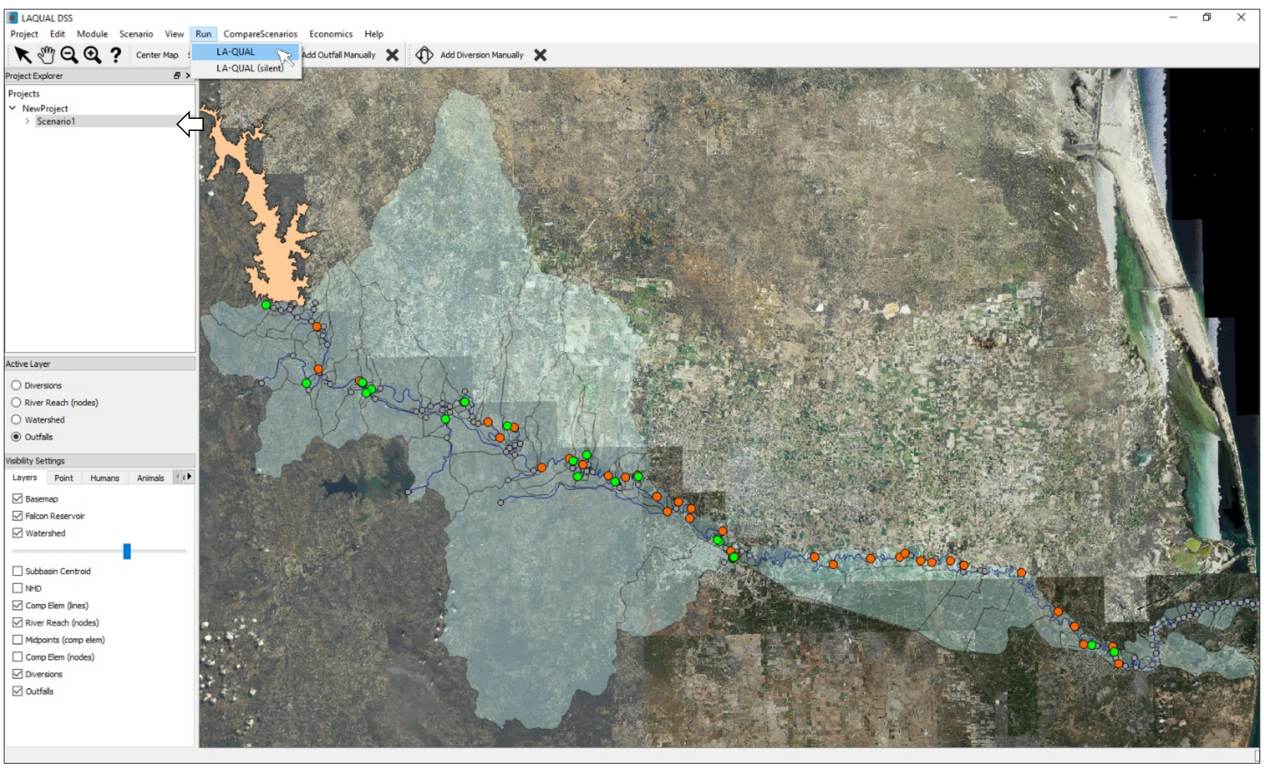


Figure 3-65. Running LA-QUAL in Standard Mode from the Run Component of the Main Menu Bar of the LRGWQIDSS GUI.

If the user opts to run a scenario in Standard LA-QUAL mode, they must execute the model manually by clicking on the “Xqt Model” command in the LA-QUAL GUI. Doing so will run the LA-QUAL software using the input file corresponding to the scenario selected by the user in the “Project Explorer” window of the LRGWQIDSS GUI.

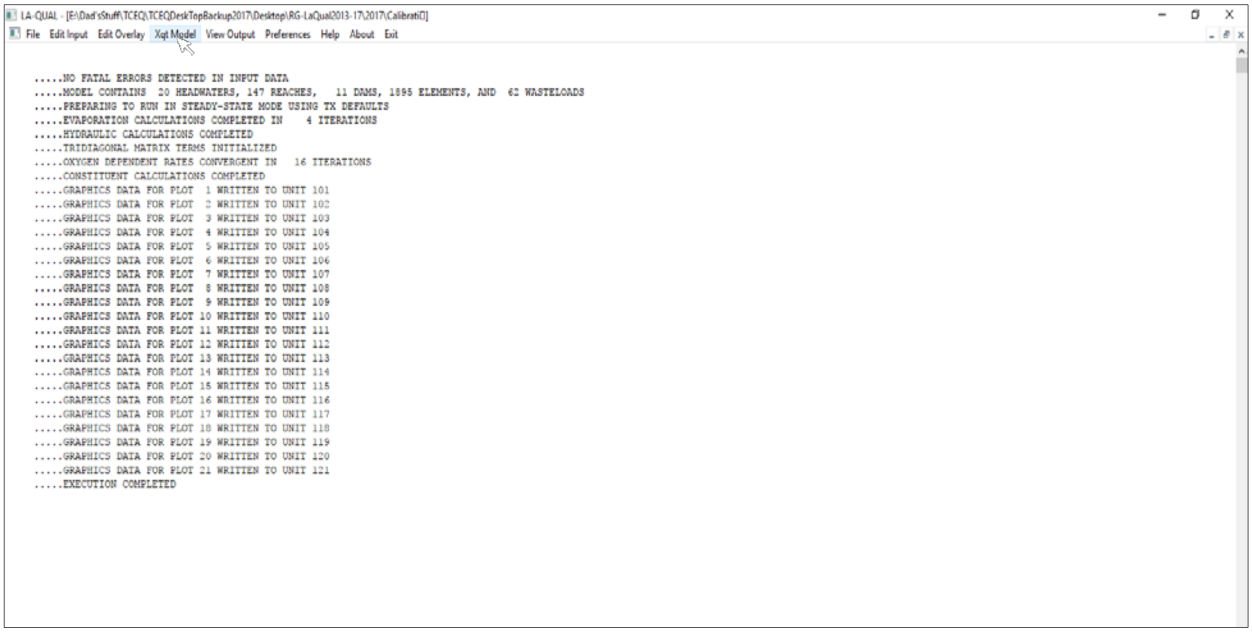


Figure 3-66. The LA-QUAL Model Execution Scroll Script in LA-QUAL GUI Window of the LRGWQIDSS GUI.

Following manual execution of the LA-QUAL model, the LA-QUAL software will automatically display the plots upon completion of the simulation, using the internal LA-QUAL plotting function. To return to the LRGWQIDSS GUI, the user must first exit the LA-QUAL plotting window by clicking on the “Exit” button on the top left of the window.

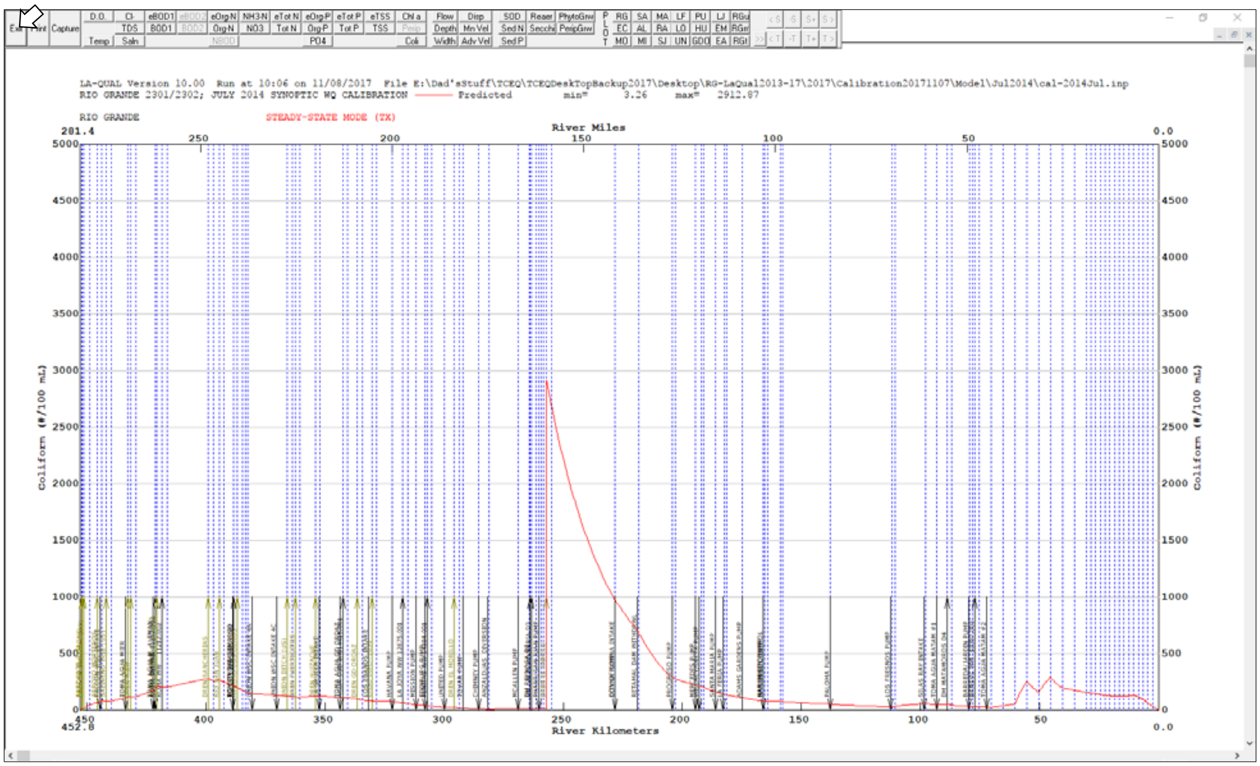


Figure 3-67. The LA-QUAL Model Plot Window in LA-QUAL GUI Window of the LRGWQIDSS GUI.

This will return the user to the main LA-QUAL GUI. Within the LA-QUAL GUI, the user can display plots of 23 water quality parameters, 6 physical parameters, 4 physico-chemical rates and 3 sediment parameters in 147 reaches simulated by LA-QUAL, including the main stem of the Lower Rio Grande, its two main tributaries and seventeen contributing drains and ditches. Clicking on the "Exit" component of the menu bar, or the ☒ symbol in the upper left corner of the main LA-QUAL GUI window, will return the user to the LRGWQIDSS GUI, where a message window will ask the user if they would like to save the results of the LA-QUAL run.

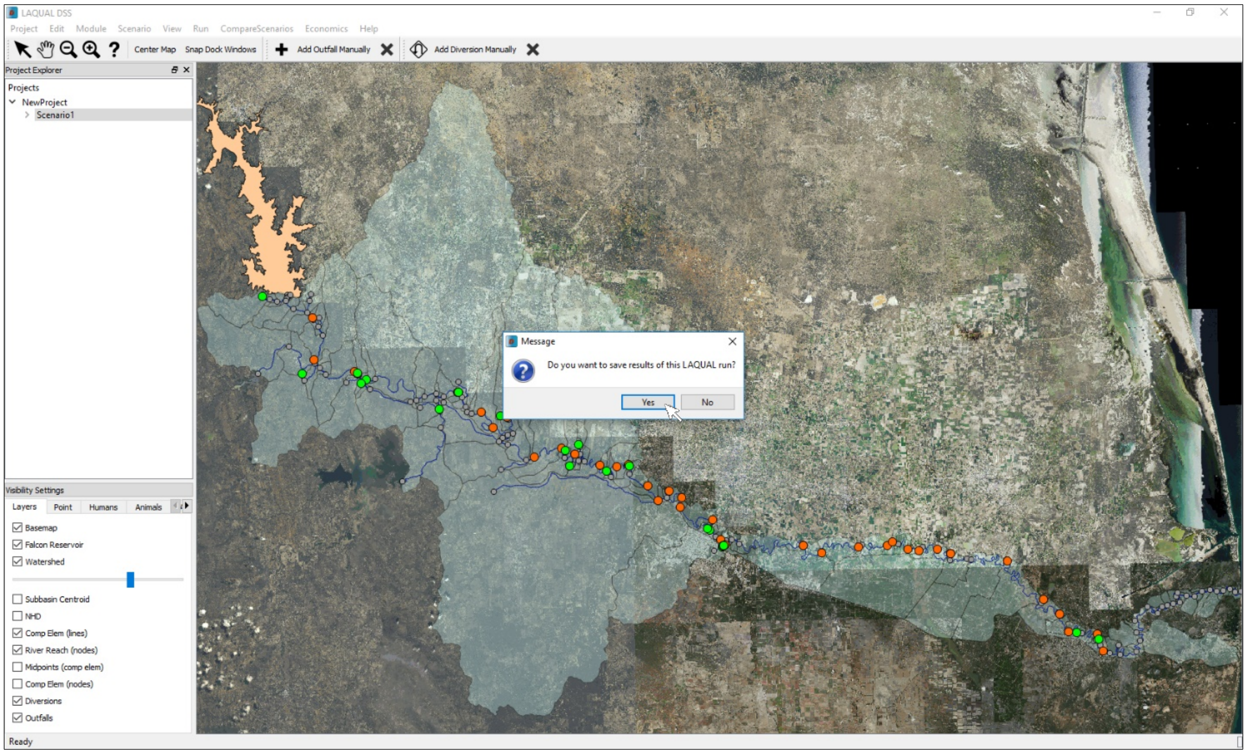


Figure 3-68. LA-QUAL Run Save Message in the LRGWQIDSS GUI.

The user can run as many simulation scenarios as are shown in the Project Explorer window, but scenario simulations can only be run one at a time. If left open, the LA-QUAL Plot window will display the results of the last simulation run performed. The LA-QUAL Plot window is part of the LA-QUAL Plot function, which is described in detail in Sub-section 3.1.2.9. Clicking on the "Close" icon  located in the upper right corner of the "LA-QUAL Plot" window will close this window.

Simulating Scenarios in LA-QUAL Silent Mode

The second option under the "Run" Component of the Main Manu Bar is "LA-QUAL (silent)." Selecting the "LA-QUAL (silent)" option will run the LA-QUAL software executable without launching the LA-QUAL GUI. In this mode, scenario simulations are completed with LA-QUAL running in the background. The LA-QUAL GUI will flash briefly and when the simulation is complete, the LRGWQIDSS GUI displays the message window asking the user if he or she would like to save the results of the LA-QUAL run (see previous figure). As previously mentioned, LRGWQIDSS Project Scenarios can only be simulated sequentially (i.e., only one at a time). It is advisable that the user ensure the correct scenario is selected in the Project Explorer window prior to conducting a simulation.

3.2.1.8 The LA-QUAL Plot Function

The "LA-QUAL Plot" window will automatically open after selecting "Yes" in the message window that appears after exiting the internal LA-QUAL GUI.

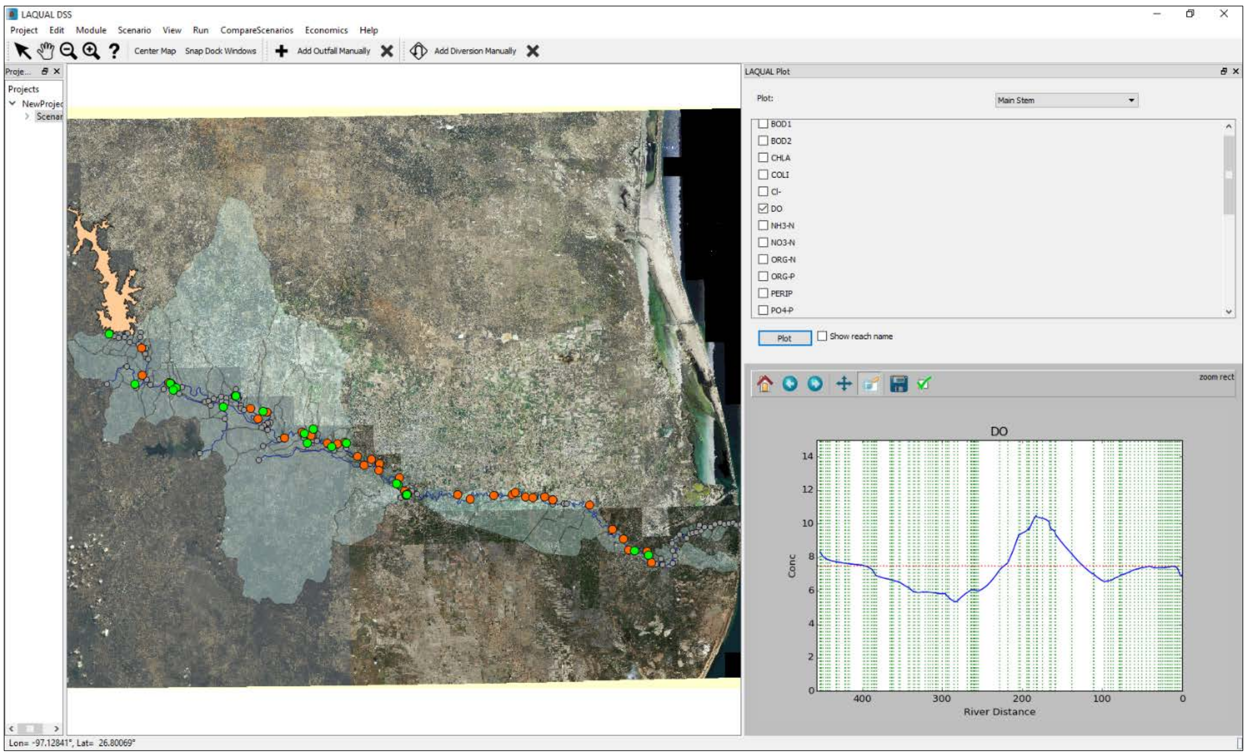
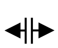


Figure 3-69. The "LA-QUAL Plot" Window of the LRGWQIDSS GUI.

The "LA-QUAL Plot" window can be maximized or exited using the window icons located in the upper right corner of the Plot window . The "LA-QUAL Plot" window can also be resized or stretched by placing the cursor on the left edge of the window, clicking it to obtain the  symbol and dragging it to the left. To restore the "LA-QUAL Plot" window, the user must double click on the Scenario name of interest in the "Project Explorer" window and then click on the "output" option that appears beneath the Scenario name. All Scenarios that have been simulated will have an output file associated with them.

The user can select the water body that is to be plotted from the pull-down menu at the top of the “LA-QUAL Plot” window (see next figure). The default setting is the “Main Stem” (of the Lower Rio Grande/Río Bravo), but the user also has the choice of selecting one of the other seventeen water bodies to plot from the pull-down menu (i.e., tributaries, drains and ditches). The user can also select the parameter(s) to be plotted by placing a check mark next to the desired parameter in the “Parameter Selection” window (see next figure). The user can select any or all of the 25 parameters shown in the “Parameter Selection” window. To avoid crowding in the “LA-QUAL Plot” window, the user should limit the number of selections.

Clicking on the” Plot” button below the “Parameter Selection” window displays the individual graphs of the parameters selected. All twenty-five parameters available in the “Parameter Selection” window can be plotted simultaneously and will appear as individual plots in the “Plot View” window. To avoid crowding in the “LA-QUAL Plot” window, the user should limit the number of selections.

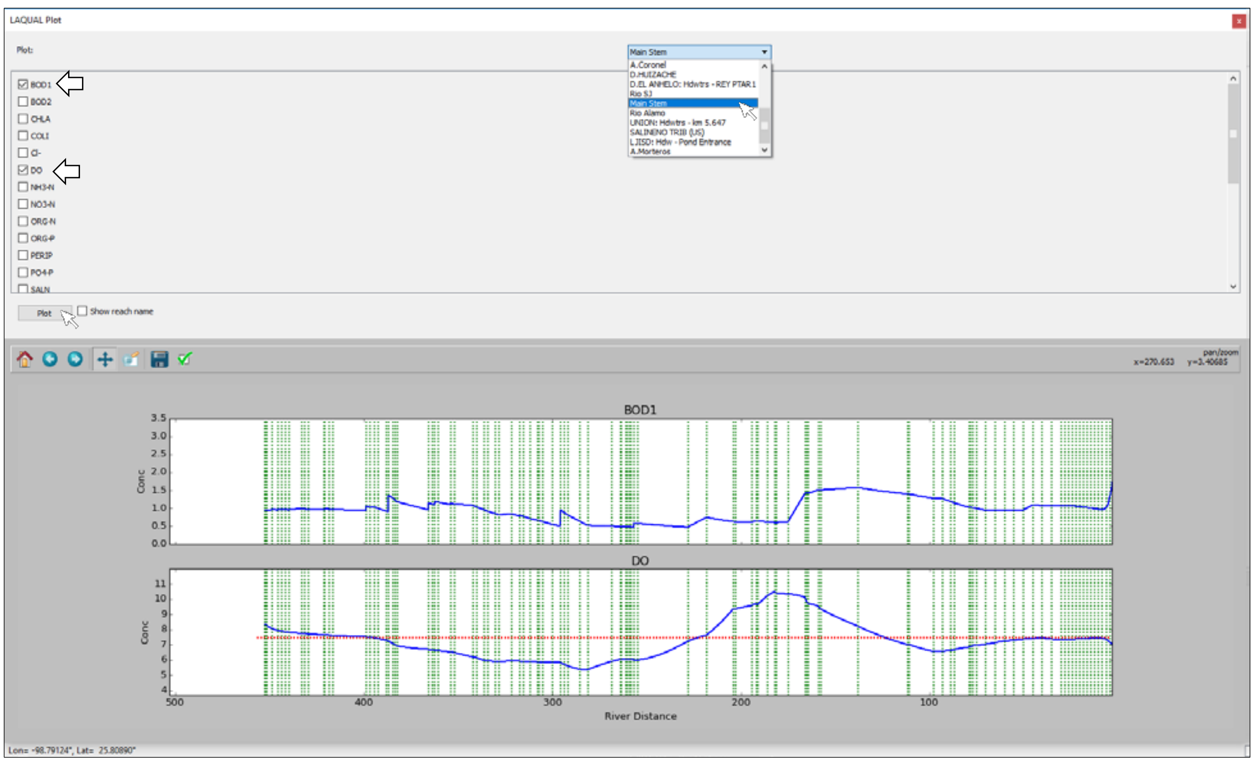


Figure 3-70. Selecting Water Bodies and Parameters to Plot in the “Plot View” Window of the “LA-QUAL Plot” Window of the LRGWQIDSS GUI.

The user also has the option of displaying the names of each LA-QUAL model reaches by clicking on the box next to “Show reach name” prior to clicking on the “Plot” button. The “Plot View” window is equipped with tools that allow the user to customize the various parameter plots. These tools are located in the menu bar at the top of the “Plot View” window.

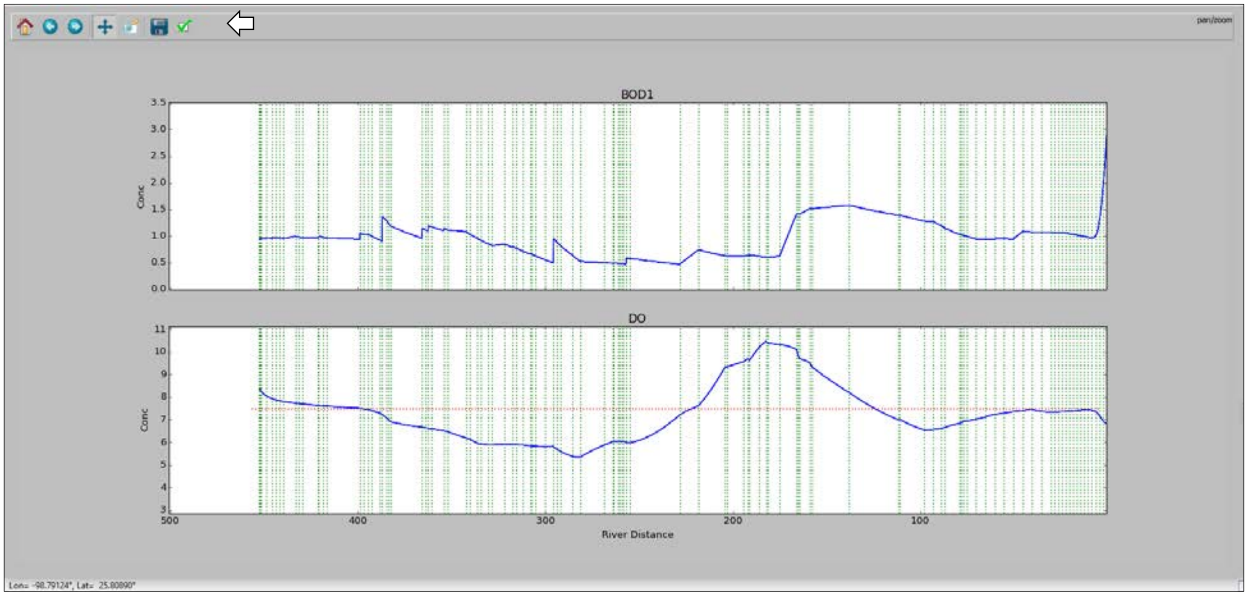


Figure 3-71. The “Plot View” Window Tools of the “LA-QUAL Plot” Window of the LRGWQIDSS GUI.

The user can use these tools to: (1) change the title of the plot; (2) specify the minimum and maximum values in the x-axis and y-axis; (3) change the axis labels; and (4) define the scale of each axis (i.e., linear or log-scale).

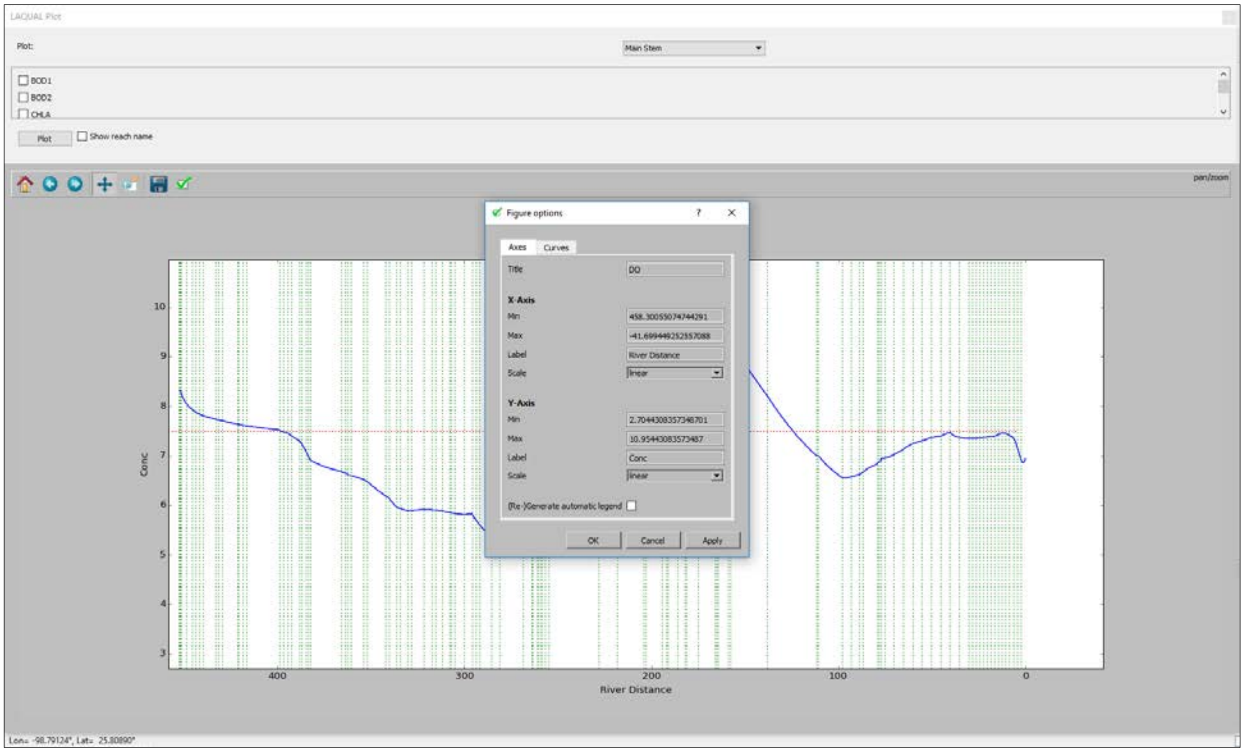
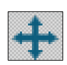


Figure 3-72. The "Figure Options" in the "Plot View" Window of the "LA-QUAL Plot" Window of the LRGWQIDSS GUI.

In the "Curves" tab of the "Figure options" window, the user can change the style, width and color of the line in the selected plot. The user can also add markers to the plot and can customize these markers.

The user can use the "Pan Plot" tool  to move the plot within the "Plot View" window. The scale of the plot is preserved during and after moving the plot using the "Pan Plot" tool. The user can use the "Zoom to Rectangle" plot tool  to decrease the scale of the axes, effectively zooming-in on portions of the plot. The "LA-QUAL Plot" function offers several other tools for manipulating LA-QUAL output plots; these are described in the LRGWQIDSS User's Manual.

Criteria Threshold Lines

The plots for nine of the parameters available from the pull-down menu in the "Parameter Selection" window contain pre-plotted criteria threshold lines. These lines represent the water quality criteria used by the TCEQ and CONAGUA to assess the achievement of standards associated with the uses designated, by each country, for the surface water bodies modeled in the LRGWQIDSS.

3.2.1.9 Comparing Water Quality Simulation Scenarios

The effects on water quality of the various scenarios simulated in LRGWQIDSS Projects can be compared using the "Compare Scenarios" function. The LA-QUAL software must have been executed on all scenarios before the "Compare Scenarios" function can be used to compare them. The function can be accessed by clicking on the "CompareScenario" component of the main menu bar. Clicking on the "Compare" option button displayed when doing so will open the "DSS" compare window.

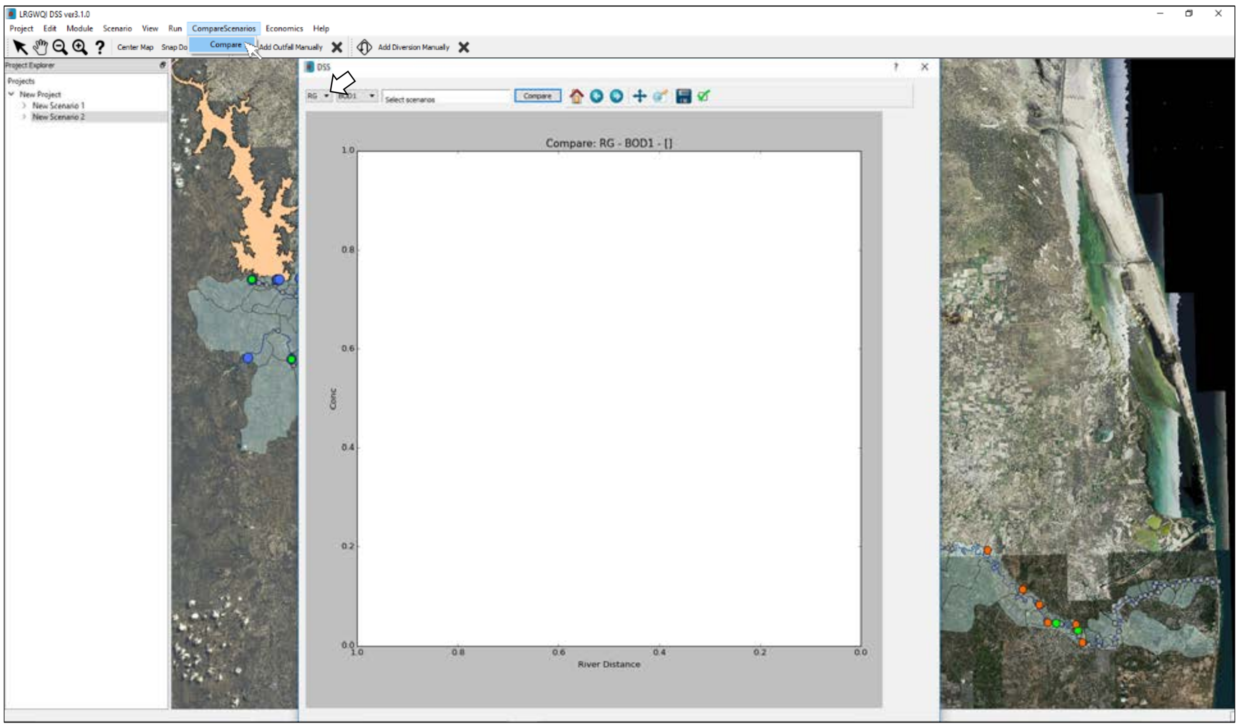


Figure 3-73. The CompareScenario Component of the Main Menu Bar of the LRGWQIDSS GUI.

Pull-down menus located in the top left of the "DSS" compare window allow the user to choose the water body for which the comparison is to be made and the water quality constituent of interest.

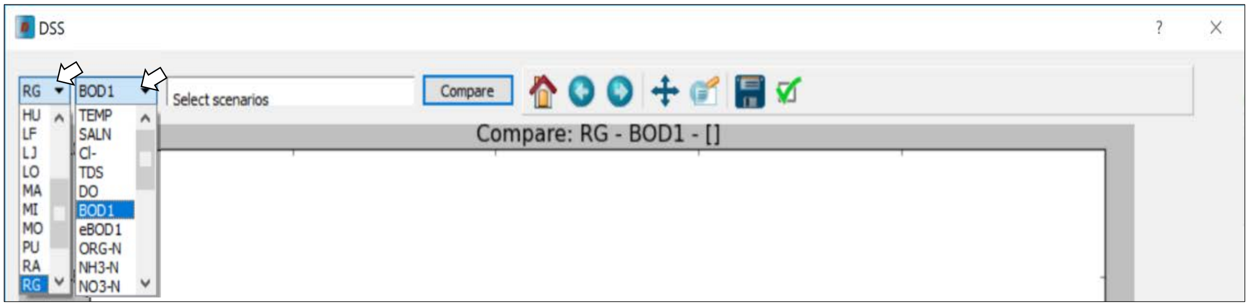


Figure 3-74. Selecting Water Bodies and Parameters to Plot in the "DSS" Compare Window of the LRGWQIDSS GUI.

The main stem of the Lower Rio Grande/Río Bravo (RG) is the default water body used for the comparison and CBOD5 (BOD1) is the default parameter that is compared. These choices can be changed by the user by selecting another water body and/or water quality constituent from pull down menus. To choose the scenarios to be compared, the user must click on the "Select scenarios" line of the "DSS" compare window and check the boxes next to the scenarios displayed when the line is clicked.

Clicking the "Compare" button draws the plots of the parameter being used to compare the scenarios in the water body chosen for the comparison.

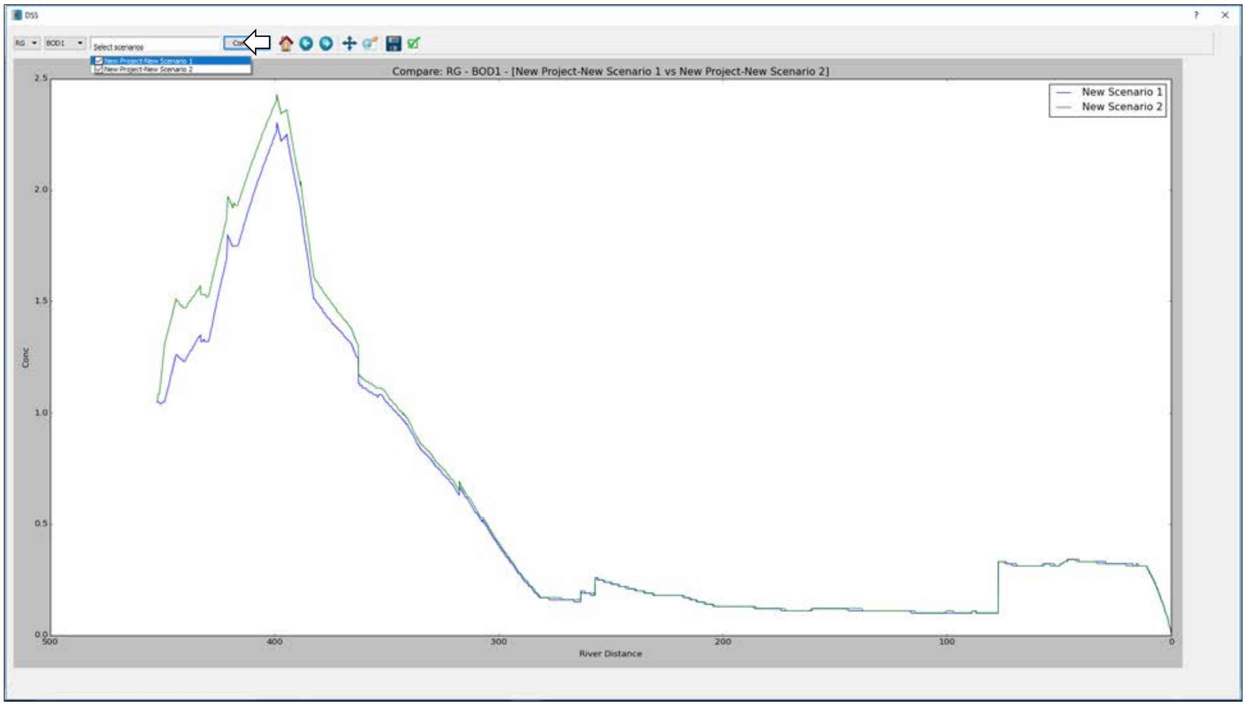


Figure 3-75. Comparing Scenario Plots Using the Compare Button in the "DSS" Compare Window of the LRGWQIDSS GUI.

The "DSS" compare window offers that same plotting tools found in the "LA-QUAL Plot" window. Scenarios are automatically color-coded and a legend indicating the color code is automatically displayed in the upper right corner of the "Compare" plot. The "Compare Scenarios" function can compare as many scenarios as are created under a given LRGWQIDSS Project.

3.1.2.10 Economics Functions

The LRGWQIDSS' economics functions allow the user to make preliminary estimates of the costs of implementing the specific control actions and management measures included in the scenarios in each LRGWQIDSS Project. The functions are designed to provide only a cursory estimate of the initial costs of implementation of these individual control actions and management measures and do not include operation, maintenance and depreciation costs over time. Unlike other functions of the LRGWQIDSS, the "Economics" functions do not require the user to run the LA-QUAL model on scenarios prior to estimating the costs of the control actions and/or management measures included in the scenarios.

The economics functions are available under the Economics component of the main menu bar and include the “Outfalls,” “Agricultural BMPs” and “Diversions” options.

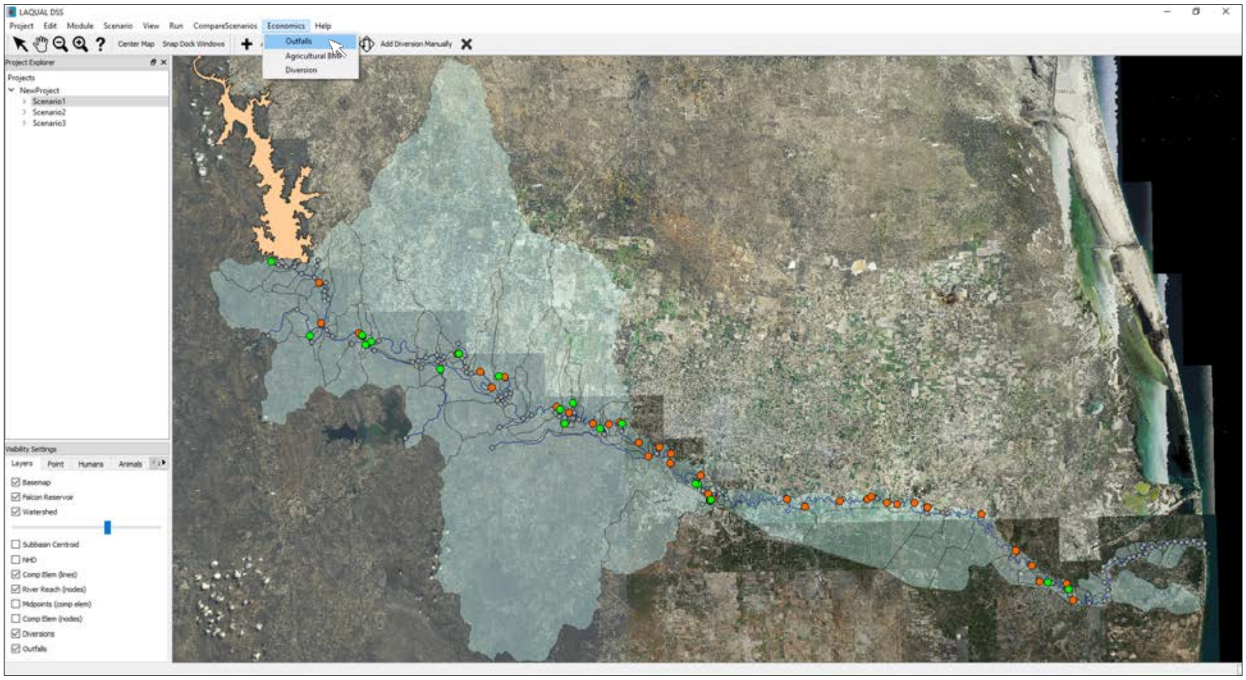


Figure 3-76. The Economics Component of the Main Menu Bar of the LRGWQIDSS GUI.

THE OUTFALLS ECONOMICS FUNCTION

The “Outfalls” economics function can calculate the costs associated with expanding the capacity of an existing wastewater treatment facility, building a new wastewater treatment facility, expanding an existing sewage collection system, or improving the efficiency of an existing sewage collection system. Selecting the “Outfalls” option in the “Economics” component of the main menu bar opens the “Outfall Cost Estimator” window.

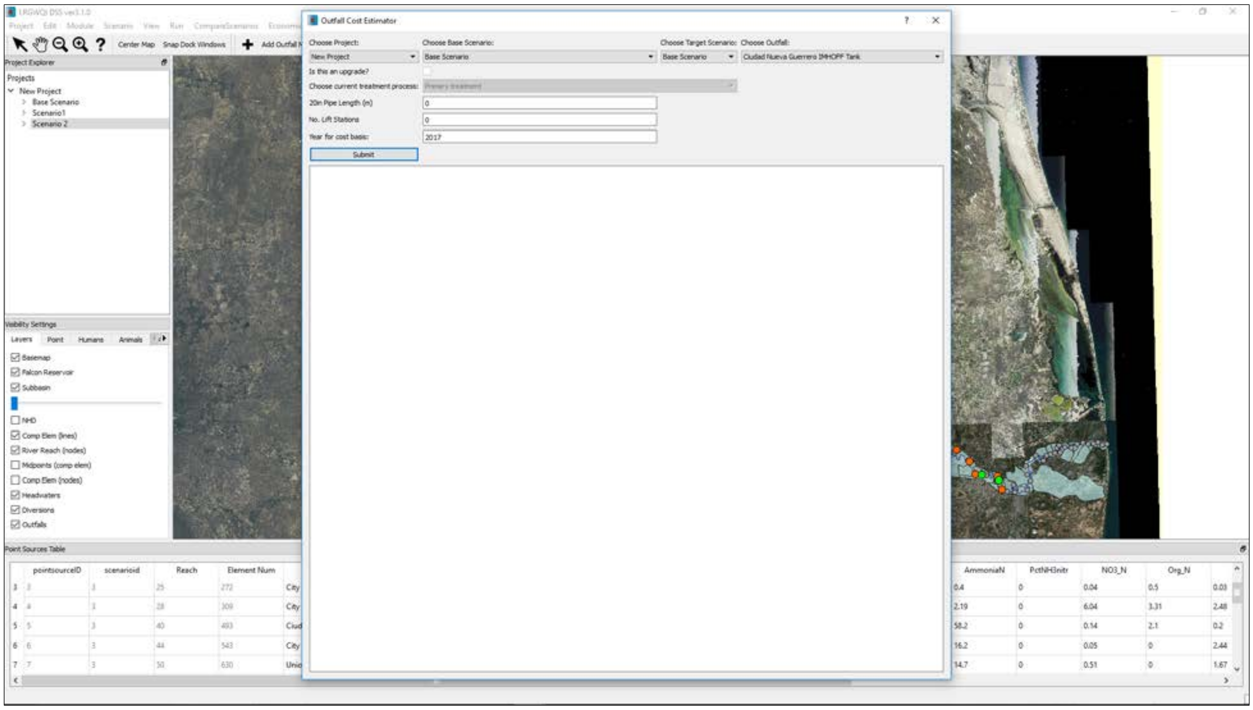


Figure 3-77. The "Outfall Cost Estimator" Window of the Outfalls Economics Function of the LRGWQIDSS GUI.

The user must specify a base scenario (i.e., a starting point) from which the estimates are to be calculated, as well as the target scenario for which the cost estimates are intended to reflect. The user must specify the outfalls (i.e., existing sewage treatment facility outfall or new sewage treatment facility outfall) that are to be assessed, as well as the length of sewer pipe associated with expanded sewer collection services or collection system rehabilitations. The user must also specify the number of lift stations that will be needed for control actions involving expanded sewer collection services or collection system rehabilitations.

The default treatment level for all new facilities or facility expansions is primary treatment. However, the user has the option of changing the proposed treatment level by checking the box next to the question "Is this an upgrade?"

If the control actions associated with the scenario being compared to the base scenario involve changes in a sewage collection system, the user must specify the length of sewage pipe that will be needed to implement the actions by entering the value, in meters, in the box next to the dialogue that reads "20 in Pipe Length (m)." Similarly, if the control actions associated with the scenario being compared to the base scenario involve installation of new lift stations, the user must specify the number of lift stations that will be needed to implement the actions by entering the value in the box next to the dialogue that reads “No. Lift Stations.”

The user must then specify the year in which the expenditures, associated with construction of the control actions, are anticipated to occur. This can be done by entering the year in the box next to the dialogue that reads “Year for cost basis.” The default year for cost basis is 2019.

Clicking on the “Submit” button produces a cost estimate based on the information submitted by the user and the information available in the “Point Sources” table (Point Sources Module) for the base and target scenarios specified in the “Outfall Cost Estimator.” The estimate produced reflects the difference in cost between the base and target scenarios. The “Outfall Cost Estimator” window will display the name of the target scenario, the name of the Permittee (i.e., name of outfall), the final effluent flow rate, the final effluent BOD concentration in mg/L, final ammonia concentration (NH4) in mg/L, the treatment process and wastewater pipeline costs.

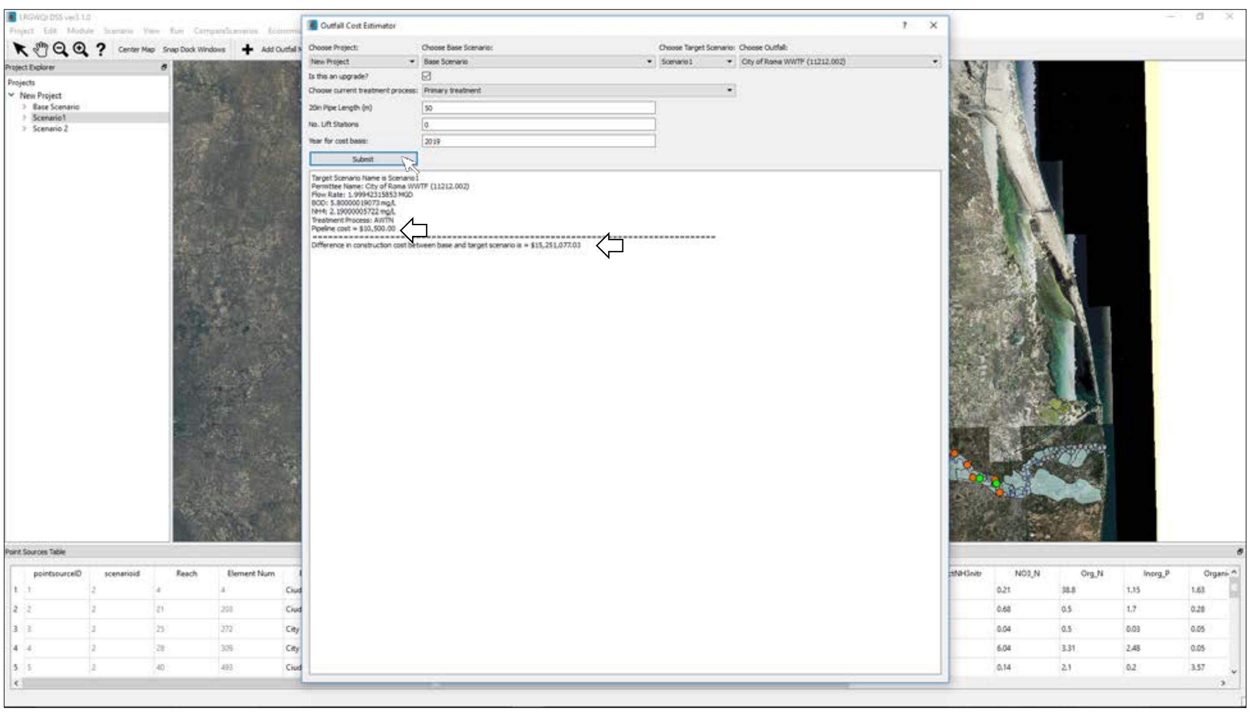


Figure 3-78. Cost Estimate Output in the “Outfall Cost Estimator” Window of the Outfalls Economics Function of the LRGWQIDSS GUI.

AGRICULTURAL BEST MANAGEMENT PRACTICES (BMPS) ECONOMICS FUNCTION

The “Agricultural BMPs” economics function allows the user to estimate the costs of implementing irrigation and agronomic management practices that reduce the loading of pollutants to the Lower Rio Grande/Río Bravo and/or its tributaries and contributing drains/ditches (i.e., Agricultural Best Management Practices [BMPs]). Selecting the “Agricultural BMP” option in the “Economics” component of the main menu bar opens the “Nonpoint Source BMP Cost Estimator” window.

As with the “Outfall Cost Estimator,” the user must specify the base scenario (i.e., starting point) from which the estimates are to be calculated, as well as the target scenario for which the cost estimates are intended to reflect. The “Nonpoint Source BMP Cost Estimator” compares the information available in the “Agriculture Loadings Table” (Nonpoint Sources Module) for the base and target scenarios and uses it to produce a cost estimate. Clicking on the “Submit” button produces the cost estimate.

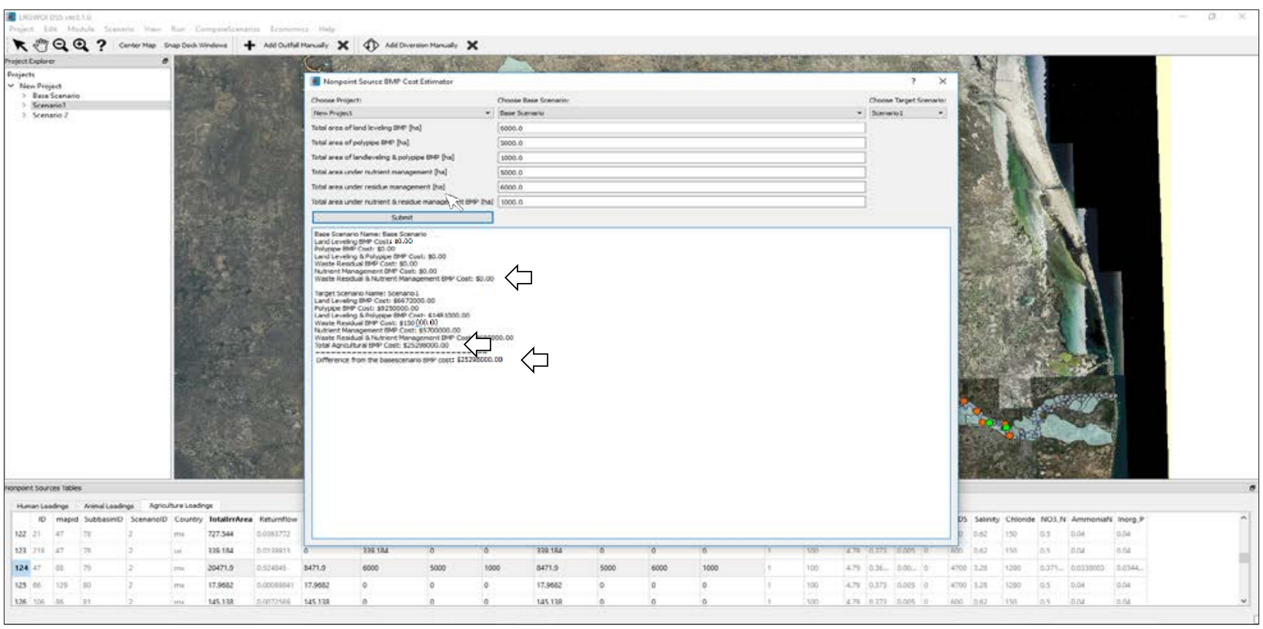


Figure 3-79. Cost Estimate Output in the “Nonpoint Source BMP Cost Estimator” Window of the LRGWQIDSS GUI.

The “Nonpoint Source BMP Cost Estimator” window will display the name of the base scenario and the costs associated with implementing agricultural irrigation BMPs (Land Leveling, Polypipe and combined Land Leveling and Polypipe) and agronomic BMPs (Residue

Management, Nutrient Management and combined Residue and Nutrient Management) under the base scenario. Below this information, the "Nonpoint Source BMP Cost Estimator" will display the name of the target scenario along with the cost of implementing the agricultural irrigation BMPs and agronomic BMPs specified by the user under the target scenario. The last line displayed in the "Nonpoint Source BMP Cost Estimator" window is the difference in cost between the base and target scenarios.

THE DIVERSIONS ECONOMICS FUNCTION

The Diversion Economics function allows the user to estimate the costs of installing additional flow diversion structures on any of the river reaches included in the LA-QUAL models that undergird the LRGWQIDSS, including the costs associated with building lined canals to convey the diverted flow.

The reason for diverting flow is usually related to the extraction of water for beneficial uses such municipal water supplies or agricultural irrigation. However, within the context of the LRGWQI, a second motivation for including the ability to add or remove flow diversion points in the LRGWQIDSS is to simulate their effect on water quality.

One of the most effective ways to mitigate the loading of dissolved solids and nutrients to the river is to divert irrigation return flows away from it. This can be accomplished by installing pumps or other diversion structures on the tributaries and ditches that drain large irrigated agricultural areas. The El Morillo Drain pump and conveyance system is a current example of an existing diversion pump system for diverting saline irrigation return flows away from the main stem of the Lower Rio Grande.

Selecting the "Diversions" option in the "Economics" component of the main menu bar opens the "Diversion Cost Estimator" window. As with the other cost estimation windows associated with the economics functions of the LRGWQIDSS, the user must specify the base scenario (i.e., starting point) from which the estimates are to be calculated, as well as the target scenario for which the cost estimates are intended to reflect. The "Diversion Cost Estimator" compares the information available in the "Diversion Table" (Diversions Module) for the base and target scenarios and uses it to produce a cost estimate.

Clicking on the “Submit” button produces a cost estimate for diversions included in the target scenario. In addition to the itemized cost information, the estimate also reports the total amount of flow diverted from all reaches of the LA-QUAL model under the target scenario. The “Diversion Cost Estimator” window displays the assumptions used to calculate construction costs (e.g., concrete lining of canals).

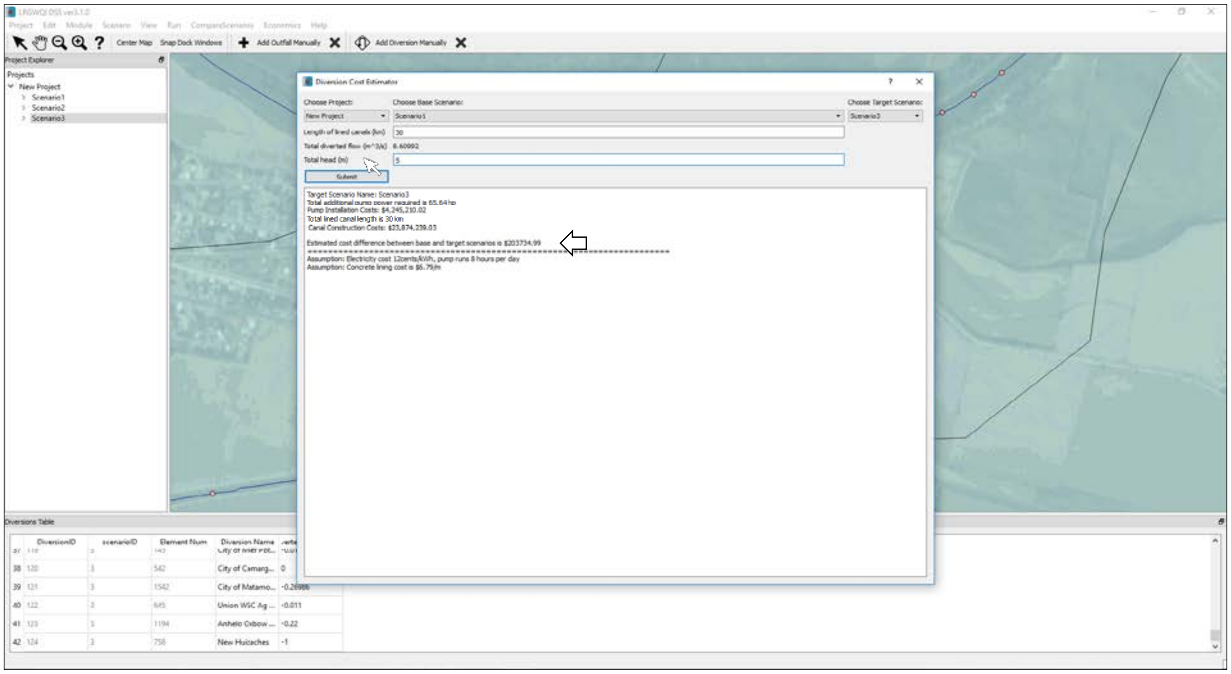


Figure 3-80. Cost Estimate Output in the “Diversions Cost Estimator” Window of the Diversions Economics Function of the LRGWQIDSS GUI.

3.1.2.11 The LRGWQIDSS Help Feature

The “Help” feature of the LRGWQIDSS provides information that can aid the user in operating and troubleshooting the decision support system. Clicking on the Help Component of the Main Menu Bar displays three options, “About…” “User’s Manual” and “LA-QUAL User’s Manual.” Clicking on the “About” option displays the LRGWQIDSS version number as well as the University of Texas at Austin Logo. Clicking on the “User’s Manual” option of the Help Component brings up the LRGWQIDSS User’s manual document, in PDF format. Clicking on the “LA-QUAL User’s Manual” option brings up the LA-QUAL User’s Manual in PDF format.

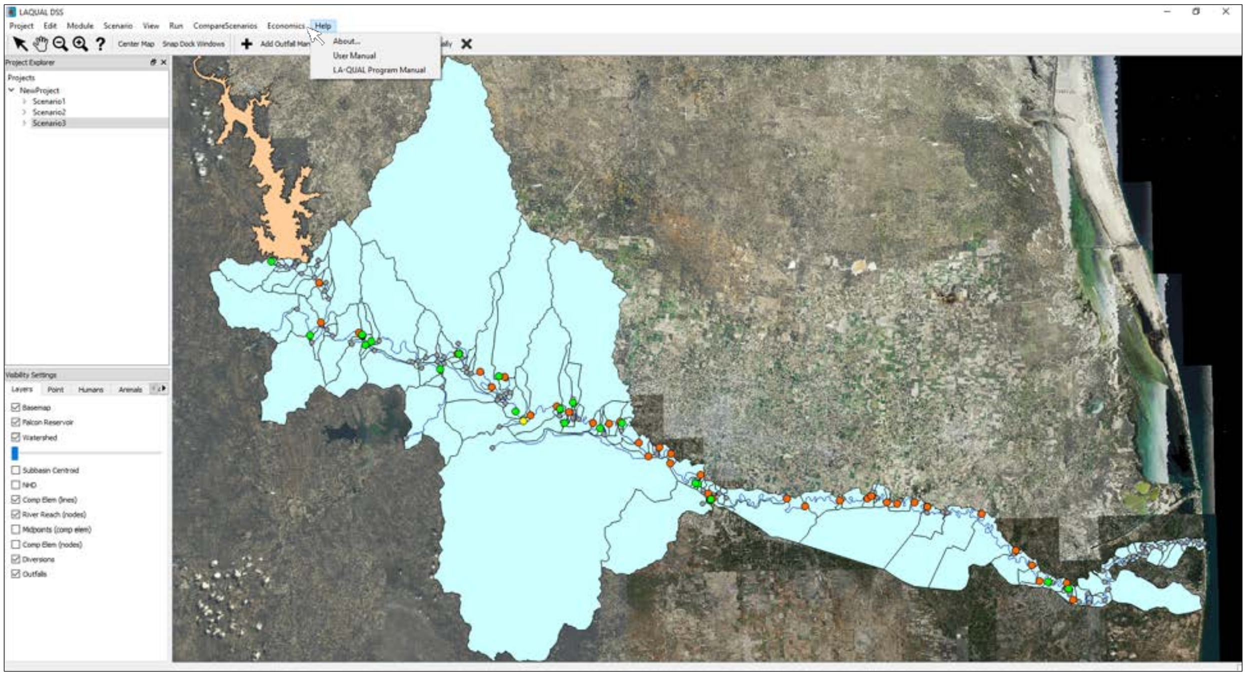


Figure 3-81. The Help Component of the Main Menu Bar of the LRGWQIDSS GUI.

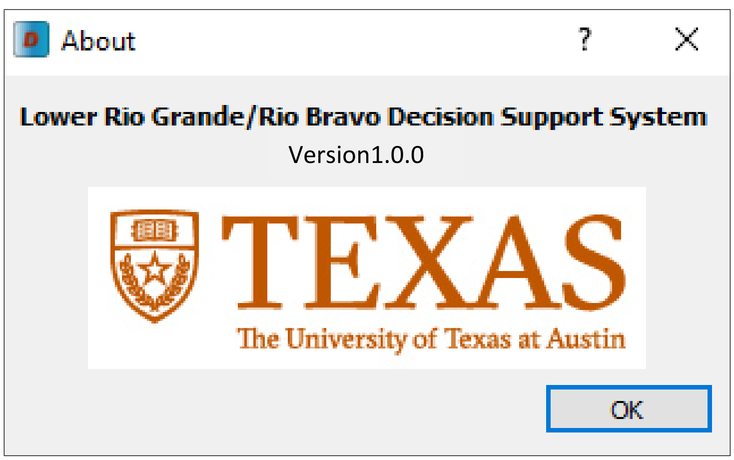


Figure 3-82. The "About" Display of the Help Component of the Main Menu Bar of the LRGWQIDSS GUI.

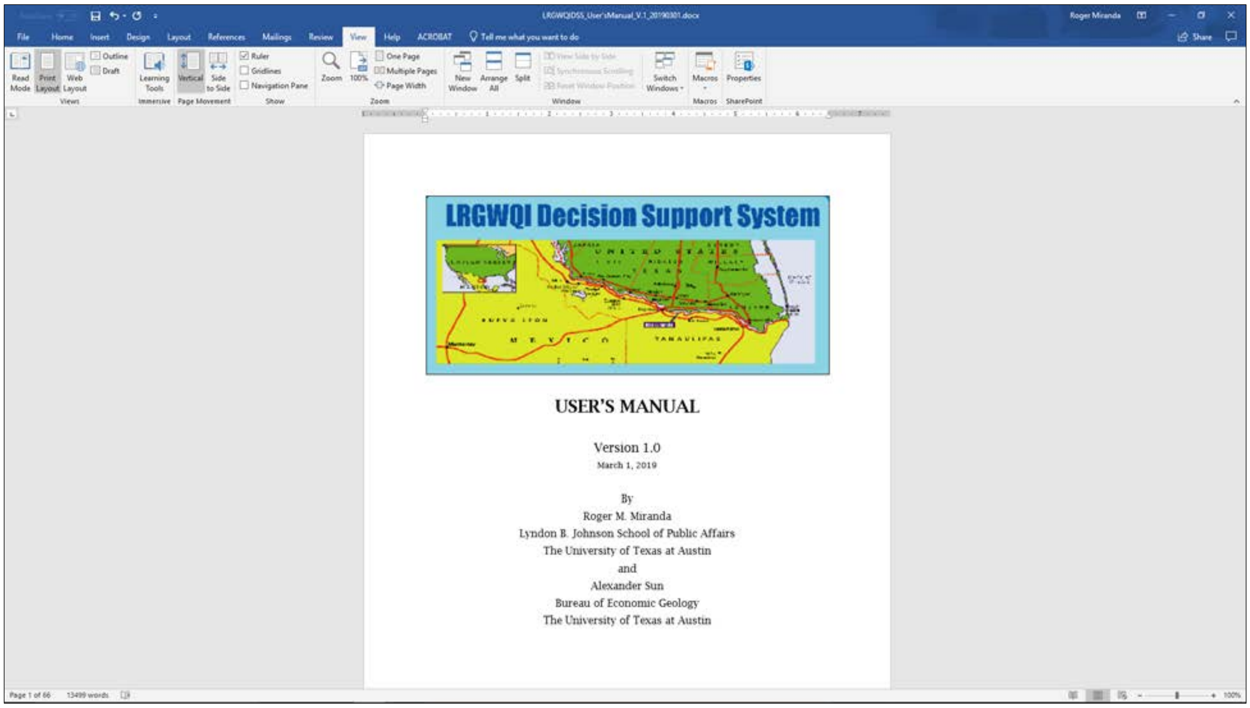


Figure 3-83. The LRGWQIDSS User's Manual in PDF Format from the "User's Manual" Option of the Help Component of the LRGWQIDSS GUI.

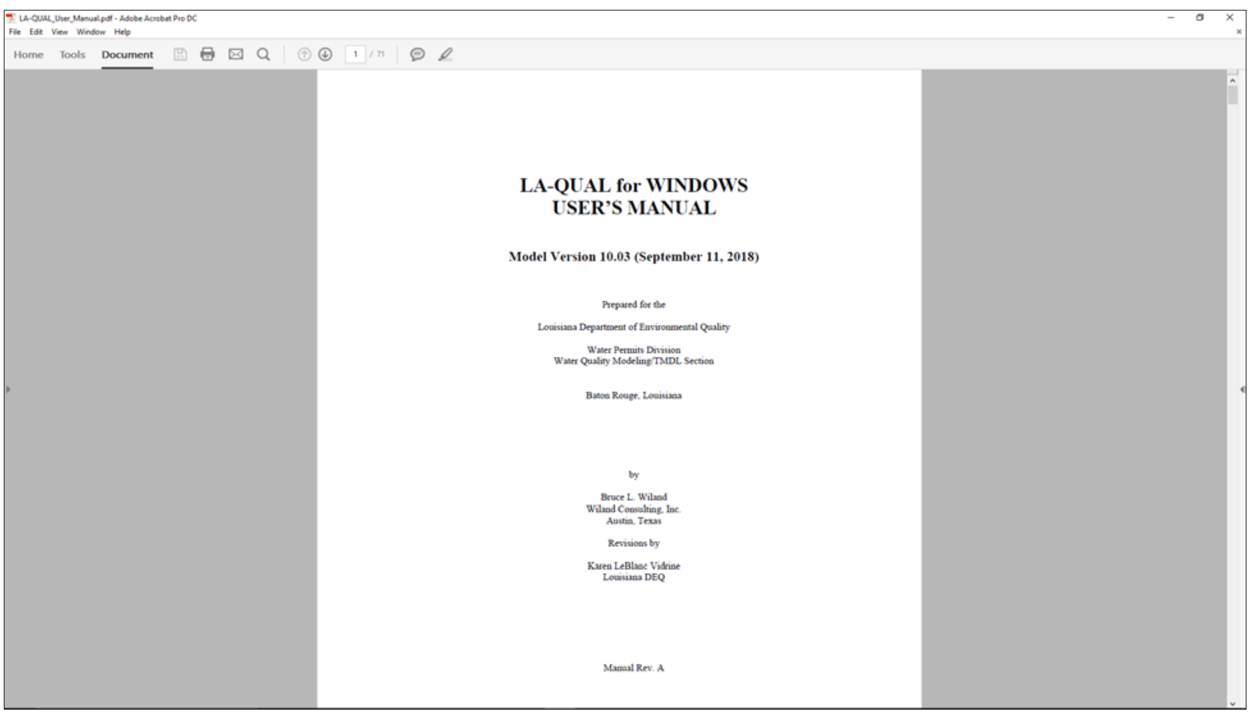


Figure 3-84. The LA-QUAL User's Manual in PDF Format from the "LA-QUAL User's Manual" Option of the Help Component of the LRGWQIDSS GUI.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Application of LRGWQIDSS

4.1.1 Application of the LRGWQIDSS in the LRGWQI Action Arena

Following approval of the LA-QUAL model calibrations by the members of the LRGWQI's BTWG in March 2018, the Mexican and US representatives of the BTWG worked jointly to identify the pollutant loading scenarios for water quality simulation to support decision making in the LRGWQI action arena. The first scenarios identified by members of the BTWG involved the simulation of alternative point source loadings under the ambient conditions used to calibrate the five LA-QUAL models of the binational synoptic surveys.

The Mexican representatives proposed using the calibrated LA-QUAL models to assess how changes in wastewater effluent flows and pollutant concentrations for Mexican dischargers would affect water quality as part of CONAGUA's Declaratoria effort. The scenarios proposed by CONAGUA were designed to set water quality-based effluent flow and pollutant concentrations limits for Mexican dischargers, but also to assess water quality and water body use attainment based on alternative Mexican instream water quality criteria. Recall that routine assessments of water quality conducted by CONAGUA rely on indices of water quality that serve as overall measures of the health of the water body being assessed. The indices are based on four individual water quality constituents, BOD (DBO_5), chemical oxygen demand (DQO), TSS (SST), and fecal coliform.

Absent a promulgated Declaratoria, permit limits for Mexican wastewater dischargers are set by CONAGUA using the Mexican regulatory criteria found in NOM-001-SEMARNAT-1996, which is based on BPT. As part of the Declaratoria effort, IMTA and CONAGUA proposed to set effluent flows and pollutant concentration limits for Mexican dischargers based on the simulated effects of these discharges on ambient water quality, instead of BPT. The Declaratoria-based assessment would include water quality constituents in addition to those used in the four-constituent indices used for routine assessment (e.g., values of DO, nitrates, ammonia nitrogen, phosphates and TSS included in the Mexican Ecological Criteria CE-CCA-001/1986). IMTA developed a preliminary "guide" of wastewater effluent concentrations to simulate for the

Declaratoria effort with the intention of modifying these values as part of the pollutant loading scenarios.

The US representatives agreed with the Mexican representatives' proposal for model use (i.e., the Declaratoria effort), but proposed that the simulations be run using full TPDES-permitted effluent flows and pollutant concentrations for all US dischargers, rather than the effluent flows and pollutant concentrations measured during the synoptic surveys. Under the TPDES program, US permittees are legally entitled to discharge treated wastewater at their full-permitted flow capacity and pollutant concentration limits. The US members of the BTWG proposed running the simulations at "critical conditions" rather than the conditions observed during the synoptic surveys. Simulation of water quality at critical conditions is standard practice for TPDES discharge permit evaluations and usually involves adjusting the flow and temperature values in the initial conditions of calibrated models to reflect critical low flow, usually the lowest average in-stream flow over a 7-day period with a recurrence interval of 2 years (7Q2), and the ninetieth percentile of water temperature recorded over the previous 10 years.

While the Mexican BTWG representatives agreed with the US members' proposal to run the scenario simulations using full-permitted US wastewater discharges, they expressed reservations over the prospect of running the simulations at the US-proposed critical conditions. The Mexican BTWG representatives' first concern was that, since the models represented seasonal conditions exemplified by the synoptic surveys used to calibrate the models, it would not be appropriate to adjust the flow of every model to the same 7Q2 value calculated from the periods of record at each of the IBWC flow gage stations. The Mexican BTWG representatives expressed a similar concern for the adjustment of temperature (i.e., it would not be appropriate to adjust the temperature of every model to the same the ninetieth percentile of water temperature recorded over the previous 10 years). After some deliberation, the members of the BTWG agreed to run simulations at both observed in-stream flows and temperatures, and at critical in-stream flows and temperatures calculated using the 10^{th} percentile of flow and 90^{th} percentile of temperature for each of the months in which the synoptic surveys were conducted (i.e., July, August, November, March, and April) over the period of record 2000-2015.

The water quality simulations of the wastewater flows and effluent pollutant concentrations included in IMTA's preliminary Declaratoria "Guide" were also run using wastewater flows and effluent limits associated with a modified version of the Declaratoria "Guide" in which values in the original "Guide" were substituted for effluent pollutant concentrations in discharges measured during the synoptic surveys if these were lower than those proposed in the original Declaratoria "Guide." IMTA and CONAGUA's apparent reasons for running these simulations were commensurate with the philosophy behind setting effluent limits at BPT. That is, if a permittee is already demonstrating the ability to meet effluent limits more stringent than those proposed in IMTA's original Declaratoria "Guide," CONAGUA could opt to hold that permittee to the pollutant concentrations currently observed in the discharge from its wastewater treatment facility.

4.1.1.1 Preliminary Point Source Loading Scenarios

Based on the binational deliberations described above, five separate point source loading scenarios were simulated as part of the preliminary effort to support decision making in the LRGWQI action arena. The scenarios included:

1. <u>Scenario A – NOM-001 and Full Permitted US Effluents at Critical Conditions</u>

   The purpose of this scenario was to investigate the effect on water quality in the Lower Rio Grande/Río Bravo if all dischargers, US and Mexican, limited their effluent flows and pollutant concentrations to their currently permitted values. The run was conducted under critical temperatures and flows (10^{th} percentile of flow and 90^{th} percentile of water temperatures for the synoptic months calculated over the period of record 2000-2015).

2. <u>Scenario A1 – Declaratoria Guide and Full Permitted US effluents at Critical Conditions</u>

   The purpose of this scenario was to investigate the effect on water quality in the Lower Rio Grande/Río Bravo resulting from the implementation of the Declaratoria "Guide" effluent values at critical conditions. US wastewater discharges were set at full US-permitted flow limits and concentrations.

3. Scenario A2 – Declaratoria Guide and Full Permitted US effluents at Observed Conditions

   The purpose of this scenario was to investigate the effect on water quality in the Lower Rio Grande/Río Bravo resulting from the implementation of the Declaratoria Guide effluent values at the ambient conditions observed during the synoptic surveys. Declaratoria Guide values were used to represent Mexican Discharges and full permitted US effluent limits and concentrations were used to represent US discharges. This simulation was set up the same as that of Scenario A1, except at ambient conditions observed during the binational synoptic surveys.

4. Scenario A3 – Modified Declaratoria Run and Full Permitted US effluents at Observed Conditions

   The purpose of this scenario was to investigate the effect on water quality in the Lower Rio Grande resulting from the implementation of the modified Declaratoria Guide effluent values (where IMTA substituted the observed synoptic values that were lower than the Declaratoria Guide values originally proposed) at the ambient conditions observed during the synoptic surveys. US discharges were set at the US full-permitted effluent flow limits and pollutant concentrations.

5. Scenario A4 – Modified Declaratoria Guide and Full Permitted US effluents at Critical Conditions

   The purpose of this scenario was to investigate the effect on water quality in the Lower Rio Grande resulting from the implementation of the modified Declaratoria Guide effluent values at critical temperatures and flows. US discharges were set at the US full-permitted effluent flow limits and pollutant concentrations. This simulation was set up the same as that of Scenario A3, except at critical conditions of flow and temperature for each of the synoptic months.

RESULTS OF PRELIMINARY POINT SOURCE POLLUTANT LOADING SCENARIOS

The water quality simulations of Scenarios A-A4, showed mixed results in terms of water quality improvement. In general, the results showed that implementation of the Modified Declaratoria effluent limits reduced the concentrations of pollutants in the portions of the river most affected by Mexican point source discharges. For example, the portion of the Rio Grande/Río Bravo downstream of the confluence with the Anhelo Drain, into which City of Reynosa's Wastewater Treatment Facility No. 1 discharges, saw a marked improvement during seasons of higher flow in the river (e.g., April and July), However, in portions of the river where steady state nonpoint sources of pollution are abundant, the Modified Declaratoria Guide effluent limits did not seem to have much effect. Simulations of the scenarios that included these effluent limits and were run at critical ambient conditions showed higher instream pollutant concentrations, as expected, in portions of the river where steady state nonpoint sources of pollution are most abundant. Figure 4-1 shows an example of this for fecal coliforms.

The top image in Figure 4-1 shows a plot of the calibration run for the July 2014 synoptic with a marked spike in fecal coliforms in the main stem of the Lower Rio Grande/Río Bravo downstream of the confluence with the El Anhelo Drain.

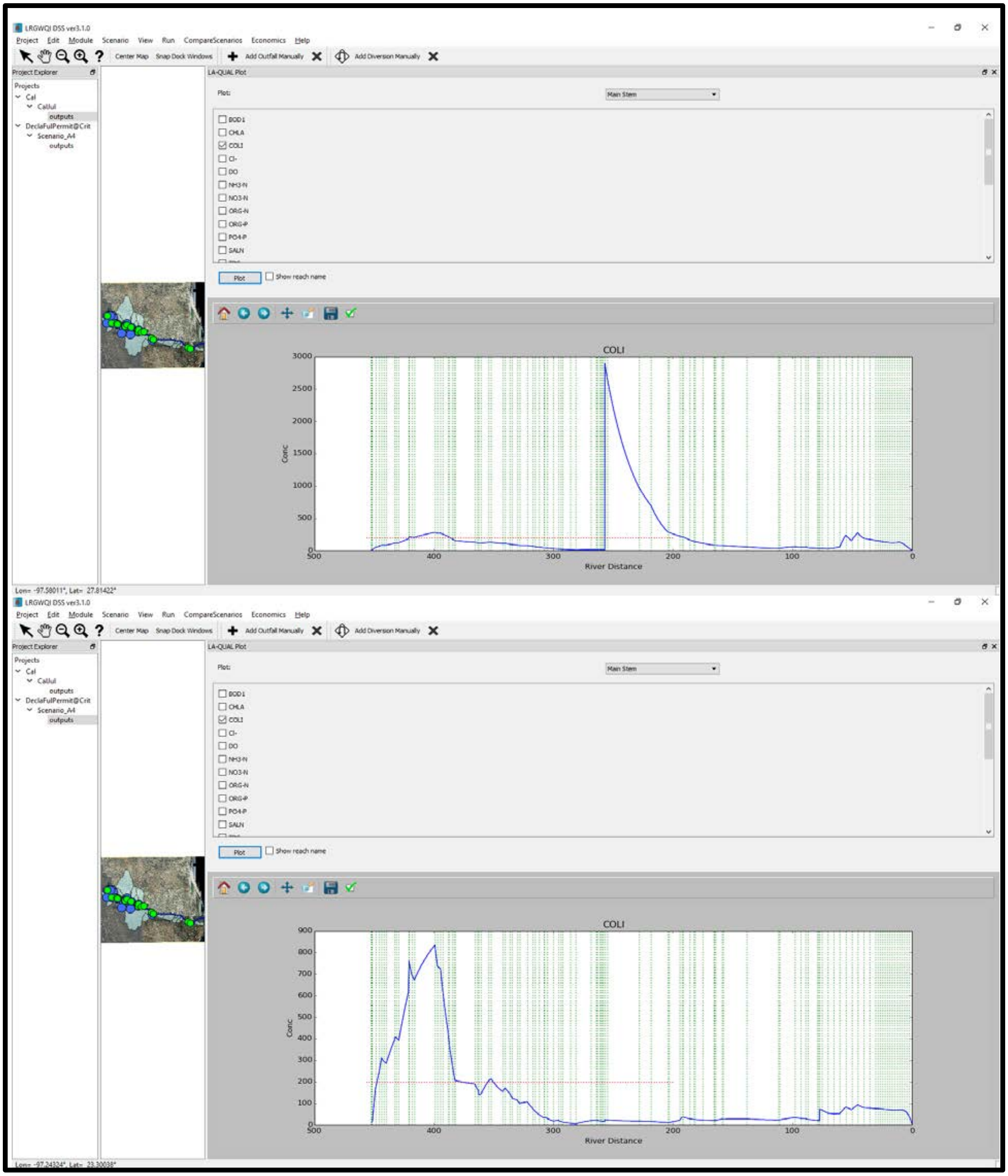


Figure 4-1. Plots of Fecal Coliform Simulation for the Base Scenario (Top) and Scenario A4 (Bottom) for the July 2014 Synoptic Case.

The bottom image shows a plot of Scenario A4 (Modified Declaratoria Guide and Full Permitted US effluents at Critical Conditions) showing improved overall fecal coliform concentrations in the river, but higher fecal coliform concentrations in the upper portion, where steady state nonpoint sources of bacteria are most abundant. Scenario A3 (Modified Declaratoria Guide and Full Permitted US effluents at Observed Conditions) does not show an increase in fecal coliform concentrations in the upper portion.

Based on the results of preliminary point source loading scenarios A-A4, the BTWG agreed to continue running scenarios using the Modified Declaratoria effluent limits for Mexican Wastewater dischargers and full-permitted flows and pollutant concentrations for US dischargers. No joint decision was not reached on whether to simulate scenarios at the ambient conditions observed during the binational synoptic surveys or to simulate scenarios under critical flow and temperature conditions.

4.1.1.2 Preliminary Nonpoint Source Loading Scenarios

In addition to the preliminary point source loading scenarios, the Mexican and US representatives of the BTWG worked jointly to identify preliminary nonpoint source pollutant loading scenarios for water quality simulation to support decision making in the LRGWQI action arena. The first set of nonpoint pollutant source loading scenarios identified by the BTWG were associated with "no action scenarios," in which the effects of population growth without additional sanitation infrastructure were to be simulated.

PRELIMINARY NONPOINT SOURCE POLLUTANT LOADING SCENARIOS ASSOCIATED WITH PROJECTED POPULATION INCREASES

The US members of the BTWG proposed a method for estimating population growth in the riparian communities of the Rio Grande/Río Bravo watershed by extrapolating existing population growth projections published by the TWDB (TWDB 2017a; TWDB 2017b) and Mexico's Consejo Nacional de Población (CONAPO), 2017a and CONAPO, 2017b.

The proposed method consisted of applying the percent population increase/decrease calculated from the TWDB's population growth projections for 17 cities with TWDB population projection values and ETJs included in the 500-meter riparian buffer. For US riparian populations outside of the ETJs of the 17 cities, the percent increase/decrease estimated from county population projections were used. A similar process was used for the Mexican riparian populations using CONAPO population projections for localidades (using localidad boundaries) and municipios. The preliminary nonpoint source modeling scenarios included two scenarios:

1. Scenario A5 – Modified Declaratoria Guide and Full Permitted US effluent limits at Observed Conditions with Riparian Populations Increased to the Projected 2020 Level

   The purpose of this scenario was to investigate the effect on water quality in the Lower Rio Grande/Río Bravo resulting from an increase in nonpoint source pollutant loadings commensurate with an increase in the riparian populations to the projected 2020 level. The simulation assumes implementation of the modified Declaratoria Guide effluent values for Mexican Discharges, full permitted US effluent limits and pollutant concentrations, and the ambient conditions observed during the binational synoptic surveys.

2. Scenario A6 – Modified Declaratoria Guide and Full Permitted US effluent limits at Critical Conditions with Riparian Populations Increased to the Projected 2020 Level

   The purpose of this scenario was to investigate the effect on water quality in the Lower Rio Grande/Río Bravo resulting from an increase in nonpoint source pollutant loadings commensurate with an increase in the riparian populations to the projected 2020 level. The simulation was conducted under critical flows and water temperatures (10^{th} percentile of flow and 90^{th} percentile of water temperatures for the synoptic months calculated over the period of record 2000-2015) and assumes implementation of the modified Declaratoria Guide effluent values for Mexican Discharges and full permitted US effluent limits and pollutant concentrations.

The BTWG conducted ten additional scenarios using the same point source inputs and ambient conditions described in scenarios A5 and A6 with nonpoint source inputs commensurate with increases in riparian populations equivalent to the values projected for the years 2030, 2040, 2050, 2060 and 2070.

PRELIMINARY NONPOINT SOURCE POLLUTANT LOADING SCENARIOS ASSOCIATED WITH AGRICULTURAL BMPS

In addition to the preliminary nonpoint source simulation scenarios associated with population growth, the US representatives of the BTWG proposed conducting a series of preliminary simulations to estimate the effects, on water quality in Lower Rio Grande/Río Bravo, of implementing irrigation BMPs on agricultural land in the Lower Rio Grande/Río Bravo watershed. The preliminary agricultural nonpoint source scenarios included two scenarios:

1. Scenario B3Irr1 – Modified Declaratoria Guide and Full Permitted US effluents and Applying Irrigation BMPs to the Agricultural Land in the Sub-basins of Mexican Agricultural Drains under Observed Conditions

   The purpose of this scenario was to investigate the effect on flow and water quality in the Lower Rio Grande/Río Bravo resulting from the implementation of irrigation BMPs on agricultural land in the watershed under the ambient conditions observed during the binational synoptic surveys. In this scenario three BMPs (land leveling, use of polypipe and land leveling plus polypipe in combination) are applied in equal measure (one third of the total agricultural land each) to LRGWQIDSS sub-basins draining the major Mexican Agricultural Drains. All US agricultural land is assumed to be land-leveled.

2. Scenario B3Irr2 – Modified Declaratoria Guide and Full Permitted US effluents and Applying Irrigation BMPs to all Mexican Agricultural Land in the Lower Rio Grande/Río Bravo Watershed under Observed Conditions

   The purpose of this scenario was to investigate the effect on flow and water quality in the Lower Rio Grande/Río Bravo resulting from the implementation of irrigation BMPs on agricultural land in the watershed under the ambient conditions observed during the binational synoptic surveys. In this scenario three BMPs (land leveling, use of polypipe and land leveling plus polypipe in combination) are applied in equal measure (one third of the total agricultural land each) to the agricultural land in all Mexican LRGWQIDSS sub-basins. All US agricultural land is assumed to be land-leveled.

The US representatives in the BTWG also ran these two simulations scenarios under critical conditions. For these simulations, adjustments were needed in the agricultural diversions, as well as incremental inflows and outflow to keep flow from going negative in the tributaries and, in some cases also, in the main stem of the river.

RESULTS OF PRELIMINARY POINT SOURCE POLLUTANT LOADING SCENARIOS

The results of the of the preliminary nonpoint source pollutant loading scenarios associated with population increases showed increased pollutant concentrations in portions of the Lower Rio Grande/Río Bravo where steady state nonpoint source pollution emanating from riparian populations is most prevalent. However the magnitude of the effects on water quality yielded by Scenarios A5-A16 call into question somewhat the LRGWQIDSS' ability to accurately predict these effects. Water quality constituent concentrations, and in particular fecal coliform, appear higher than would be expected from moderate increases in riparian populations. An example of this concern is shown in Figure 4-2 which shows the simulation results of Scenario A5 (Modified Declaratoria Guide and full permitted US effluent limits at observed conditions with riparian populations increased to the projected 2020 level) for the April synoptic model.

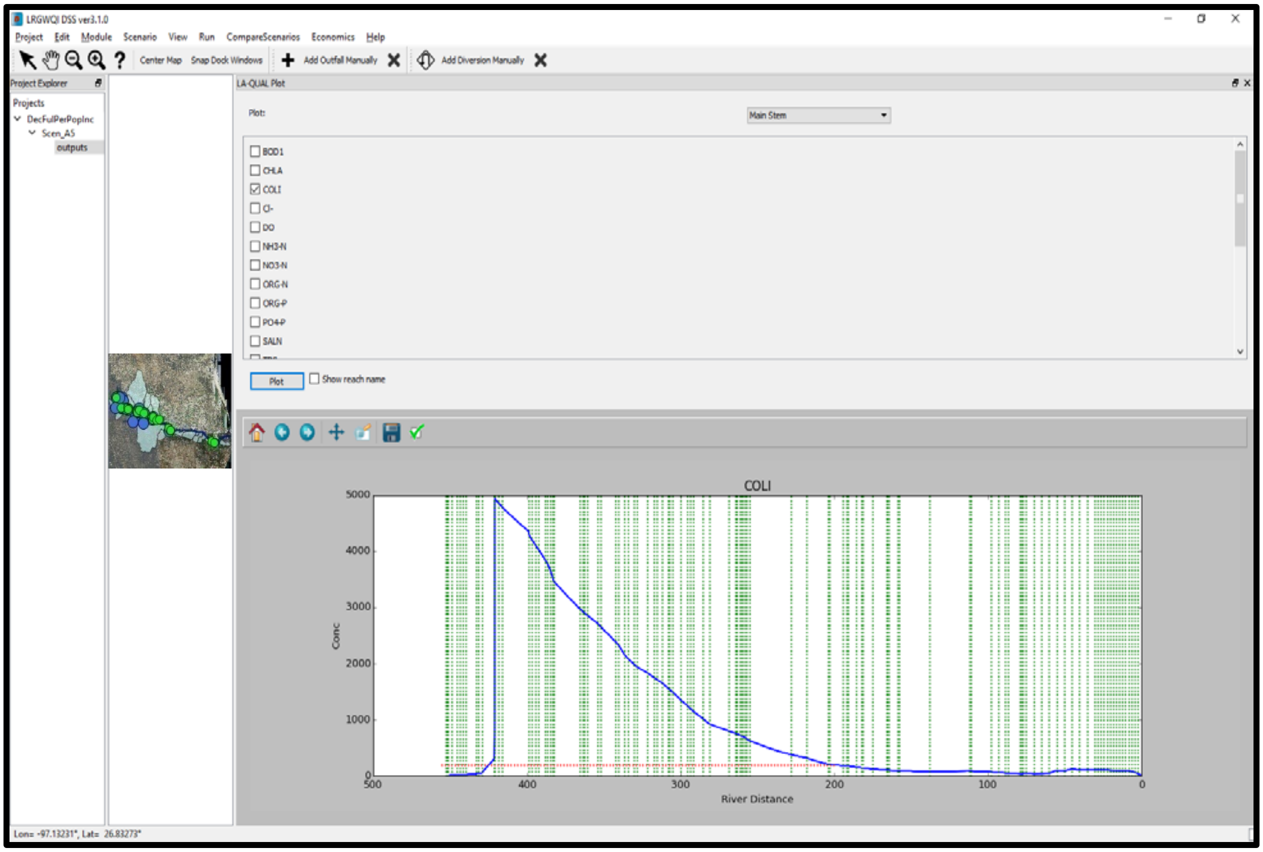


Figure 4-2. Plot of Fecal Coliform Simulation for Scenario A5 for the April 2016 Synoptic Case.

The results show fecal coliform concentrations peaking at approximately 5000 MPN, which is at least an order of magnitude higher than TCEQ water quality monitoring data show for samples collected in that portion of the river in 2018, only two years prior to the year of the population projection simulated in Scenario A5. Nevertheless, the simulation identifies the portion of the river where in-stream pollutant concentrations have the potential to become problematic from unsewered riparian populations under a no action scenario.

Based on these results the US representatives of the BTWG recommended adjustments to the LRGWQDSS' human NPS loading algorithm. These adjustments are likely to improve the LA-QUAL model calibration for fecal coliform simulations.

The results of the preliminary nonpoint source simulation scenarios associated with the implementation of agricultural BMPs revealed important insights into the potential effects of the measures simulated in these scenarios. Implementation of irrigation BMPs on agricultural land in the watershed reduced flow in the river and also reduced the loading of dissolved solids to the river. In some scenarios, the balance of these two effects resulted in an improvement of TDS and chlorides in the river. However, in some simulation scenarios conducted under critical conditions, the implementation of irrigation BMPs had the opposite effect, raising TDS and chloride concentrations in the river above those currently observed. Figure 4-3 shows an example of this result for Scenario B4Irr2 (Modified Declaratoria Guide and full permitted US effluent limits and applying irrigation BMPs to all Mexican agricultural in the Lower Rio Grande/Río Bravo watershed under critical conditions) for the July 2014 synoptic case.

While the preliminary point source loading scenarios discussed in Subsection 4.1.1.1 were conducted jointly by the members of the BTWG, the preliminary nonpoint source simulation scenarios discussed in this sub-section were conducted by the US representatives of the BTWG.

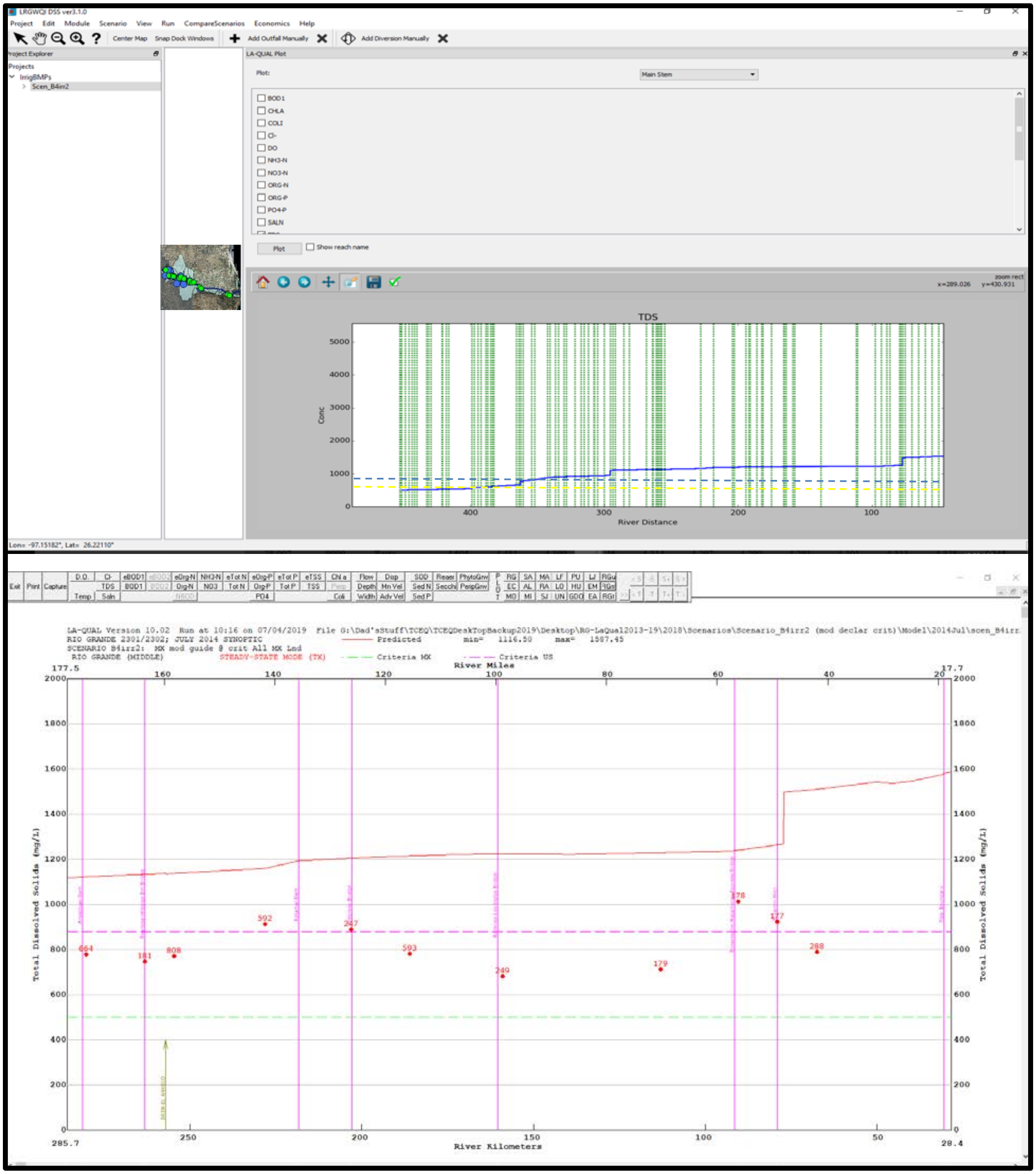


Figure 4-3. Plot of TDS Simulation for Scenario B4Irr2 for the July 2014 Synoptic Case; LRGWQIDSS plot (Top) and a Portion of the Same Plot as Displayed in the Internal LA-QUAL GUI Showing Synoptic Calibration Data (Bottom).

All scenarios discussed in Sub-section 4.1.1 were simulated while the LRGWQIDSS was still in development, with several modules not yet operational (e.g., the economics module). The experience gained from simulation of the scenarios discussed in this sub-section was instrumental in the development of Version 1.0 of the LRGWQIDSS.

Version 1.0 of the LRGWQIDSS, considered the beta version of the software was completed in April 2019. On March 8, 2019, the author posted a zip file containing the installation executable file as well as the two accompanying installation data files on the TCEQ secure ftp site and sent an email to the lead IMTA and CONAGUA BTWG representatives letting them know the software was ready for final testing. On March 10, 2019, the author received an email response from the Mexican BTWG representatives letting the author know that they had successfully downloaded and installed the LRGWQIDSS on their computers and that they had begun final testing of the software. As of this writing, the final testing of Version 1.0 of the LRGWQI is still ongoing.

4.1.2 UNCERTAINTY

Addressing uncertainty is an important aspect of modeling and of EDSS development. The level of acceptance of a model or EDSS is dependent on the degree of error the users and decision makers are willing to accept (Jakeman et al., 2006; McIntosh et al., 2011; Voinov et al., 2016). As part of model development, and in keeping with best modeling practices, the LRGWQI's BTWG agreed to establish model performance measures for the LA-QUAL model(s) developed as part of the LRGWQI. The author documented these model performance measures along with the source and quality requirements for input and calibration data in a quality assurance project plan (QAPP) titled "A Steady State, One Dimensional Model of Water Quality in the Lower Rio Grande/Río Bravo (Segments 2301 and 2302) Addressing Total Dissolved Solids, Indicator Bacteria, Nutrients, Dissolved Oxygen and Total Suspended Solids" (TCEQ, 2018). Acceptance of the LA-QUAL models by USEPA and CONAGUA is based on the criteria specified in the QAPP.

As of this writing, there have been no substantive efforts to quantify uncertainty in LRGWQIDSS results. However, the author and the LRGWQIDSS development team advocate including such efforts in future work. The following sub-sections identify the main sources of uncertainty in LRGWQIDSS development and provide a set of options to quantify uncertainty.

4.1.2.1 Uncertainty Associated with the Use of Steady State Models

Steady state deterministic models are essentially snapshots in time. Whereas inputs and outputs of dynamic deterministic models are time series values which can represent a variety of simulation conditions, the inputs and outputs of steady state models are single values which represent a particular simulation condition. Since the accuracy of steady state models is confined to the simulation conditions they represent, using steady state models to predict water quality creates uncertainty about simulations conducted under conditions other than those in which the model(s) are calibrated. To reduce uncertainty, modelers sometimes develop and calibrate multiple steady state models representing a number of simulation conditions. However, it is not always practical to develop a sufficient number of “snapshots” to reduce uncertainty to the level associated with dynamic models. Modelers sometimes use measures of centrality of historical data for input and calibration of steady state models to represent “average conditions” over a specified period of time.

Another source of uncertainty associated with steady state models is their limited ability to model nonpoint sources of pollution. Nonpoint sources are typically associated with rainfall runoff. Although some steady state models, such as LA-QUAL, allow input of nonpoint source pollutant loadings, steady state models are not designed to model rainfall runoff. The mechanism by which nonpoint sources enter a water body under steady state conditions is not well understood and is difficult to represent accurately using steady state models. For example, a source of uncertainty in the LRGWQI LA-QUAL models is steady state nonpoint source loading from unsewered human populations. Even though unsewered human populations can be quantified using geospatial methods, it is unclear exactly how, or to what extent, untreated sewage from riparian populations enters a water body under steady state conditions.

To reduce uncertainty associated with steady state loading of pollutants from unsewered human populations, the representatives of the BTWG opted to limit the population estimates to residents living within 500 meters of the Rio Grande/Río Bravo, one of its tributaries, or a contributing drain or ditch. However, the buffer distance was chosen by consensus of the BTWG participants and is based on collective professional judgement. The BTWG chose to apply attenuation factors to the estimates of steady state nonpoint source pollution. These factors can be adjusted during the water quality calibration process. One option to reduce uncertainty in the LRGWQIDSS results is to adjust these factors further to improve model calibration.

4.1.2.2 Uncertainty Associated with Estimates of Steady State Nonpoint Sources

Another source of uncertainty associated with the LRGWQIDSS emanates from the geospatial methods used to estimate steady state nonpoint sources. In addition to measurement error inherent in the base data, including human and animal census figures and GIS data layers, the methods and assumptions made to disaggregate, re-aggregate. and categorize census data into final population values introduces error into the estimates. For example, when disaggregating US Census block data and re-aggregating it into LRGWQI watershed sub-basins, the author estimated populations living in census blocks intersected by sub-basin boundaries using area ratios of the portions of the census blocks bisected by the sub-basin boundaries. This method assumes there is an even distribution of the population in each census block. This assumption introduces error into the estimate. The error was amplified when the author intersected the resulting human sub-basin populations using the 500-meter riparian buffer polygon layer, colonia polygon layer, and utility service area polygon layer to determine the riparian populations and categorize them by sanitation type. Error was introduced into the geospatial analysis of Mexican human populations when the author and his Mexican collaborators categorized localidad residents by sanitation type applying the municipio proportions of residents using each type of sanitation category.

The geospatial analysis of animal populations introduced error into the model input by: (1) assuming even distributions of animal populations within counties and wildlife management areas; (2) using estimates of the amount of time animals spend in the water; and (3) using population density reduction factors based on distance from the coast (i.e. waterfowl estimates). Measurement error in the land use layer used to identify animal habitats in the geospatial analysis of animal populations also introduces error into the resulting animal population values.

The estimates of pollutant loading from both human and animal populations may contain measurement error in the base data. The assumptions made of per-person feces and per-animal manure (feces and urine combined) production rates and pollutant composition also introduce error into the LRGWQIDSS output. As authorized by the BTWG, the author applied attenuation factors to the estimates of animal-based steady state nonpoint pollution. As with human-based loadings, these factors can be readjusted to improve model calibration, thus reducing uncertainty.

4.1.2.3 Uncertainty Associated with the LA-QUAL Model

A lack of data and information about the physical attributes of the Lower Rio Grande/Rio Bravo contributes to the uncertainty associated with the LA-QUAL model(s) included in the LRGWQIDSS. The absence of information regarding base flow contributions to in-stream flow relegated the author to adjusting irrigation return flow yields to achieve a water balance in some reaches of the models. A lack of information regarding phreatophytes in the river led the author to addressed water deficits in some reaches of the river by assigning withdrawals to small ungagged diverters. An inability to link poor in-stream water quality value observed during the synoptic surveys to sources of pollution (e.g., high in-stream bacteria values upstream and downstream of Reynosa) made it difficult to calibrate the model for certain water quality constituents and contributed to lapses in model performance.

Error contributes to overall uncertainty in the output of the LRGWQIDSS. Measurement error inherent in the data used for model input and calibration contribute to lapses in model performance. This includes error in estimates of channel geometry data (i.e., cross-section data), flow gage data, diversions data, synoptic and historical field measurements (e.g., instantaneous flow, stream velocity, temperature, specific conductivity, pH, dissolved oxygen, etc.), and synoptic and historical water quality data. Error inherent in the GIS layers used to characterize the watershed and hydrography of the Lowe Rio Grande/Río Bravo (e.g., digital elevation models and USGS and INEGI hydrography layers) and to estimate channel widths (satellite images) also contribute to lapses in model performance.

Measurement error inherent in model input and calibration data can be identified and investigated by examining associated quality assurance information and metadata. In some cases, the source of such error can be identified, and additional data can be collected if funding is available. This is more difficult to do for GIS data.

Measurements of channel geometry used to characterize hydraulics are important component of water quality modeling. As LA-QUAL uses depth-discharge and width-discharge relationships to calibrate hydraulics (Equations 4 and 5), more detailed channel geometry data would improve model calibration in general. Travel time studies could also provide data useful for improving hydraulic model calibration.

Synoptic data can provide modelers: (1) a characterization of current pollutant loading and ambient conditions; and (2) a dataset of parameters measured within a short period time. While ideal for input and calibration of steady state models that represent snapshots in time, the predictive ability of models calibrated using synoptic data is limited to the conditions existing during the time of data collection. Steady state models that use measures of centrality of historical data for input and calibration can produce simulations of average and/or median conditions. In certain cases, steady state models that reflect average conditions may be better suited for planning purposes as they take into account the range of pollutant loadings and ambient conditions. Developing LA-QUAL models using historical data and incorporating these models into the LRGWQIDSS could help reduce uncertainty in the system's output.

Model calibration involves the adjustment of certain variables, such as pollutant attenuation/decay rates, suspended constituent settling rates, oxygen reaeration coefficients, temperature constants, etc. Model performance depends, in part on a modelers ability to select appropriate values for these variables. Sensitivity analysis can help modelers focus on the variables that most influence model calibration and select values for those variables that result in optimal model calibration.

4.1.2.4 Communicating Uncertainty

Communication with EDSS users, stakeholders and decision makers about uncertainty is an important aspect of participatory modeling (Voinov et al., 2016) and is included in the set of best practices for modeling (Jakeman et al., 2006) and EDSS development (McIntosh et al., 2011). Doing so in an effective manner fosters trust and increases the chances of EDSS adoption. To communicate uncertainty effectively, EDSS developers should seek to quantify and contextualize uncertainty to the fullest extent possible (Jakeman et al., 2006). Because uncertainty associated with the LRGWQIDSS has not been quantified, future work should focus on this topic.

Even though the LA-QUAL models have been used by IMTA and CONAGUA to develop the Declaratoria for the Lower Río Bravo, LA-QUAL model performance can and should be improved to lower the current level of uncertainty in LRGWQIDSS output. Future work associated with the LRGWQIDSS should include work associated with improving the accuracy of LA-QUAL model simulations, reducing overall uncertainty in the system's output, and communicating uncertainty to users, stakeholders and decision makers. A more detailed description of the future work proposed for the LRGWQIDSS is included in Chapter 5.

4.1.3 Potential Implications of LRGWQIDSS Development and Use

In Chapter 2, the author identified potential users of the LRGWQIDSS in three different, but related, institutional action arenas. Development of the LRGWQIDSS was discussed in detail in Chapter 3. Subsection 4.1.1 of this chapter discussed the initial uses of the LRGWQIDSS. An important consideration regarding the development of the LRGWQIDSS, and perhaps also other EDSSs, is the evolutionary nature of the DSS development process in general. In essence, developers of EDSSs can never truly count on producing a "final" version of the system they are developing, even if the system is successfully used for prolonged periods of time because continuous improvement is part of the software development process in general. With this in mind, and viewing the development and use of the LRGWQIDSS from an institutional perspective, it is helpful to examine the potential implications of the use of the LRGWQIDSS at different operational levels.

4.1.3.1 Binational Implications

The LRGWQIDSS was originally conceived as a tool to aid in binational decision making in the institutional action arena produced by the creation of the LRGWQI through the official exchange of letters between the USIBWC and CILA. The general objective of the LRGWQI, as described in the initiative's TOR, is to "establish, under the auspices of the IBWC, a group of representatives from the United States and Mexico to explore border sanitation issues and water quality management with potential binational benefits." In addition to this general objective, the LRGWQI TOR describes six specific objectives which charge the "group of [binational] representatives" with tasks of problem evaluation and program implementation. Notably, the first of these specific objectives charges the group with addressing, not only current but also, "future water quality issues of the Lower Rio Grande/Rio Bravo." One implication is that the LRGWQI may be viewed as an institutional mechanism for addressing binational water quality issues over time. This interpretation is bolstered by statements in the Annex to the TOR, such as: “The effort, the Lower Rio Grande/Rio Bravo Water Quality Initiative (LRGWQI), is intended to serve as a pilot project to develop the binational mechanisms necessary to improve water quality throughout the Rio Grande/Río Bravo” (Appendix B).

As discussed in Chapter 2 the LRGWQIDSS has the potential to become a tool that helps institutional actors overcome the barriers to cooperative decision-making in transboundary water resource management by bringing the parties closer to developing a common understanding of the state of the shared resource. Harmonization of the legal standards and regulatory procedures used by each nation to assess and protect the Lower Rio Grande/Río Bravo may not be within reach at this time. However, use of a common helps stakeholders: (1) visualize pollutant sources; (2) relate pollutant loads to their effect on water quality; and (3) visualize these effects. This is is an important step towards achieving effective transboundary water quality management. In providing a common platform for decision making, the LRGWQIDSS has the potential to transform water quality management in the Lower Rio Grande/Río Bravo into a more coordinated and, perhaps more effective binational water quality planning and management process. The first manifestation of binational water quality planning facilitated by the LRGWQIDSS may be the development of a binational watershed-based plan, which is an objective explicitly stated in the TOR Annex.

Despite the statements in the TOR inferring sustained, long-term planning efforts, use of the LRGWQIDSS is currently focused on the immediate, high-level planning objectives of the LRGWQI participants. CONAGUA’s goal is the development of the Declaratoria for the Lower Río Bravo. The TCEQ’s and USEPA’s goal, is development of a binational watershed-based plan to improve water quality in the Lower Rio Grande. Beyond these goals, there is no well-defined long-term use of the LRGWQIDSS. The LRGWQIDSS, could be institutionalized further by defining its use beyond the promulgation of the Declaratoria and the development of a binational watershed-based plan. For this to happen, the tool, as well as the forum in which it is used, must also evolve.

4.1.3.2 National Implications

The development and use of the LRGWQIDSS have different implications for Mexico and the United States. As previously mentioned, the LRGWQI's facilitation of the Declaratoria on the Lower Río Bravo implies Mexican institutionalization, at least, of the LA-QUAL models contained within the LRGWQIDSS. As the point and nonpoint source loadings input into the LA-QUAL synoptic models used in the Declaratoria are exactly those currently in the LRGWQIDSS and these can be changed through the LRGWQIDSS GUI, use of the LRGWQIDSS could also facilitate CONAGUA's and CEAT's assessment of the effect, on water quality in the Lower Rio Grande/Río Bravo, of proposed changes in wastewater effluent flows and pollutant concentrations, effectively incorporating the LRGWQIDSS into CONAGUA's operational procedures. This implication, however, hinges on successful testing of the LRGWQIDSS by CONAGUA and CEAT. Unilateral modification of one or more of the LA-QUAL models by CONAGUA would effectively decouple the models from the LRGWQIDSS, unless commensurate changes were made in the LA-QUAL models in the LRGWQIDSS.

The primary use of the LRGWQIDSS by the TCEQ and USEPA is related to decision making associated with the development of a binational watershed-based plan. The TCEQ and USEPA have already used the results of simulations of pollutant loading scenarios conducted using the LRGWQIDSS to assess the effect on water quality in the Lower Rio Grande/Río Bravo of control actions and management measures proposed for inclusion in the binational watershed-based plan (e.g., Scenarios B3Irr1, B3Irr2, B4Irr1 and B4Irr2). Approval of a final binational plan by the USEPA could result in the facilitation of federal funding sources for implementing some of the measures in the plan, primarily those implemented on the US side. USEPA approval of the plan may also consign the TCEQ-listed water quality impairments and concerns being addressed by the plan to a regulatory status that obviates the need for a TMDL and could lead to the de-listing of Segment 2302 from Texas' list of impaired water bodies, a goal shared by TCEQ and USEPA.

The well-established wastewater permitting system developed through the years by the TCEQ (i.e., TPDES), as well as the current regulatory oversight arrangements between USEPA and TCEQ (i.e., Texas' State-wide Water Quality Management Plan and the 1998 MOA between TCEQ and EPA regarding the permitting of Texas wastewater discharges to the Rio Grande), make it unlikely that the TCEQ would begin using the LRGWQIDSS as an internal tool for the assessment of TPDES wastewater permit actions. However, it is not unreasonable to assume that TCEQ would accept and review scenarios involving changes in TPDES-permitted effluent flows and pollutant concentrations for Texas utilities along the Lower Rio Grande/Río Bravo simulated using the LRGWQIDSS (e.g., Environmental Information Documents prepared by NADB). To be successful, entities submitting permit applications backed by LRGWQIDSS simulation scenarios would have to ensure that all model inputs include current discharges to the river and that all nonpoint source inputs reflect current riparian population values. For its part, the TCEQ would need to verify that the information used to simulate the scenarios in the LRGWQIDSS is current and accurate. While the TCEQ currently can verify information on Texas dischargers and riparian populations, it cannot verify the commensurate information from the Mexican side of the river.

4.1.3.3 Local Implications

Participants in the US and Mexican wastewater treatment action arenas could benefit from using the LRGWQIDSS to simulate water quality scenarios involving proposed changes to their wastewater infrastructure systems. Texas utilities and Mexican OOs providing wastewater collection and treatment services to communities in the Lower Rio Grande/Río Bravo Watershed could use the LRGWQIDSS for planning purposes. These entities could use the system to simulate scenarios involving expansions and upgrades to existing wastewater treatment facilities or for locating, sizing, exploring treatment options, and developing preliminarily costs estimates for new treatment facilities and for facility upgrades and expansions. Use of the LRGWQIDSS would be especially beneficial for small utilities and OOs, as use of the system by these entities could potentially reduce the costs of planning, which would disproportionately benefit small-budget operators.

As with users of the LRGWQI at the national level, local users of the LRGWQIDSS would need to verify that the information used to simulate scenarios in the LRGWQIDSS is current and accurate. To do this, local users would have to download the latest version of the LRGWQIDSS prior to using it to simulate their wastewater infrastructure scenarios and the users must be aware that the scenarios they run would have a limited "shelf-life." That is, the scenarios will become obsolete after a certain amount of time. Nevertheless, the LRGWQIDSS is designed to be used by non-modelers, which makes the capability of water quality simulation accessible to non-technical users on both sides of the US-Mexico border. Obviously, web-based access to the system would increase the convenience and usability of the LRGWQIDSS at all levels.

4.1.4 POTENTIAL EFFECT OF LRGWQIDSS ON EXISTING INSTITUTIONAL ARRANGEMENTS

At the binational level, existing institutional arrangements associated with the Rio Grande/Río Bravo emanate from two bilateral agreements signed between the United States and Mexico, the 1944 US-Mexico Water Treaty and the 1983 La Paz Agreement. Through the 1944 US-Mexico Water Treaty and subsequent treaty Minutes, the IBWC has developed protocols and procedures for sharing boundary waters between the two nations. Together these procedures define a system for managing and distributing boundary waters, including those of the Lower Rio Grande/Río Bravo. Using a series of jointly-operated hydrometric and meteorological stations, and external data accessible to both sections of the IBWC, the system is capable of assessing available water volumes and forecasting the availability of future volumes. Through a common water accounting system, water is apportioned to users along the river according treaty provisions and mutually-agreed upon operational procedures. Beyond the involvement of the US and Mexican Sections of the IBWC, the water distribution system used to apportion water from the Lower Rio Grande/Río Bravo also involves the State of Texas (i.e., the TCEQ Rio Grande Water Master) and CONAGUA, which regulate water usage on a regional and local basis through a system of water rights.

Several Minutes to the 1944 US-Mexico Water Treaty also compel the USIBWC and CILA to jointly address sanitation problems and other problems affecting water quality along the US-Mexico border (e.g., Minutes 261 and 289). However, while the USIBWC and CILA have worked together to address specific sanitation and water quality problems along the border, their cooperative efforts on these issues has been on a case-by-case basis. Thus, unlike water quantity, the IBWC lacks an established system to ensure the effective and efficient protection of water quality in the Rio Grande/Río Bravo.

The stated goal of the La Paz Agreement is to protect and conserve the environment along the US-Mexico border. The Agreement describes the responsibilities of both nations to prevent and control pollution in air, water, and land in the border region, which it defines as a 100-kilometer buffer straddling the US-Mexico border. Building on the unilateral environmental protection efforts associated each country's regulatory systems, the agreement imparts the responsibility of coordinating the creation of national pollution prevention and mitigation programs and cooperating on scientific and educational exchanges, environmental monitoring, environmental impact assessments, and periodic exchanges of information on pollution sources in their respective territories. Information exchanges between the two nations occur yearly during annual meetings of high-level delegates. The USEPA's Border 2020 Program is an example of a national program created to support the goals of the La Paz Agreement. Border 2020 is essentially a small grants program that funds pollution mitigation and prevention projects on both sides of the border.

Although not yet the case, Minutes 261 and 289 of the 1944 US-Mexico Water Treaty and the La Paz Agreement both provide the legal foundation to create a systematic binational arrangement or system to manage and protect water quality in the Lower Rio Grande/Río Bravo. Either or both, could provide the basis to establish a system of water quality protection and management based on a shared understanding of the pollutant assimilative capacity of the river. Just as the IBWC developed a system by which the United States and Mexico jointly assess the volume(s) of water available for distribution and jointly forecast the availability of future volumes, the LRGWQI can serve as a pilot for the development of a system by which the United States and Mexico jointly and systematically assess the capacity of the Lower Rio Grande/Rio Bravo to assimilate pollutants, identify potential risks to water quality, and develop strategies to mitigate these risks. The LRGWQIDSS could play a role in the creation of such a binational system by providing a common tool that could be used by Mexico and the United States for identification, assessment, and mitigation of these risks.

There remain many barriers to institutional change and transboundary cooperation, such as past practices, agency turf battles, the influence of other action arenas connected to the LRGWQI, divergence of interests among participants, issues of sovereignty, etc. The author is under no illusion that the creation of a binational system of water quality management is feasible in the near future. Such a system could evolve from a simpler binational association, such as a forum for regular information exchange among participants of the LRGWQI.

4.2 Lessons Learned

The development and preliminary use of the LRGWQIDSS provided the author with some lessons learned. With the caveat of potentially containing case study bias, the author offers the following set of lessons learned from his experience collaboratively developing and using the LRGWQIDSS.

4.2.1 Transboundary DSS Development by Affiliated Parties

Within the context of participatory modeling, Voinov et al. (2016) recommend the use of trusted intermediaries when intrinsic levels of trust are low among the participants. This notion can be extended to the development of transboundary EDSSs. Even under the best of circumstances trust levels among participants of transboundary action arenas are influenced by sovereignty. Although it could be argued that LRGWQIDSS development, including software development by UT-BEG and the supporting qualitative research effort conducted by the UT LBJ School, was conducted ostensibly by an uninterested, unaffiliated party (i.e., UT), the TCEQ provide 100% of the funding for the LRGWQIDSS development effort. Most importantly, as lead designer and member of the LRGWQIDSS development team, the author's work on the LRGWQIDSS was hampered by his own affiliation with one of the participants in the LRGWQI action arena (i.e., the TCEQ).

Despite the recommendation to EDSS developers by McIntosh et al. (2011) to foster representatives or "champions" embedded within targeted organizations to promote the use of the EDSS being developed, the funding and development of a transboundary EDSS by one of the parties participating in the transboundary action arena presents barriers to the system's development. In the case of the LRGWQIDSS, a significant barrier to EDSS development was related to the problems presented by the developer's lack of access to potential Mexican users of the system. As discussed in Chapter 2 (Sub-section 2.2.1.9, Best Practices in DSS Design), stakeholder involvement is essential in EDSS development. The LRGWQI's operational policy of limiting access to foreign stakeholders limited the LRGWQIDSS development team's ability to gather important input thereby weakening the system's range of usability.

4.2.2 TRADEOFFS IN TRANSBOUNDARY EDSS DEVELOPMENT

Some of the most important lessons learned during the development of the LRGWQIDSS related to tradeoffs made to ensure its completion and usage. These tradeoffs affected the design and functionality of the EDSS. They also enhanced the usage of the software by members of the transboundary LRGWQI action arena at the potential expense of usage by a broader user group.

4.2.2.1 Sovereignty, Institutionalization and Accuracy

Several initial challenges to the development of LRGWQIDSS involved issues of sovereignty. For example, the challenge of dealing with two sets of water quality criteria and of deciding what input and calibration data to use when developing the models of water quality in the Lower Rio Grande/Río Bravo were two subjects of significant deliberation among members of the BTWG. Although these challenges were eventually overcome, their resolution came at a cost. The US partners agreed to use, as primary model inputs and calibration data sets, the physical and water quality data collected during a series of binational synoptic water quality surveys conducted jointly by the members of the BTWG. The US representatives of the BTWG agreed to the Mexican representative's request, even though they believed the 16 years of data in the TCEQ's Surface Water Quality Monitoring database represented a better input and calibration dataset for the development of the LRGWQI water quality models because the measures of centrality that could be derived from the TCEQ dataset would produce more accurate models. While the BTWG's final consensus decision to collect and use synoptic data for the LRGWQI modeling effort eliminated a technical impasse, ostensibly related to issues of sovereignty and path dependency, the snap shots in time that the synoptic data represents adds to the uncertainty of the output produced by the LA_QUAL models in the LRGWQIDSS. However, the collaboration of US and Mexican representatives in the collection of synoptic data for the project helped to build trust, not only in the data collected, but also mutually among the participants in the surveys.

Another example of a tradeoff made in the development of the LRGWQIDSS is the choice of water quality modeling software incorporated into the LRGWQIDSS (LA-QUAL). From a usability perspective, the choice of LA-QUAL was important because it fit well into the decision strategies of all LRGWQI participants. The choice of LA-QUAL also increased the chances of institutionalization of LRGWQIDSS by an important participant in the LRGWQI action arena, CONAGUA. By incorporating a tool used as part of the regulatory process of the participants in the LRGWQI action arena (including the TCEQ), the developers increased the chances for prolonged use of the LRGWQIDSS. However, as is apparent from some of the initial scenario simulation results, use of a steady state model to represent nonpoint sources of pollution to the river increases the level of uncertainty in the simulation results. Some of this uncertainty can be mitigated by making adjustments to the LRGWQIDSS as the system is used further and additional information is incorporated into the system. However, there was a tradeoff in accepting higher initial levels of uncertainty to construct a tool that would be used by the participants in the LRGWQI action arena.

4.2.2.2 Technical and Administrative Aspects of DSS Development

Overcoming some of the technical and administrative challenges associated with the development of the LRGWQIDSS also involved tradeoffs. The development team's choice to use open source software for the development of the LRGWQIDSS accomplished several objectives. This choice kept development costs within the TCEQ's project budget; development of the LRGWQIDSS using customized proprietary software owned by commercial software firm(s) would have increased development costs. The choice of open source software avoided the potential problems associated with product licensing. Restrictive licensing agreements have the potential to hamper distribution of software, hindering usage of the software by users. On the other hand, use of public domain software left the responsibility of training and technical support on the developer and promoter of the LRGWQIDSS (i.e., the TCEQ). While this responsibility is currently being met, there is no long-term commitment on the part of the TCEQ to continue training and technical support for the LRGWQIDSS.

Product accessibility was another tradeoff. A web-based decision-support tool would be more accessible to users. However, some stakeholders did not want to share data outside of the LRGWQI action arena. Also, any web-based tool would have required additional development and maintenance costs. To limit development costs and in the interest of time, the LRGWQIDSS was developed as a downloadable, self-contained executable, installed through a self-extracting installer.

Users of the LRGWQIDSS in its current form may not be able to verify all information in simulation scenarios, such as the location and nature of current wastewater outfalls or changes in riparian populations. This would not be necessary if a master version of the LRGWQIDSS, consistently updated by the host organization, could be available over the world wide web.

4.2.3 Importance of Boundary Rules and Information Rules

While the examination of all working rules under which the identified action arenas function was important for the design of the LRGWQIDSS, the implications of the boundary rules and information rules of the LRGWQI action arena had the biggest effect on the development of the LRGWQIDSS. It may be the case in other water resources management forums, or even other transboundary settings, that other working rules have as significant a consequence for EDSS design as boundary and information rules did in the development of the LRGWQIDSS. However, given the consensus, among EDSS developers and practitioners, regarding the importance of stakeholder involvement in EDSS development and the crucial role information plays in decision making and EDSS development, it is likely that these two action-arena working rules warrant special attention in similar settings.

Boundary rules not only define the actors of an action arena, they also point to the potential users of an EDSS. After identification of the pertinent action arenas, examination of the boundary rules of the arena(s) identified is the first step in determining who the stakeholders and users of the EDSS are likely to be.

As exemplified by the development of the LRGWQIDSS, information rules played a fundamental role in the development of a transboundary EDSS. Beyond affecting the developer’s ability to acquire input from stakeholders, information rules can limit access to an EDSS by potentially important stakeholders, a situation which IWRM and IRC theory suggest perpetuates inadequate water resources management. The constraints placed on information sharing and binational stakeholder involvement also limited the choices available to the LRGWQIDSS developers during tool development. It is beyond the scope of this dissertation to make recommendations about ways to mitigate or lessen the effect of an action arena's information rules on the development of a transboundary EDSS. However, the experience gained from the development of the LRGWQIDSS highlights the value of closely examining the information rules of the action arena(s) in which the transboundary EDSS is likely to be used for decision making.

4.2.4 TRANSBOUNDARY EDSS DEVELOPMENT AS A PERPETUAL TASK

As discussed in Sub-section 4.1.2.1, current use of the LRGWQIDSS is focused on the immediate, high-level planning objectives of the LRGWQI participants. This despite statements in the TOR and TOR Annex suggesting an active role for the LRGWQI action arena in long-term water quality planning efforts for the Lower Rio Grande/Río Bravo. These suggestions imply decision making, within the LRGWQI action arena, beyond that which addresses current water quality impairments and concerns. The modular structure of the LRGWQIDSS is designed to accommodate modifications commensurate with shifts in the focus of management and/or planning efforts within the LRGWQI action arena and in the US and Mexican wastewater treatment action arenas. While these changes in focus are difficult to predict, the establishment of an ongoing process by which the LRGWQIDSS is maintained and modified, as needed, would guarantee the availability, to participants of these action arenas (and perhaps other action arenas), of a common binational decision support tool to manage and protect water quality in the Lower Rio Grande/Río Bravo. Beyond changes in the focus of management and planning efforts changes to the LRGWQIDSS will likely involve increasing its accessibility and information content commensurate with changes in inclusivity of LRGWQI decision making process.

The larger lesson learned regarding the evolution of needs associated with water resources management, planning, and decision making in general is that it is helpful to view development of transboundary EDSSs as an evolutionary process designed for continuous improvement.

4.3 Applicability of this Research to Other Transboundary Settings

As noted in Chapter 2 (Sub-section 2.1.2, Review of Transboundary Water Resource Management Agreements), the physical, political and economic conditions and institutional arrangements associated with transboundary water resource management efforts can vary greatly from one situation to another. In the case studies presented in Chapter 2, a variety of physical settings were examined, most of which involved multiple riparian countries and a variety of economic conditions. In at least one example, the Nile River Basin, the author documented a power asymmetry similar to that existing between the United States and Mexico, with other case studies also containing examples of power asymmetries of various degrees.

While each transboundary situation is unique, there are certain attributes that all water resources management forums have in common. Those attributes are related to the institutional nature of the arrangements under which the participants interact. Applicable aspects of the research conducted as part of the development the LRGWQIDSS include: (1) the usefulness of identifying and analyzing the action arenas involved in decision making; (2) the benefits of efforts by the developers to institutionalize the use of the transboundary EDSSs; and (3) the conceptualization of transboundary EDSS development as efforts to establish a sustainable program of decision support, rather than efforts to develop individual tools to support decision making.

4.3.1 Usefulness of Identifying and Analyzing Action Arenas Involved in Decision Making

Given the importance of stakeholder involvement in environmental modeling and EDSS development, researchers and practitioners have employed a variety of methods for fostering and maintaining stakeholder participation in EDSS development, including stakeholder analysis and "stakeholder mapping." Identifying and analyzing the actors involved in transboundary water resources management forums from an institutional perspective provides a clearer picture of the context and the internal and external elements that influence the decision space, including the working rules under which the participants function. The knowledge gained through institutional analysis extends beyond that of stakeholder characterization and it can be applied to any water resources management situation in which action arenas can be identified. The IAD framework provides a systematic method for identifying and analyzing the components of the decision situation and the variables that influence decision making within a given decision making forum (i.e., the action arena).

4.3.2 Benefits of Efforts to Institutionalize the Use of Transboundary EDSSs

Several of the best practices for EDSS design listed in Sub-section 2.2.1.9 discuss the advantages of designing EDSSs for organizational adoption. For example, considering the use of the system at different organizational levels, striving for broader organizational adoption, and cultivating organizational commitment to long term support. Viewing transboundary water resources management forums from an institutional perspective is instrumental in identifying opportunities for EDSS developers to design systems better suited for organizational adoption and extended use. Identifying and analyzing the rules (working and hierarchical) that enable and constrain the actions of the participants of water resources management action arenas provides EDSS developers with knowledge useful in designing systems that fit well with established processes and procedures, thereby enhancing the chances of adoption and prolonged use by decision makers, or at least by users of the system. Understanding these rules, and the processes and procedures developed to implement them, helps the EDSS designer make choices that can satisfy multiple organizational requirements. This knowledge can also help the developer find commonalities and compromises that can guide a design based on negotiated analytical choices.

Incorporating as many elements of existing processes and procedures as possible into an EDSS reduces resistance to its adoption and increases the likelihood of prolonged use of the system. The developer should, however, be aware of the tradeoffs that may occur as a result of these efforts, such as reduction in analytical accuracy and an increase in uncertainty of results.

4.3.3 Conceptualizing Transboundary EDSS Development as a Decision Support Program Development Effort

One challenge for EDSS design is developing a strategy for transitioning from development to support. Regardless of the transboundary water resource management situation, shifts in the focus of management and/or planning efforts are likely to occur over time. The establishment of an ongoing process not just for maintaining, but also for adjusting and modifying existing decision support tools, guarantees the availability of these tools for decision making in the future. As is the case in the LRGWQI, potential changes in the decision-making process itself would necessitate changes in the tools needed to accommodate these modifications; for example, changes in accessibility and information content.

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

The first research question posed at the end of Chapter 1 was "How does the insight gained form institutional analysis inform the development of decision support tools designed to facilitate and enhance transboundary water quality planning and management efforts such as the Lower Rio Grande/Río Bravo Water Quality Initiative?" Systematically analyzing institutional arrangements to protect water quality in the Lower Rio Grande/Río Bravo gives the EDSS developer insight not only into the nature of the decision situation, the decision makers and the potential users of the EDSS, but also into the individual components of the context of the decision space that affects the patterns of stakeholder interaction.

Adoption and sustained use of EDSSs are often cited by developers as major challenges to system design. Researchers have developed comprehensive lists of best practices aimed at overcoming the difficulties associated with user adoption and prolonged use of decision support tools. Institutional analysis provides the EDSS designer a systematic means to customize best practices to particular decision situations, thereby increasing the likelihood of user adoption and sustained system use. Viewing transboundary EDSS development from an institutional perspective exposes the factors that coalesce to form barriers to system adoption and use, such past practices, organizational turf battles, etc. An institutional perspective can enable an EDSS developer to overcome these barriers. Knowledge of the components of the context of the decision space (i.e., the participant's perception of the physical and material conditions of the resource, stakeholder community attributes, historic antecedents/precipitating events, the working rules of the action arena, etc.) provides the EDSS designer the means to increase the usefulness of the tools that are eventually incorporated into the system. The knowledge gained from institutional analysis can also equip the developers of transboundary EDSSs to negotiate across established organizational processes and procedures weaving through the tortuous path of institutional structures already established by the participating riparian nations.

The IAD framework's focus on identifying the pertinent action arenas and analyzing the working rules of these action arenas provides a systematic method of identifying and overcoming barriers to system adoption and use. In transboundary water resources management arenas, such as the LRGWQI, the participant's evaluation of the physical and material conditions of the resource is framed by the processes each actor uses to assess the resource. These processes are based on the legal standards and regulatory procedures under which the participants operate (i.e., their operational rules). Consequently, each participant's notion of acceptable water quality is based on their own operating rules.

By identifying and analyzing these rules the author and the LRGWQIDSS development team successfully negotiated and incorporated decision-making tools into the LRGWQIDSS that can be used for decision making by all participants of the pertinent action arenas. In doing so, the LRGWQIDSS contributes to the creation of a common understanding among transboundary stakeholders of the physical and material conditions of the resource, which according to IRC theory is an important step towards managing the resource sustainably. In terms of system adoption and use, incorporating decision-making tools that are based on, or are at least compatible with, established operational rules, helps to institutionalize the EDSS, minimizing the effects of adoption barriers and increasing the likelihood of prolonged system use.

In addition to enhancing efforts to develop more useful decision support tools, the AID framework's focus on analyzing the working rules of an action arena also exposes potential pitfalls in EDSS development. In Sub-section 4.2.3, the author describes the importance of boundary and information rules in identifying and characterizing decision makers and EDSS users and in identifying and overcoming barriers to stakeholder participation in EDSS development. In water resources management forums such as the LRGWQI, stakeholder involvement in EDSS development is affected by the action arena's working rules. These rules are in turn affected by contextual factors such as sovereignty and the influence of associated action arenas operating at different hierarchical rule levels. In-depth knowledge of the working rules of the action arenas pertinent to EDSS development can help developers navigate through these barriers. Systematic institutional analysis can be helpful in transboundary settings, where issues of sovereignty, political and economic asymmetries, and general lack of trust may affect working rules to such degree that they affect the EDSS developer's ability to follow recommended best practices. Knowledge of other contextual factors (e.g., position, choice, aggregation, and payoff rules, historical antecedents, stakeholder community attributes, etc.) can be used to partially compensate for boundary rules and information rules that may present barriers to effective EDSS development.

In summary Institutional analysis:

- Helps define who the decision makers are and who the DSS users are and describes their relationship within the decision space
- Helps identify action arenas for analysis (e.g., analysis of rules-in-use, the context of the decision situation, etc.)
- Helps identify institutional barriers and constraints that affect the efficacy of the DSS (e.g., information rules, action arenas at different hierarchical levels that affect decision making, etc.)
- Identifies opportunities for ‘institutionalization’ of the DSS

Table 5-1 summarizes attributes and features of the LRGWQIDSS that were informed by the institutional analysis performed by the author using the IAD framework. Table 5-2 summarizes the attributes and features of the LRGWQIDSS that were informed by the case studies of transboundary water resource management agreements.

Table 5-1. Attributes and Features of the LRGWQIDSS Informed by the Institutional Analysis Conducted Using the IAD Framework

Institutional Analysis Finding	LRGWQI Attribute/Feature
Contextual focus on recurring drought conditions	Headwater module for simulation at variable flow conditions other than synoptic surveys
Contextual manifestation of operational inefficiency	Incorporation of percent conveyance system losses in point source module
Financial consideration of management measures revealed through actor analysis and analysis of rules-in-use	Expansion of point and source economics modules to include additional costs (e.g., collection system costs)
Analysis of operational-level rules-in-use for US and Mexican Wastewater treatment action arenas	Optional base scenarios at critical conditions, full permitted limits for US wastewater treatment facilities, and Declaratoria de Clasificación limits for Mexican wastewater treatment facilities
Contextual manifestation of barriers associated with protection and preservation of sovereignty	Use of binational synoptic data for model parameterization and calibration
Analysis of operational-level rules-in-use	Selection of LA-QUAL modeling software

Table 5-2. Attributes and Features of the LRGWQIDSS Informed by the Case Studies of Transboundary Water Resources Management Agreements

Case Study Finding	LRGWQI Attribute/Feature
Need for framework for spatially aided infrastructure planning for use by non-modelers	GIS-based interface; detailed information on existing infrastructure; standard functionalities such as pan, zoom and point-and-click features
Need for a means to evaluate economic viability of proposed pollution mitigation measures	Point and nonpoint source economics modules
Need for incorporation of multiple endpoint criteria	US and Mexican instream water quality criteria threshold lines in water quality output plots

To answer the second research question, the author offers the following premise: All water resources management forums have one common attribute, the institutional nature of the arrangements under which the participants interact. If this premise is accepted, the author provides an answer to the second research question in Sub-section 4.3: "What aspects of a decision support system (DSS) developed using the insight gained from an analysis of existing institutional arrangements to protect water quality in the Lower Rio Grande/Río Bravo can be identified as transferable to other transboundary settings?": (1) the usefulness of identifying and analyzing the action arenas involved in decision making; (2) the benefits of efforts by the developers to institutionalize the use of the transboundary EDSSs; and (3) the conceptualization of transboundary EDSS development as efforts to establish a sustainable program of decision support, rather than efforts to develop individual tools to support decision making.

5.2 Future Work

As of this writing, the LRGWQIDSS has been used by US and Mexican LRGWQI participants to produce preliminary point source pollutant loading scenario simulations and by US participants of the LRGWQI to produce preliminary nonpoint source pollutant loading scenario simulations. The LRGWQIDSS software is still in "beta version." As with most beta version software, adjustments and modifications of the LRGWQIDSS are likely. Based on the results of the preliminary nonpoint source pollutant scenario simulations, adjustments are warranted to the nonpoint source loading modules to increase the accuracy of population growth simulations. This may also entail adjustment to the calibrations of the synoptic LRGWQI models. These adjustments would have to be conducted under a binational consensus as part of the LRGWQI.

Another area of LRGWQIDSS improvement identified during the preliminary scenario simulations is the economics module. Currently this module provides general cost information about the scenarios simulated in the LRGWQIDSS, which appears to be adequate at the LRGWQI action arena level but does not provide the type of detail useful for wastewater treatment action arena participants. Adjustments to the LRGWQIDSS' economics module will also require participation and consensus approval of the members of the LRGWQI action arena groups and US and Mexican wastewater treatment action arena participants. This would entail a change, at least, in the current information rules of the LRGWQI.

Communication of uncertainty to users, stakeholders and decision makers is needed in all action arenas analyzed in this dissertation. This includes honest and open discussion about the sources of uncertainty discussed in Subsection 4.1.2 as well as the performance and presentation of sensitivity and uncertainty analysis on the LA-QUAL models and other features of the LRGWQIDSS. The communication should be two-way, with developers soliciting input, answering questions, and gathering information from users, stakeholders and decision makers.

A change in the information rules of the LRGWQI could also open the door to conversion of the LRGWQIDSS into a web-based tool. If funded by the participants of the LRGWQI, this conversion would be an important step towards increasing the usefulness of the LRGWQIDSS. It would also be a complicated task due to the technical difficulties involved, as well as questions of where the system would be hosted and what entity would pay the long-term costs of administration and maintenance of the databases and website. A dedicated LRGWQIDSS website could increase the usefulness of the LRGWQIDSS beyond updating and enhancing the software's current capabilities to include decision making related to other areas commensurate with shifting water resources management needs, such as emerging contaminants, flood mitigation, habitat protection, etc. A decision support system containing interactive maps, monitoring information, news items, professional reports, and links to other websites with pertinent information, all accessible via the internet, would transform the value of the LRGWQIDSS.

Perhaps the most important recommendation for future work on the LRGWQIDSS emanates from the third lesson learned as a result of the research presented in this dissertation: conceptualization of transboundary EDSS development as efforts to establish a sustainable program of decision support. In Sub-section 4.2.4, the author mentioned the likely change in the focus of water quality planning and management efforts in the Lower Rio Grande/Río Bravo in the near future. The author states that the establishment of an ongoing process by which the LRGWQIDSS is maintained and modified, as needed, would guarantee the availability, of a binational decision support tool to manage and protect water quality in the river in the future. These changes to the LRGWQIDSS will likely involve increasing its accessibility and information content.

APPENDIX A: TERMS OF REFERENCE FOR THE LOWER RIO GRANDE WATER QUALITY INITIATIVE

INTERNATIONAL BOUNDARY AND WATER COMMISSION
UNITED STATES AND MEXICO

Cd. Juárez, Chihuahua
September 10, 2013

TERMS OF REFERENCE

UNITED STATES-MEXICO JOINT COOPERATIVE ACTIONS IN THE LOWER RIO BRAVO/RIO GRANDE RIVER BASIN

Legal Framework

Article 3 of the 1944 Treaty Relating to Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande authorizes the International Boundary and Water Commission (IBWC) "to give preferential attention to the solution of all border sanitation problems...." Article 24 authorizes the Parties "to initiate and carry on investigations and develop plans for the works which are to be constructed or established" dealing with transboundary waters.

The Commission in Minute 261 agreed to define as a "border sanitation problem" each case in which the waters that cross the boundary, including coastal waters, or that flow in the limitrophe reaches of the Rio Grande and the Colorado River, have sanitary conditions that present a hazard to the health and well-being of the inhabitants of either side of the border or impair the beneficial uses of these waters.

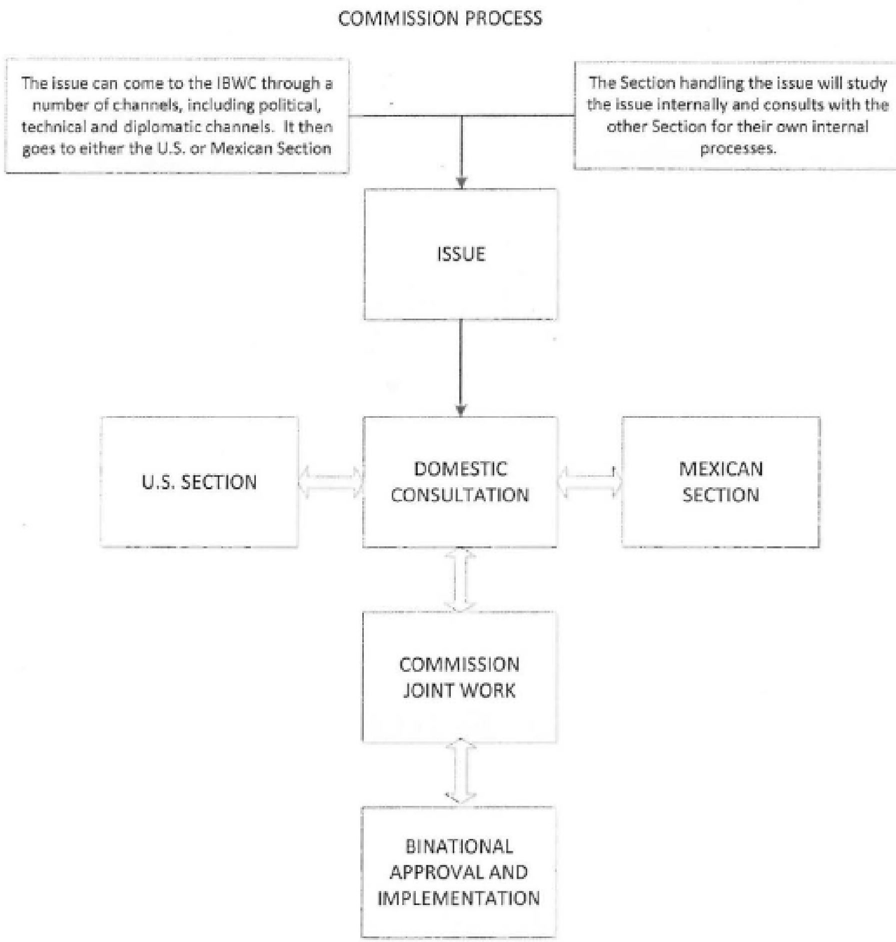
The IBWC Commissioners agreed in Point 6 of Minute 261 "That in each case where the approved course of action provides that the border sanitation problem be jointly corrected by the two Governments, the Commission develop the plans and designs for the work necessary therefore, as well as the division of work and costs between the two countries, submit them for approval of the two Governments, and upon such approval, each Government through its Section of the Commission proceed to carry out the construction, operation and maintenance, with the greatest speed and timeliness possible." Under IBWC Minute No. 289 entitled "Observation of the Quality of the Waters along the United States and Mexico Border," the Commission agreed to evaluate water quality and develop an integrated program for the observation of water quality in the international waters of the United States and Mexico.

IBWC Position and Process Framework

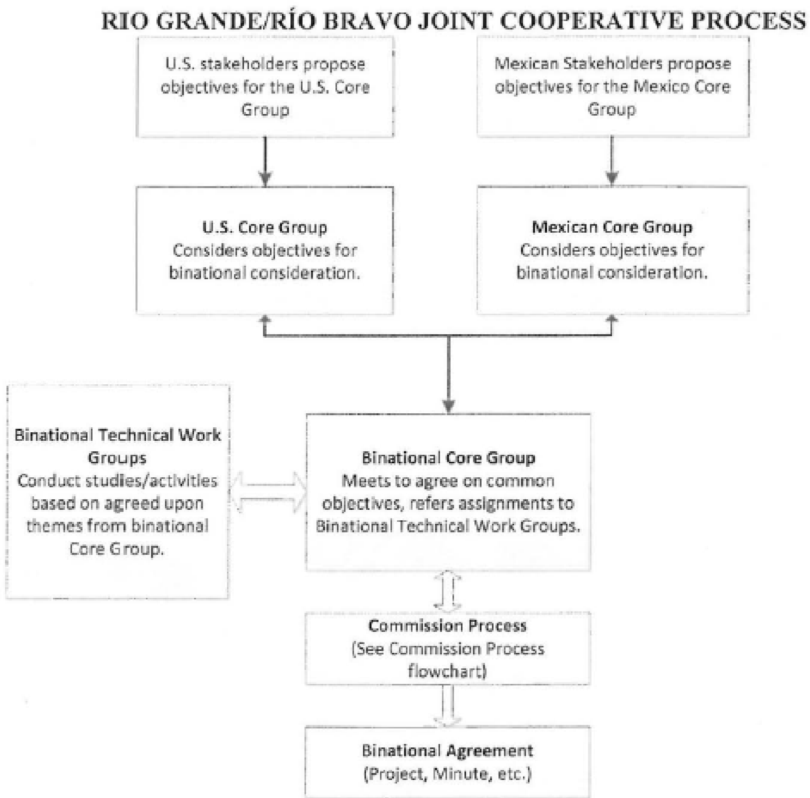
Both Sections of the IBWC are aware of the binational interest to pursue the evaluation of cooperative, innovative and holistic measures that could benefit water users in the United States and Mexico. As binational initiatives that can affect international waters

between the U.S. and Mexico have to be accomplished under IBWC auspices, the Commission will follow the normal binational cooperation process used by both Sections. Due to the complexity and the numerous stakeholders involved, both sections of the Commission will establish the necessary framework to allow for the joint evaluation of proposed cooperative measures that could benefit both nations.

The Terms of Reference will serve as the framework used by all entities participating in the joint cooperative process. The following flowchart depicts the binational cooperation process that is normally followed by the Commission when addressing binational issues.



The following chart shows the framework that will be used in the evaluation of binational cooperative actions.



Once a project is agreed for implementation by the binational Core Group, the Commission will determine the appropriateness of preparing a Minute to ensure continuity of projects regardless of administration changes in each government.

Not all projects may require the development of a Commission Minute. The necessity for a Minute will be determined on a case-by-case basis.

General Objective

The objective of the joint cooperative process is to establish, under the auspices of the IBWC, a group of representatives from the United States and Mexico to explore border sanitation issues and water quality management with potential binational benefits. Any joint cooperative projects and measures must be consistent with the 1944 Treaty.

Specific Objectives

a. Address current and future water quality issues of the Lower Rio Grande/Río Bravo.
b. Implement management procedures and programs that enable affected parties to manage wastewater discharges and improve water quality conditions.
c. Evaluate current wastewater discharge infrastructure and management strategies for the potential for improving the quality of effluent discharges into the Lower Rio Grande/Río Bravo.
d. Evaluate new mechanisms and strategies for system operations that could improve ambient water quality and address border sanitation concerns.
e. Improve salinity management for return flows into the Lower Rio Grande/Río Bravo.
f. Based on the results of the evaluations carried out, implement programs and projects to meet these objectives as appropriate, and result in measurable and sustainable improvements in the ambient water quality of the Lower Rio Grande/Río Bravo.

Organization and Management

The IBWC, acting under the foreign policy guidance respectively of the U.S. Department of State and the Mexican Foreign Ministry, will be the lead in the joint cooperative process.

The Commission will form a binational Core Group of members representing each Section of the IBWC, other federal agencies, and the States of Tamaulipas and Texas. Other stakeholders, which may include local government officials or non-governmental organizations (NGOs), may be invited to participate in the Core Group. To enhance the availability of information to all parties, any U.S. or Mexican Core Group member may invite a technical expert to advise the Core Group with approval from IBWC, as there can be a benefit from utilizing research or outreach efforts of other organizations and agencies.

The composition of the U.S. Core Group will be as follows:

- U.S. Section, International Boundary and Water Commission (USIBWC)
- U.S. Environmental Protection Agency (EPA)
- Government of Texas, through the Texas Commission on Environmental Quality (TCEQ)

U.S.-based non-governmental organizations or local government institutions may participate if invited by the Core Group, but not as members of the U.S. Core Group.

The composition of the Mexican Core Group will be as follows:

- Mexican Section, International Boundary and Water Commission (MxIBWC)
- National Water Commission (CONAGUA)
- Government of the State of Tamaulipas, through the State Water Commission of Tamaulipas (CEAT)

Mexican-based non-governmental organizations or local government institutions may participate if invited by the Core Group, but not as members of the Mexican Core Group.

The binational Core Group may form technical work groups to work on specific issues, measures and projects selected by the binational Core Group. Each binational Technical Work Group will be composed of a representative from each Section of the IBWC and members from each country with the required knowledge and expertise to work on specific issues related to the objectives. A group leader from each country will be selected by the binational Core Group members from that country. To enhance the availability of information to all parties, any member of the U.S. or Mexican Core Group may invite a technical expert to advise the Core Group with approval from IBWC. The BECC and NADB representatives also may be helpful when binational work groups meet.

The names of the members that participate in each work group will be documented in the meeting minutes for these groups.

Conduct of Meetings

Each nation's Core Group meetings will be conducted as necessary and as determined by each delegation. Each nation's Core Group will be free to schedule and conduct its meetings.

Binational meeting minutes will be exchanged between U.S. and Mexican Core Group delegations following each meeting that takes place. The binational Core Group meetings will be conducted as follows:

- Meetings will be convened by the U.S. and Mexican Commissioners of the IBWC or their designated representatives and will be held, as required, at alternating meeting sites in the United States and Mexico if possible. When a Core Group member or stakeholder is unable to attend a meeting in person, other methods of participation will be made available.

- Binational Core Group meetings will be chaired jointly by the U.S. and Mexican Principal Engineers of the IBWC or by their designated representatives. The binational Core Group can establish work groups to undertake specific tasks or projects under the direction of the binational Core Group and then present the results to them. These work groups will not have decision-making authority.

- The binational Core Group will develop joint work plans and meeting agendas. The agendas will, to the extent practical, be shared in advance of the meetings.

- The co-chairing Principal Engineers will make every effort possible to achieve a consensus among the binational Core Group for all those activities under consideration.

- The binational Core Group will strive to ensure that the principal points of the presentations and dialogue at the meetings and events are documented in summary reports in the English and Spanish languages. All binational meetings will have professional simultaneous interpretation support furnished by the country hosting the meeting and/or event. To the extent possible each Section will provide its presentation documents to the other Section prior to binational Core Group meetings so that the documents can be translated. Also, to the extent possible, each Section will provide presentation documents in the primary language of the country to its Core Group committee members 48 hours prior to the meeting.

- Every effort will be made to convene meetings at times and places where all members can be present. In the event that a designated primary Core Group member is not able to be present, the designated alternate person may represent the primary person. In extraordinary circumstances, accommodations may be made for group members to participate by telephone or video conference; however, the availability of simultaneous interpretation cannot be guaranteed for remote participants.

- Other personnel of the government and non-government organizations and agencies, including consultants, personnel involved in presentation of information studies and

progress reports, may participate in support of work groups as established in the work plan and meeting agendas. The binational Core Group must approve their participation. Representatives of the U.S. Department of State and the Mexico's Secretariat of Foreign Relations may attend national and binational Core Group meetings at their discretion. The two Principal Engineers or their designees must approve the participation of other personnel who are not members of the Core Group.

Framework of Activities

The binational Core Group will conduct its activities in accordance with work plans that cover the following framework:

- Definition of objectives and selection of binational items to be evaluated.
- Selection and establishment of binational work groups that will be working on the topics for which binational data gathering, analysis and other work can be advanced through work groups.
- Identification of tours and field visits necessary to initiate dialogue and enhance understanding of U.S. and Mexican objectives.
- Definition of obligations for Core Group and work group members and definition of the required progress reports and work products for presentation by binational work groups at binational Core Group meetings.
- Provide advice and guidance to each work group in reference to assignments.
- Establishment of deadlines for exchange of information required for binational review.
- Recommendation of projects for binational implementation.

Binational work groups will conduct their activities in accordance with the guidance provided by the binational Core Group. National work groups will conduct their activities in accordance with the guidance provided by each country's Core Group. The binational technical work groups will be responsible for the following activities:

- Evaluation of assigned issues to include feasibility, cost and potential benefit for both nations.

- Arrangement of tours and field visits.
- Preparation of reports outlining findings and recommendations.
- Presentation of reports.

Unofficial interaction between U.S. and Mexican interest groups is encouraged in order to have a creative environment, foster better relations and promote productive dialogue that could lead to the generation and/or positive evaluation of joint cooperative measures and projects that could be beneficial to both nations. Any formal discussions and evaluations of any proposal will follow the Terms of Reference established for the "United States-Mexico Joint Cooperative Actions in the Lower Rio Grande/Río Bravo River Basin."

Funding and cost share decisions will be made on a case-by-case basis and are subject to appropriations. All projects and measures considered under this joint cooperative process are subject to the availability of funds. Any agreement to pursue the evaluation of a specific project or measure does not commit any of the parties to provide funding for the execution of projects and measures.

Core group members and work group members participating in this process will not be compensated by either Section of the Commission, nor will participants' travel expenses related to this process be reimbursed by either Section.

Communication and Use of Information

The two Sections of the IBWC will be the official repository of records generated by the national or binational Core Group and work groups, at meetings, studies, and any information exchanged and/or presented to the Core Group.

Credit shall be given to those who provide information.

Outcomes and Performance Measurement

The United States and Mexican Sections of the IBWC will prepare reports on the progress of United States-Mexico joint cooperative actions in the Lower Rio Grande/Río Bravo. Each report will include results from monitoring of ambient water quality within the Lower Rio Grande/Río Bravo. This effort seeks significant and sustainable improvements in ambient water quality within the main stem of the Lower Rio

Grande/Río Bravo from the Falcon Reservoir to the Gulf of Mexico. This project will be considered a success if it has demonstrated that:

1. Opportunities to improve water quality have been identified, and
2. Implementation of these opportunities improves water quality in the Lower Rio Grande/Río Bravo.

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APPENDIX B: ANNEX TO THE TERMS OF REFERENCE FOR THE LOWER RIO GRANDE WATER QUALITY INITIATIVE

INTERNATIONAL BOUNDARY AND WATER COMMISSION
UNITED STATES AND MEXICO

Cd. Juárez, Chihuahua
September 10, 2013

Lower Rio Grande/Rio Bravo Water Quality Initiative
Pilot Project

Introduction

Binational efforts to improve water and wastewater infrastructure along the U.S./Mexico border have resulted in marked improvements in water quality in the Rio Grande. However, there are areas where continued efforts are needed. In particular, the portion of the river from the Falcon International Reservoir to where the river enters the Gulf of Mexico (hereafter termed the Lower Rio Grande/Río Bravo) has experienced persistently high bacteria levels.

Binational water quality planning efforts can be an effective tool in controlling the effects of growth and development on transboundary water resources. In addition to enhancing and improving the effectiveness of existing unilateral efforts to improve water quality, by focusing and coordinating those efforts, binational water quality planning can reduce the cost of water quality management and increase the level of protection of the resource through increased collaboration of stakeholders on both sides of the border.

This document describes a binational effort to improve and protect water quality in the Lower Rio Grande/Río Bravo, which currently experiences bacteria levels that have, at times, been higher than recommended for approved water uses of the river. This effort, the Lower Rio Grande/Río Bravo Water Quality Initiative (LRGWQI), is intended to serve as a pilot project to develop the binational mechanisms necessary to improve water quality throughout the Rio Grande/Río Bravo.

Goals and Objectives

The Mexican partner agencies (International Boundary and Water Commission, Mexican Section [CILA], the Mexican National Water Commission [CONAGUA], and the Tamaulipas State Water Commission [CEAT]) and the U.S. partner agencies (International Boundary and Water Commission, U. S. Section [USIBWC], the U.S. Environmental Protection Agency [USEPA] and the Texas Commission on Environmental Quality [TCEQ]) agree that the goals and objectives of the LRGWQI pilot project should be to restore, protect, and improve the water quality in the Lower Rio Grande/Río Bravo, downstream of Falcon Reservoir. Additional efforts could include a survey to identify sources of salinity in the Lower Rio Grande/Río Bravo. Specific water quality targets are to be agreed-upon through a binational consultation and deliberation processes conducted under the auspices of the IBWC, U.S. and Mexico.

Geographic Scope

The focus of the LRGWQI pilot project is on water quality management in the Lower Rio Grande/Río Bravo, below Falcon Dam to the Gulf of Mexico. This effort is a pilot project for a single reach, which, if successful, may serve as a model for other segments along the river.

Technical Approach

The set of technical tasks for the LRGWQI project includes:
1. Historical data review
2. Identification of data gaps
3. Data collection
4. Data analysis and modeling

The analysis is to include point and steady-state nonpoint sources of pollution. The first phase of analysis will focus on characterizing and modeling water quality under steady state conditions. The technical work associated with the LRGWQI should be conducted through cooperation between Mexico and the United States.

Identifying Feasible Options to Improve Water Quality

A goal of this initiative is to identify potential feasible pollution prevention and control options (the options) that will result in the restoration, conservation, and improvement of the water quality in the Lower Rio Grande/Río Bravo through a facilitated stakeholder process that includes the participating agencies, stakeholders from both sides of the river and representatives of the local binational community of water users. The options will be incorporated into a binational water quality improvement plan along with the technical analysis justifying their selection, including estimation of option costs.

Legitimizing the Analysis

The official mechanism for obtaining binational concurrence on technical aspects of the plan is the IBWC process. Once completed, the binational water quality plan resulting from the LRGWQI effort (or the main elements of the plan) could be incorporated as an agreement approved through the IBWC, US and Mexico.

Legal Framework

The 1944 Water Treaty is the most appropriate institutional mechanism for reaching a binational agreement on the elements of any binational water quality plan in the Lower Rio Grande/Río Bravo resulting from the LRGWQI.

Plan Development and Implementation

The LRGWQI pilot project should proceed in three stages:

- The **first stage** will include initial binational discussions and development of a binational study plan. The first stage will also include initial historical data review, identification of key stakeholders, and development of a stakeholder participation strategy
- The **second stage** will include binational data collection, technical analysis/modeling, and stakeholder involvement. The second stage of the LRGWQI will result in a binational water quality improvement plan.
- The **third stage** would assess implementation and would result in a report(s) evaluating the progress achieved under the LRGWQI.

Implementation and Monitoring

Two (2) types of monitoring associated with the LRGWQI pilot project, programmatic monitoring and ambient monitoring are envisioned:

- Programmatic Monitoring - the project will develop a plan to monitor the progress of implementation of the measures and solution strategies detailed in the binational water quality plan.
- Ambient Monitoring - the project will also develop a plan for each nation to monitor the progress in achieving the water quality goals specified in the plan.

Both nations should be willing to share Mexican and U.S. information sources so that each side and its residents have confidence regarding sources of effluents and the ambient quality of the river.

Sustaining the Effort

The LRGWQI pilot project should develop consensus procedures for Mexico and the U.S. to cooperate in future water quality planning beyond the scope of the initial plan. Both parties should state their interest in continuing with a long-term effort to improve water quality of the river.

Stakeholder Involvement

Each of the binational partner agencies involved in water quality (TCEQ, EPA, IBWC-U.S. and Mexico, CONAGUA, and CEAT) will determine their appropriate stakeholder involvement. There can be a benefit from utilizing research or outreach efforts of other organizations and agencies from both countries. The stakeholder involvement processes

will rely as much as possible on existing public and stakeholder outreach forums and mechanisms such as EPA-SEMARNAT Border 2012 (2020) Program, USIBWC's Citizen Forums and the TCEQ and USIBWC's Clean Rivers Program Basin Steering Committee meetings in the United States, as well as other efforts led by Mexican organizations such as Basin Councils.

Schedule

The development of a binational water quality plan resulting from the LRGWQI, based on a starting point of September 2012, would consist of the following stages:

- Stage 1 – 12 months: beginning in September 2012;
- Stage 2 – up to 2 years (2014); and
- Stage 3 – 12 months (2015).

/PE

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APPENDIX C: LOWER RIO GRANDE WATER QUALITY INITIATIVE SURVEY OF WATER QUALITY PREFERENCES

Survey of Water Quality Preferences **ENGLISH**

Lower Rio Grande Watershed Initiative (University of Texas at Austin)

The purpose of this survey is to gather information about water quality where you live. Your answers will help us understand local attitudes about water quality in the Rio Grande. If you are not sure about an answer, simply write "Not sure." <u>All answers will be kept completely anonymous</u>.

1. On a scale of 1-5, how important is it to you that the Rio Grande be clean? *Please circle <u>one</u> number.*

   1 2 3 4 5
   Not important *Very important*

2. Why did you choose this answer?____________________

3. Would you in the near future do the following activities in the Rio Grande?

   ☐ Yes ☐No Go swimming or wading?
   ☐ Yes ☐No Participate in water sports (boating, canoeing, water skiing, etc)?
   ☐ Yes ☐No Go fishing?
   ☐ Yes ☐No Let your dog go swimming?

4. Is it important that people be able to do the above activities in the Rio Grande? ☐ Yes ☐No

5. On a scale of 1-5, how polluted is the Rio Grande in your opinion? *Please circle <u>one</u> number.*

   1 2 3 4 5
   Not polluted *Very polluted*

If you chose "1" please SKIP TO QUESTION 9. If you chose 2, 3, 4 or 5 please answer questions 6-8, below.

6. What do you think is the **<u>biggest</u>** source of pollution in the Rio Grande?____________________

7. How do you think pollution in the Rio Grande affects someone like you?____________________

8. Who do you think **<u>should be</u>** responsible for making sure the Rio Grande is clean?____________________

9. Where do you get information about water quality in the Rio Grande? *Check <u>all</u> that apply.*

   ☐ TV ☐Radio ☐Newspaper ☐Internet
   ☐ Friends/Family ☐ Personal experience
   ☐ Other____________________

10. What do you think should be done to improve water quality in the Rio Grande?____________________

11. About how much is your water bill each month?____________________

12. How much extra would you be willing to pay **<u>each month</u>** to make sure the Rio Grande is clean enough to swim in?____________________

13. What year were you born? ____________________

14. Were you born in Starr, Willacy, Cameron or Hidalgo county? ☐ Yes ☐No

15. What is your gender? ☐Male ☐ Female

16. Do you consider yourself Latino or Latina?
    ☐Yes ☐No

17. What is your highest education level?
    Please check one of the boxes below.
    ☐Elementary School
    ☐Middle School
    ☐High School or GED
    ☐Some College
    ☐College Degree
    ☐Graduate or Professional Degree

18. How many years have you lived in your current home?____________________

19. What is the **<u>monthly</u>** household income of your family?

    ☐ Up to $800 ☐ $4,201 – $6,250
    ☐ $800 - $2,500 ☐ More than $6,250
    ☐ $2,501 – $4,200

20. Do you or someone in your family own your home or is the home rented? ☐ Own ☐Rent

Encuesta de Preferencias de Calidad del Agua **ESPAÑOL**

Iniciativa de la Cuenca del Bajo Río Grande/Río Bravo (Universidad de Texas, Austin)

El propósito de esta encuesta es obtener información sobre la calidad del agua donde usted vive. Sus respuestas nos ayudarán a comprender las actitudes acerca de la calidad del agua en el Río Grande/Río Bravo. Si no está seguro/a de una respuesta, simplemente escriba "No estoy seguro/a." Todas sus respuestas se mantendrán completamente anónimas.

1. En una escala de 1-5, ¿qué tan importante es para usted que el Rio Grande/ Río Bravo esté limpio? *Por favor circule solo uno numero.*

   1 2 3 4 5

   No importante *Muy importante*

2. ¿Por qué eligió esta respuesta?______________________

____

____

3. ¿Haría usted las siguientes actividades en el Río Grande / Río Bravo?

   ☐ Sí ☐ No ¿Nadar o meterse en el agua?
   ☐ Sí ☐ No ¿Participar en deportes acuáticos (canotaje, esquí acuático, etc...)?
   ☐ Sí ☐ No ¿Pescar?
   ☐ Sí ☐ No ¿Dejar que su perro nade?

4. ¿Es importante que la gente sea capaz de hacer cualquiera de las actividades mencionadas anteriormente?
   ☐ Sí ☐ No

5. En su opinión, en una escala de 1-5, ¿qué tan grave es la contaminación en el Rio Grande/ Río Bravo? *Por favor circule solo uno numero.*

   1 2 3 4 5

   No contaminado *Muy contaminado*

Si contestó "1" por favor SALTE A PREGUNTA 9. Si contestó 2, 3 ,4 o 5 por favor conteste preguntas 6-8 abajo.

6. ¿Qué cree usted que es **la mayor** fuente de contaminación en el Río Grande/Río Bravo? ____________

____

____

7. ¿Cómo cree usted que la contaminación en el Río Grande afecta a alguien como usted? ____________________

____

____

8. ¿Quién cree usted que **debería** ser responsable de asegurar que el Río Grande/Río Bravo esté limpio?_______

____

____

9. ¿Donde consigue usted información sobre calidad de agua en el Rio Grande/Río Bravo? Por favor *marque todo lo que corresponda.*
   ☐ TV ☐ Radio ☐ Periódico ☐ Internet
   ☐ Amigos/Familia ☐ Experiencia Personal
   ☐ Otra Cosa? ________________________________

10. ¿Qué cree usted que se debería hacer para mejorar la calidad del agua en el Río Grande/Río Bravo?

____

____

11. ¿Aproximadamente cuánto es su factura del agua cada mes? ________________________________

12. ¿Cuánto más estaría usted dispuesto a pagar **cada mes** para asegurar que el Río Grande/Río Bravo sea lo suficientemente limpio para nadar? __________________

13. ¿En qué año nació usted?______________________

14. ¿Nació usted en el condado de Starr, Willacy, Cameron o Hidalgo? ☐ Sí ☐ No

15. ¿Cuál es su sexo? ☐ Masculino ☐ Femenino

16. ¿Se considera usted Latino o Latina? ☐ Sí ☐ No

17. ¿A que nivel de educación a llegado usted? *Marque una de las cajas abajo.*
   ☐ Elementary School (Primaria)
   ☐ Middle School (entre primaria y secundaria)
   ☐ High School o GED (Diploma de escuela secundaria o su equivalente)
   ☐ Algunos Estudios Universitarios
   ☐ Título Universitario
   ☐ Título Universitario de Postgrado o Profesional

18. ¿Por cuántos años ha vivido usted en su hogar actual?

____

19. ¿Qué es su ingreso familiar **mensual**?

   ☐ Hasta $800 ☐ $4,201 – $6,250
   ☐ $800 - $2,500 ☐ Más de $6,250
   ☐ $2,501 – $4,200

20. ¿Es usted o alguien de su familia el dueño de la casa o es la casa alquilada? ☐ Dueño ☐ Alquilada

APPENDIX D: LRGWQI SYSTEM REQUIREMENTS SPECIFICATIONS DOCUMENT

TEXAS PROJECT DELIVERY FRAMEWORK

SYSTEM REQUIREMENTS SPECIFICATION

[Texas Commission on Environmental Quality]

[Decision Support System for the Lower Rio Grande/Río Bravo Water Quality Initiative]

VERSION: [1.0] REVISION DATE: [NA]

Approver Name	Title	Signature	Date

Contents

Section 1. Introduction

1.1 Purpose

The purpose of this project is to develop a computer-based Decision Support System (the DSS hereafter) for the Lower Rio Grande/Río Bravo Water Quality Initiative (LRGWQI), which is a binational effort to restore and protect water quality in the Lower Rio Grande/Río Bravo downstream of Falcon Reservoir to the Gulf of Mexico.

Texas Commission on Environmental Quality (TCEQ) is currently working with other US and Mexican partner agencies to develop a steady-state water quality model that will aid this effort. The DSS will improve partner access to critical data and facilitate use of the water quality model developed by the partner agencies.

The DSS will address the following segments and assessment units in the Lower Rio Grande/Río Bravo watershed:

- Rio Grande Tidal, Segment 2301 – Assessment Units 2301_01, 2301_02
- Rio Grande below Falcon Reservoir, Segment 2302 – Assessment Units 2302_01, 2302_02, 2302_03, 2302_04, 2302_05, 2302_06, 2302_07
- Arroyo Los Olmos, Segment 2302A (unclassified water body) – 2302A_01
- Various Mexican tributaries, arroyos and drains that contribute flow to Segments 2301 and 2302, including (but not limited to), Rio San Juan, Rio Alamo, Puertecitos Drain, Rancherías Drain, El Morillo Drain, and Anhelo Drain – None of these water bodies are classified segments under Appendix C of TAC §307.10 (Texas Surface Water Quality Standards), as they emanate in Mexico.

The intended audience of the system will be binational stakeholders involved in the LRGWQI.

1.2 Business Context

Development of the DSS is funded by the TCEQ/LRGWQI project which in turn is funded by US Fish & Wild Life Service through the Texas General Land Office. TCEQ is the environmental agency for the state of Texas. The TCEQ business unit funding this project is in charge of Total Maximum Daily Load (TMDL) program in the state of Texas. The DSS will help stakeholders examine options for improving instream water quality. Examples of such options may include (a) emplacement of infrastructures (e.g., installation of collection lines and lift stations, repair of existing collection system components such as broken collection lines and leaking lift stations); (b) non-urban best management practices (e.g., keeping livestock and wildlife away from ditches, tributaries, or the river itself).

1.3 Scope

The main scope of the DSS is to provide necessary software tools with graphic user interface (GUI) for LRGWQI partners to

(a) Develop nonpoint source loading scenarios

(b) Perform computer simulations of water quality

(b) Visualize modeling outputs for each scenario.

Here a <u>*scenario*</u> may be created to model the effect of improvements in urban collection instrastructures such as the installment of wastewater treatment facilities or other infrastructures along Rio Grande/Río Bravo that can potentially improve water quality in the Lower Rio Grande/Río Bravo. Other examples may include installation of collection lines and lift stations, repair of existing collection system components, such as broken collection lines and leaking lift stations. Scenarios can also be created to model the effect of non-urban best management practices, such as keeping livestock and wildlife away from ditches, tributaries or the river itself.

The net effect of the scenarios described herein is to affect point and nonpoint source loading rate of a certain constituents at a particular location on the river or within a subbasin of the subject watershed. The DSS does not calculate the affected loading rates;instead, as part of the inputs, it asks the user to provide the expected change in the pollutant loading rate expected from each control action or management measure outside the DSS and then enter these values for the affected regions included in the model through the DSS GUI.The water quality modeling software underlying the DSS will be LA-QUAL, which is a steady-state, one-dimensional water quality computer program that was developed by the Watershed Support Division of the Louisiana Department of Environmental Quality.

The role of the DSS GUI will be facilitating and streamlining the preparation of LA-QUAL model input files. The user is assumed to be familiar with the type of steady-state water quality modeling performed by the LA-QUAL program and is expected to have relevant information ready before starting the DSS. The LA-QUAL program itself will not be modified as part of this project.

In particular, the following information may be needed when creating a scenario:

(d) Pollutant loading rate (or changes in loading rate) due to each individual control action or management measure), for example,

Ammonia, nitrate, organic nitrogen

Phosphorous loading rate

Bacteria (mainly fecal coliform) loading rate

Dissolved and suspended sediments rate

(e) Pollutant Sources:

Irrigation return flow volume

Population served by public sewage system

Population incompletely served by public sewage system

(f) Subbasin-specific collection system infrastructure failure rate

Detailed functional requirements are provided in Section 3 of this document.

The LA-QUAL calibration effort is separate from DSS code development.

The DSS will be designed to be a standalone application to be downloaded (ftp site to be specified by TCEQ) and deployed on a Microsoft Windows-based operating system. The final product will be a self-contained installation file with all necessary components included. The development team will adopt a Python-based package for developing the DSS GUI. Although the Python programming language is platform independent, the development team will mainly test the functionalities of the DSS on a Microsoft Windows Operating System under the scope of this project. This is because the DSS will call an external Windows-based program LA-QUAL.

1.4 User Characteristics

The intended users of this DSS will include a diverse binational group of stakeholders involved with LRGWQI project. The potential users will be from:

- TCEQ,
- Comisión Estatal del Agua de Tamaulipas (CEAT),
- International Boundary and Water Commission – US Section (IBWC),

- Comisión Internacional de Limites y Agua (CILA),
- Border Environmental Cooperation Commission (BECC),
- US Environmental Protection Agency (EPA),
- Local US and Mexican municipal and county governments

The users will use the DSS to examine the effect of different water and wastewater management scenarios on instream water quality.

Section 2. General System Description

2.1 System Context

This System Requirement document will be illustrated using UML (unified modeling language) diagrams extensively. Rational Rhapsody Modeler v7.5, which is an open-source UML tool developed by IBM®, was used to generate all the UML diagrams used in this document.

An overview of DSS functionalities is provided in Figure 1, which is presented in the form of a use case diagram.

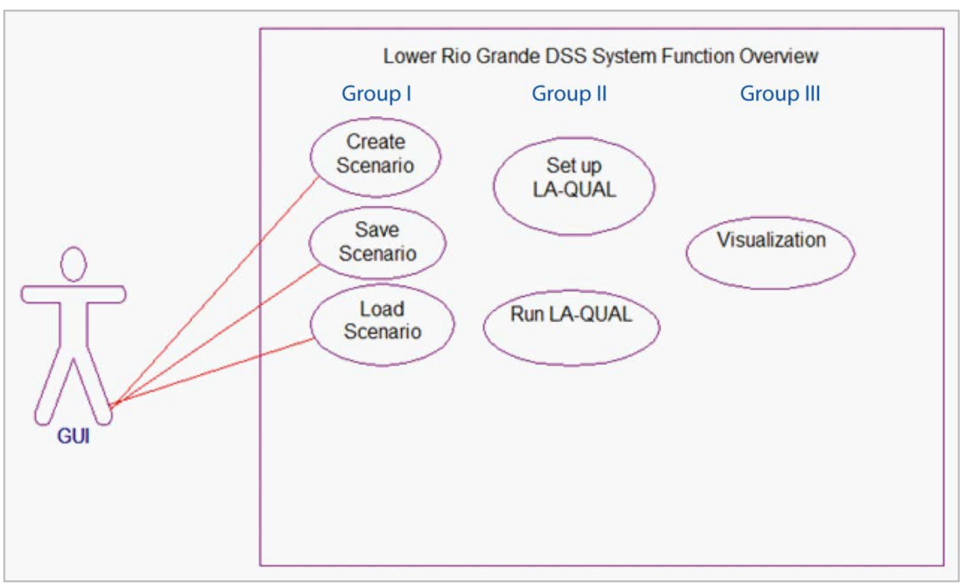


Figure 1. Function overview of the LRGWQIDSS.

The use case diagram in Figure 1 depicts six use cases that are needed to enable user interactions with LA-QUAL program. The use cases can be classified into three functional groups:

(a) Group I: Functions related to LA-QUAL model file handling, including creating, saving, and loading a scenario

(b) Group II: Functions related to LA-QUAL handling, including providing GUI for soliciting user inputs and for setting up LA-QUAL and subsequently running a model file

(c) Group III: Functions related to shapefile handling and visualization. Shapefiles are GIS files that spatially describe vector features (e.g., points, lines, and polygons).

The DSS is designed to be a standalone software product. The main cross-boundary interaction is to call the LA-QUAL program, which is a windows-based executable file. The interactions will be done in two steps: first, the DSS creates and places a functional LA-QUAL input file in a working directory; second, the DSS calls the LA-QUAL executable.

2.2 System Modes and States

The DSS will have a single operating mode, in which a user launches the program, performs LA-QUAL modeling by specifying nonpoint source loading parameters and infrastructure component types and locations, and the rest of the post-processing is shifted outside the system domain to the LA-QUAL program.

2.3 Major System Capabilities

Major capability groups of the DSS include:

(a) Group I: Model file handling: creating, saving, and loading a scenario

(b) Group II: LA-QUAL handling: setup LA-QUAL and run a model file

(c) Group III: Visualization: manipulation of GIS files

Several UML diagrams are provided in the sequel to better illustrate the major system capabilities.

Figure 2 shows a use case diagram for Group I, which include functionalities related to model file handling. When a user launches the DSS, he/she enters a work session with the GUI. The functionalities described here are used to record and restore a user's work session. Details are provided in Section 3 of this documentation.

Figure 3 to 5 show use case diagrams for Group II, which implements core logics of the DSS that are needed to create a LA-QUAL model input file. Most of the Group II capabilities are designed to solicit the necessary data from the user to generate a valid LA-QUAL model input file.

Figure 6 shows a use case diagram for Group III. These include functionalities to load background image and to enable simple GIS shapefile handling capabilities, such as displaying the watershed delineation file and river reach shape file. Most of the GIS tasks will be implemented using an open-source GIS library. Technical details are provided in Section 3 of this documentation.

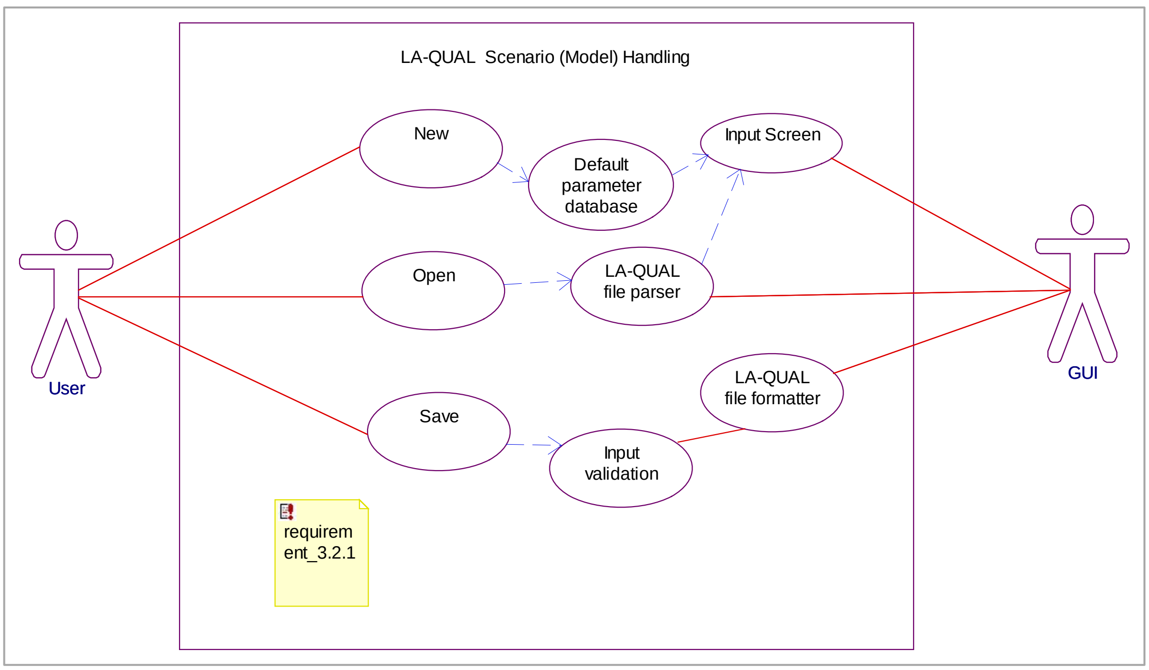


Figure 2. Use case diagram for Functional Group I, handling of DSS model files. The functional requirement is documented under Section 3.2.1.

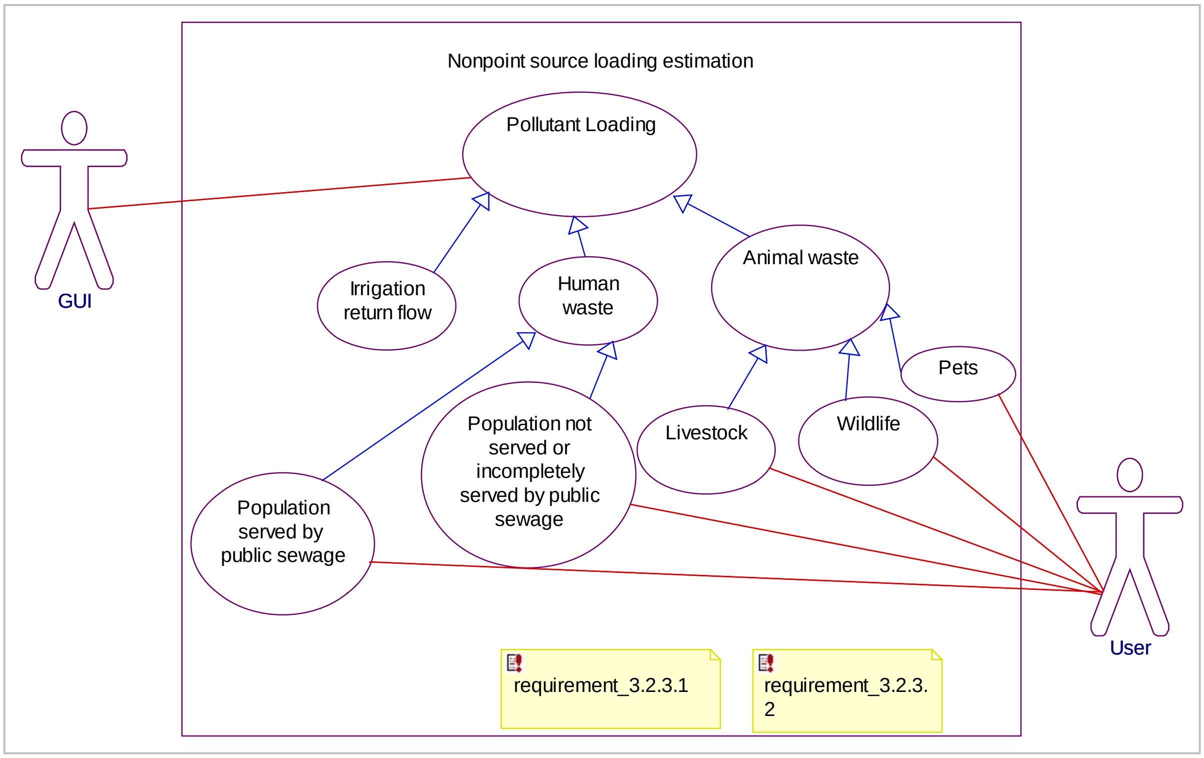


Figure 3. Overview of nonpoint source loading estimation. The functional requirements are documented under Section 3.2.3.1 and 3.2.3.2.

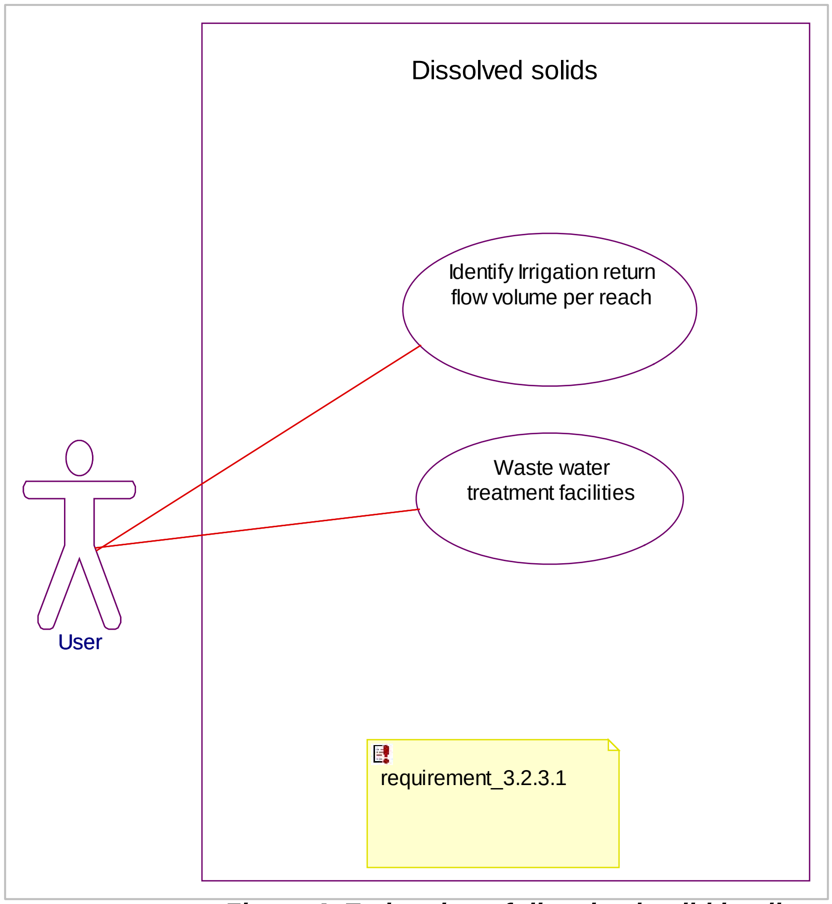


Figure 4. Estimation of dissolved solid loading.

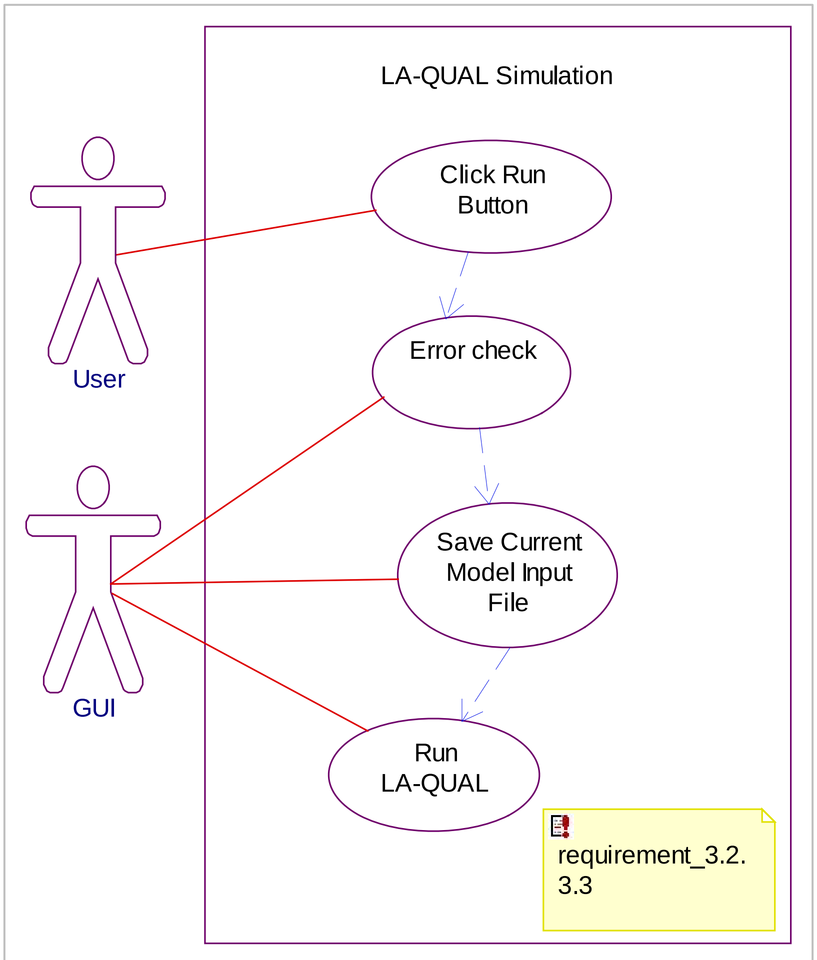


Figure 5. LA-QUAL simulation.

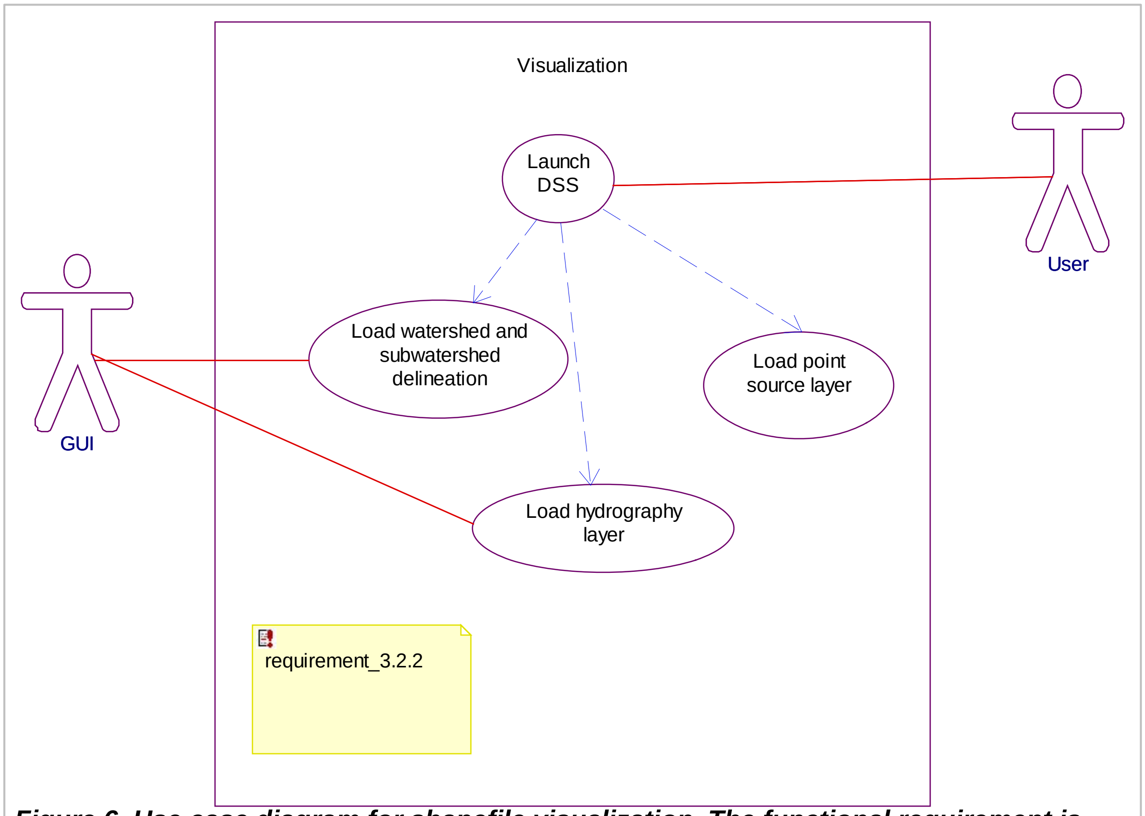


Figure 6. Use case diagram for shapefile visualization. The functional requirement is documented under Section 3.2.2.

2.4 Major System Conditions

The DSS is designed for nontechnical users to use LA-QUAL interactively. The user is not required to know technical details of LA-QUAL. However, familiarity with general nonpoint source pollution concepts will be helpful.

The DSS uses a pre-defined discretization for the LA-QUAL river reaches. It is assumed the grid resolution is fine enough to handle all scenarios to be input by the user.

The DSS assumes that watershed and subbasin delineation files already exist.

The DSS assumes that the user is comfortable with LA-QUAL's own visualization tool for displaying simulation results.

The DSS assumes that the user has information on all required data/constants, including but not limited to, waste water produced per day per capita, population in each county, population served by public sewage, population served incompletely, land use, time animals spend in stream, and etc.

Unless specified by the project manager, the DSS will use information from Lynch (2012).

2.5 Major System Constraints

The DSS is designed to be a standalone software running on a Microsoft Windows 7 operating system. The system uses a pre-defined discretization for the LA-QUAL reaches and pre-defined watershed delineation, which will be provided by the TCEQ project manager. The system calls an external windows executable to perform simulation.

The DSS does not intend to be fully featured GIS software and, thus, the use of spatial graphics is mainly intended for visualization of watershed delineation and hydrography, rather than for direct GIS shapefile manipulation.

2.6 Assumptions

The calibration of LA-QUAL is done separately.

The number of Lower Rio Grande/Rio Bravo reaches is fixed for the scope of this study.

The pre-defined reach discretization level is assumed suitable for all LA-QUAL modeling activities to be conducted through the DSS.

2.7 Dependencies

Main dependencies of the DSS include:

- Windows-based LA-QUAL executable

- An open-source Python library (PyQt) for developing GUI
- An open-source Python GIS library (QGIS) for visualizing shapefiles
- Python interpreter (v 2.7 or greater), needed for running Python-based programs

2.8 Operational Scenarios

In most cases, the operation involves a user specifying the installation of new wastewater treatment plant(s) at (a) certain location(s), or adding of a new collection system(s) to (a) subbasin(s). The core functionalities of the DSS will be facilitating the creation, saving, and loading of scenarios as represented by a LA-QUAL input file. In the course of doing so, the GUI will solicit user inputs and will perform internal calculations to process and prepare user inputs for simulation in LA-QUAL.

Offline, the user may need to estimate the change of loading rates due to implementation of certain load reduction measures.

Section 3. System Capabilities, Conditions, and Constraints

3.1 Business Requirements

LRGWQIDSS will serve as a GUI to facilitate pre-processing activities for LA-QUAL, including defining loading rates (or changes in loading rates) for subbasins associated with LA-QUAL stream reaches, and creating and loading modeling scenarios.

3.2 Functional Requirements

This subsection defines the fundamental actions that must take place within the DSS system to accept and process the inputs and to process and generate the outputs.

3.2.1 Model File Handling

The user can create a new scenario, open an existing scenario and save a valid LA-QUAL file. The DSS GUI responds to user actions. Internally, the DSS performs the following events triggered by the GUI:

- On Open, the DSS populates the GUI with LA-QUAL parameters parsed from a valid input file.
- On New, the DSS loads default parameters from an underlying database and opens the GUI with default LA-QUAL values.
- On Save, the DSS performs validation and saves a model input file to disk.

The DSS will use an underlying database to organize different user inputs. The database can be text-based because of the relatively small size of data records. A database schema will be designed to encapsulate main data objects and relationships among them (Figure 7). The data objects (or tables) include subbasins, pollutants, reaches, pollutant loading rates (or changes) per subbasin.

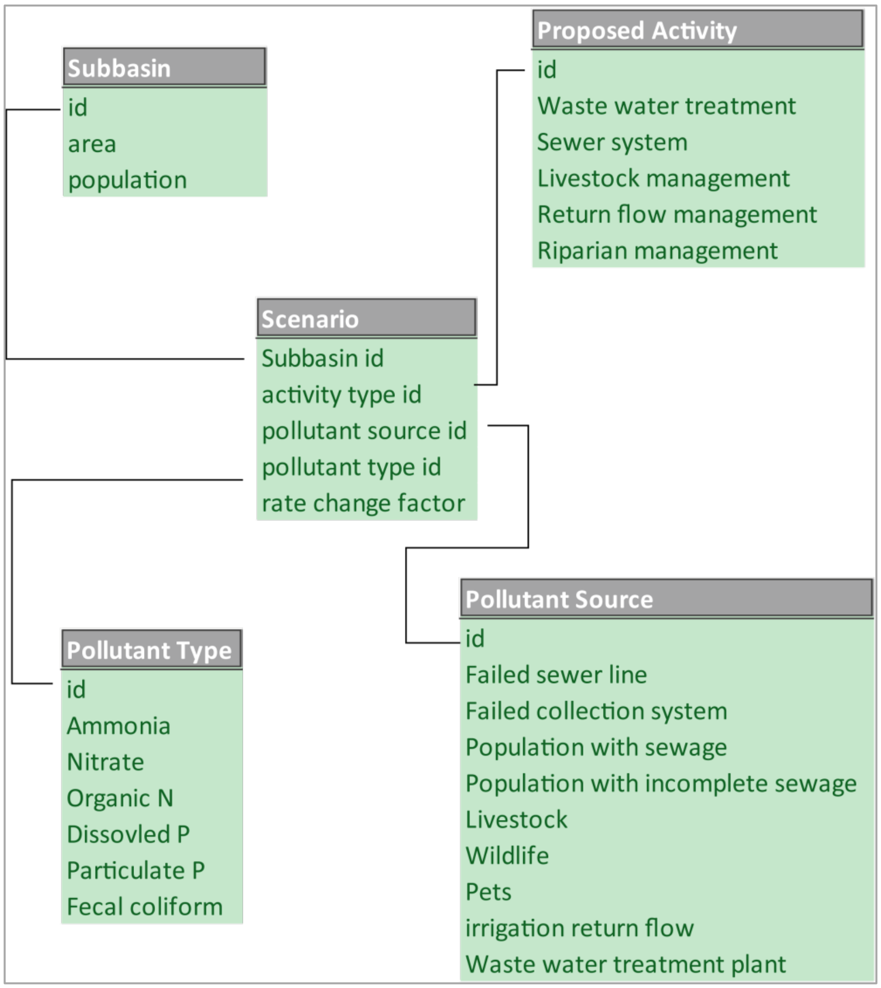


Figure 7. Data schema proposed.

3.2.2 Visualization Handling

Visualization focuses on GIS file handling.

On Launch, the DSS loads a watershed delineation shape file for the background. The DSS loads a reach file to be used for LA-QUAL modeling.

3.2.3 LA-QUAL Handling

The LA-QUAL GUI facilitates pre- and post-processing activities for LA-QUAL by creating a LA-QUAL input file using more user-friendly input screens than would normally be required for simulation using LA-QUAL.

3.2.3.1 LA-QUAL Inputs

Documentation of LA-QUAL inputs is provided in the LA-QUAL user's manual.

Methodology for bacteria nonpoint source loading is based on the master thesis of R. Lynch (Lynch, 2012) and is briefly summarized below:

Loading due to human waste is divided into four types of waste treatment (treated sewage, partially treated sewage, untreated sewage, and other) and two types of communities (rural and urban). In theory, a household that has access to a public sewer system does not pollute rivers or stream beyond what is permitted by the regulating entity. Households with septic systems are assumed to pollute only when the septic system fails; only septic systems near rivers or streams or their tributaries are assumed to pollute (a riparian corridor or buffer around pertinent rivers or streams or their tributaries will be used). Populations lacking any sewage treatment are assumed to contribute waste directly to the river if they live within the riparian corridor of a relevant river, stream or tributary.

Dissolved solids loading will be estimated based on user specified irrigation return flow volumes.

Loadings due to livestock and wild animal wastes will be estimated on user specified rates and riparian corridor affected.

3.2.3.2 LA-QUAL Operations

LA-QUAL provides the following major operations:

(a) Enable user interactions for inputting parameters required for estimation of the effects of point and nonpoint source pollutant loading on water quality in the Lower Rio Grande.

(b) Interact with LA-QUAL executable

3.2.3.3 LA-QUAL GUI Outputs

LA-QUAL GUI output will be a valid LA-QUAL input file.

On Run, the DSS does error checking, saves the DSS model file, generates an input file in LA-QUAL format, and calls the LA-QUAL executable. The actual simulation and graphing of model output is handled by LA-QUAL.

3.3 Physical Requirements

3.3.1 Construction

Windows 7, 32-bit operating system

3.3.2 Durability

The DSS is designed to be compatible with Windows 7 32-bit; Python version 2.7 or higher.

3.3.3 Adaptability

The DSS is designed to be standalone software. Growth and expansion of the DSS will be determined by the TCEQ project manager under a separate effort.

3.3.4 Environmental Conditions

The DSS will be used on any PC running Windows operating system specified in Section 3.3.

3.4 Logical Data Requirements

The DSS assumes that the user is knowledgeable of the methods used to estimate pollutant contributions, to surface waters, from point and nonpoint sources of pollution, and it will provide limited error checking of inputs.

3.5 User Requirements

The user needs some familiarity with the methods used to estimate pollutant contributions, to surface waters, from point and nonpoint sources of pollution and LA-QUAL modeling.

3.6 Information Management Requirements

The LRGWQIDSS is designed to facilitate the creation and of LA-QUAL input files and evaluation of (LA-QUAL) modeling scenarios, mechanisms for the storage and retrieval of modeling scenarios and associated LA-QUAL input and output files, outside of those currently available in the Windows 7 operating system, are beyond the scope of this project.

3.7 Systems Requirements

3.7.1 Performance Requirements

The DSS will be designed to run on Windows 7 operating system, 32-bit.

3.7.2 Quality Requirements

The DSS will be tested using a list of test scenarios supplied as part of this project.

3.8 Policy and Regulation Requirements

University of Texas will own the copyright of the developed DSS but will give a royalty-free, nonexclusive, and irrevocable license to reproduce, publish or otherwise use, and to authorize others to use for Federal and State Government purposes:

1) The copyright

2) Any rights of the copyright.

TCEQ can authorize others to reproduce/publish/use the DSS, but only for noncommercial (government) purposes. Therefore, TCEQ would only authorize a third party to use the DSS if they were using it for TCEQ purposes. This could include another government agency or a contractor working on behalf of government, but TCEQ would not be releasing the software to anyone and everyone.

3.9 System Life Cycle Sustainment Requirements

The subcontractor (UT-BEG) will support bug-fixing during the span of the project contract term and provide limited technical support after the contract ends. The DSS distribution will contain all Python library files required for a working installation. Thus, the DSS is expected to self-sustain beyond the project life.

Section 4. System Interfaces

The DSS will be designed to be a standalone software tool and will only interact with LA-QUAL. Although not covered by the current work scope, future modifications may include a web-hosted executable with similar or expanded capabilities.

Section 5. Requirements Traceability Matrix

A list of functional requirements is summarized below for traceability purposes.

1. The DSS calls LA-QUAL to perform loading calculations
2. The system uses an internal database to organize information, data, and tables
3. The DSS enables creation/modification/storage of load reduction scenarios
4. The DSS provides a GUI to facilitate collection of information on
    - Proposed infrastructure/control type
    - Loading rate changes,
    - The reach/subbasin that a scenario will affect
    - Pollutant source affected
    - Pollutant type affected
5. The system provides simple GIS display capabilities
6. The major system output is a valid LA-QUAL input file
7. The system runs on a Windows 7, 32-bit operation system

Section 6. References

Document No.	Document Title	Date	Author
	LA-QUAL User's manual	2010	B. Wiland
	R. Lynch's Master's Thesis	2012	R. Lynch
	LRGWQI Terms of Reference	2013	IBWC

IBWC, 2013. Terms of reference. United States-Mexico Joint Cooperative Actions in the Lower Rio Grande/Río Bravo River Basin.

Lynch, R.S., 2012. A GIS-based estimation of steady-state non-point source bacteria pollution in the Lower Rio Grande below Falcón Reservoir.

Wiland, B., 2010. LA-QUAL User's manual, prepared for Louisiana Department of Environmental Quality, Watershed Support Division.

Section 7. Glossary

BECC: Border Environmental Cooperation Commission

CEAT: Comisión Estatal del Agua de Tamaulipas

CILA: Comisión Internacional de Limites y Agua

Data object: An instance of a data structure or class

DSS: Decision support system

EPA: US Environmental Protection Agency

GIS: Geographic information system.

GUI: Graphic user interface

IBM Rational Rhapsody Modeler: An open-source, unified modeling language software for defining system requirement and software design

IBWC: International Boundary and Water Commission

LA-QUAL: A one-dimensional steady-state water quality modeling software package developed by the Watershed Support Division of the Louisiana Department of Environmental Quality

LRGWQI: Lower Rio Grande/Río Bravo Water Quality Initiative

PyQt: A python library for programming interactive software.

Python: A platform-independent, high-level programming language

Qgis: An open-source python-based GIS library.

TCEQ: Texas Commission on Environmental Quality

UML: Unified modeling language

UT-BEG: Bureau of Economic Geology at the University of Texas

Watershed: A surface area that drains into a river.

XML: Extensible Markup Language

Section 8. Revision History

Changes made to the Texas Project Delivery Framework SyRS template for this document.

Version	Date	Name	Description

APPENDIX E: LRGWQI SYSTEM DESIGN DESCRIPTION DOCUMENT

TEXAS PROJECT DELIVERY FRAMEWORK

SYSTEM DESIGN DESCRIPTION

[Texas Commission on Environmental Quality]

Decision Support System (DSS) for the Lower Rio Grande/Río Bravo Water Quality Initiative]

VERSION: [1.0] REVISION DATE: [NA]

Approver Name	Title	Signature	Date

Contents

Section 1. Introduction

1.1 Purpose

The purpose of this System Design Description (SyDD) is to present the top-level system architecture for the Decision Support System (the DSS hereafter) for Lower Rio Grande/Río Bravo Water Quality Initiative (LRGWQI). This SyDD identifies all components of hardware, software, and manual operations. In addition, it identifies system-wide design decisions, concept of execution, interface design, and requirements traceability to design components.

The intended audience is the TCEQ project manager.

1.2 Scope

The main scope of the DSS is to provide necessary software tools with graphic user interface (GUI) for LRGWQI partners to

(c) Develop point and nonpoint source loading scenarios

(d) Perform computer simulations

(b) Visualize modeling outputs for each scenario.

Here, a *scenario* may include the installment of wastewater treatment facilities or other sanitary infrastructures along Rio Grande/Río Bravo that can potentially improve water quality in river. Other examples include installation of collection lines and lift stations, repair of existing collection system components such as broken collection lines and leaking lift stations. Scenarios can also be created to model the effect of non-urban best management practices, such as keeping livestock and wildlife away from ditches, tributaries or the river itself.

The net effect of the scenarios described herein is to affect nonpoint source loading rate of a certain constituents at particular subbasins associated with river reaches to be modeled. The DSS does not directly calculate the effect some of the measures being modeled have on pollutant loading rates (e.g. improvements in wastewater collection systems). For these measures, it is a user's responsibility to supply the loading reduction factors expected from each measure.

The water quality modeling software underlying the DSS will be LA-QUAL, which is a steady-state, one-dimensional water quality simulation program that was developed by the Watershed Support Division of the Louisiana Department of Environmental Quality.

The role of the DSS GUI will be to facilitate and streamline the preparation of LA-QUAL input files. The user is assumed to be somewhat familiar with the LA-QUAL program and is expected to have relevant information available (see Section 2.6 in this document) before using the DSS. The LA-QUAL program itself will not be modified as part of this project.

Detailed functional requirements are provided in Section 3 of this document.

The LA-QUAL calibration effort is separate from DSS code development.

The DSS will be designed to be a standalone application to be downloaded (ftp site to be specified by TCEQ) and deployed on a Microsoft Windows-based system. The final product will be a self-contained installation file with all necessary components included. The development team will adopt a Python-based package for developing the GUI. Although the Python programming language, to be used for developing the DSS, is platform dependent, the development team will only test the functionality of the DSS on a Windows-based operating system (Windows 7, 32-bit) under the scope of this project.

Section 2. System Architecture

2.1 Architectural Design Approach

The DSS architectural design follows an object-oriented approach. First, the top-level system functionality groups identified under System Requirements Specification (SyRS) are translated into different subsystems. In the next step, the connection or communication among these subsystems are identified. The results are condensed in the form of a structural diagram.

2.2 Architecture Design

Figure 1 depicts the overall system architecture, which provides three subsystems.

Section 3. Data Dictionary

A data dictionary is discrete information describing the contents, format, and structure of a database or data system and the relationship between its elements. Within the context of this project, the data dictionary for the LRGWQIDSS is shown below.

DSS Components

GUI - provides an interface for the user to interact with the LA-QUAL program.

ModelFileHandling - provides the input-output support needed to manipulate LA-QUAL input files

LAQUAL Management - provides support to generate valid LA-QUAL input files

LAQUAL Exe - is the external LA-QUAL program executable

VisualManager - loads map files and enables simple GIS operations (i.e., displays lat/long)

Data Ports

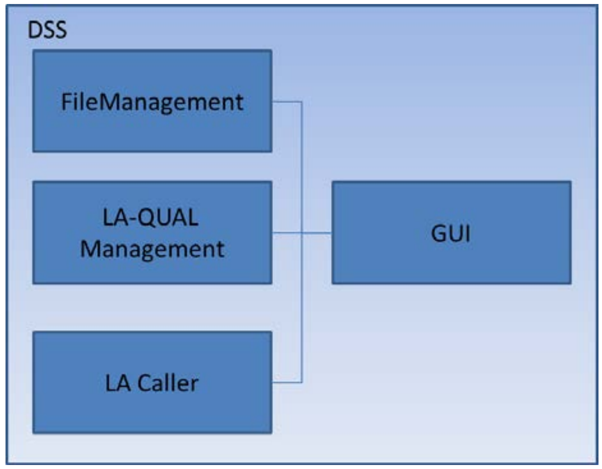
UI_req - provides event handler for GUI inputs

File_req - provides file handler for loading and parsing the LA-QUAL input files

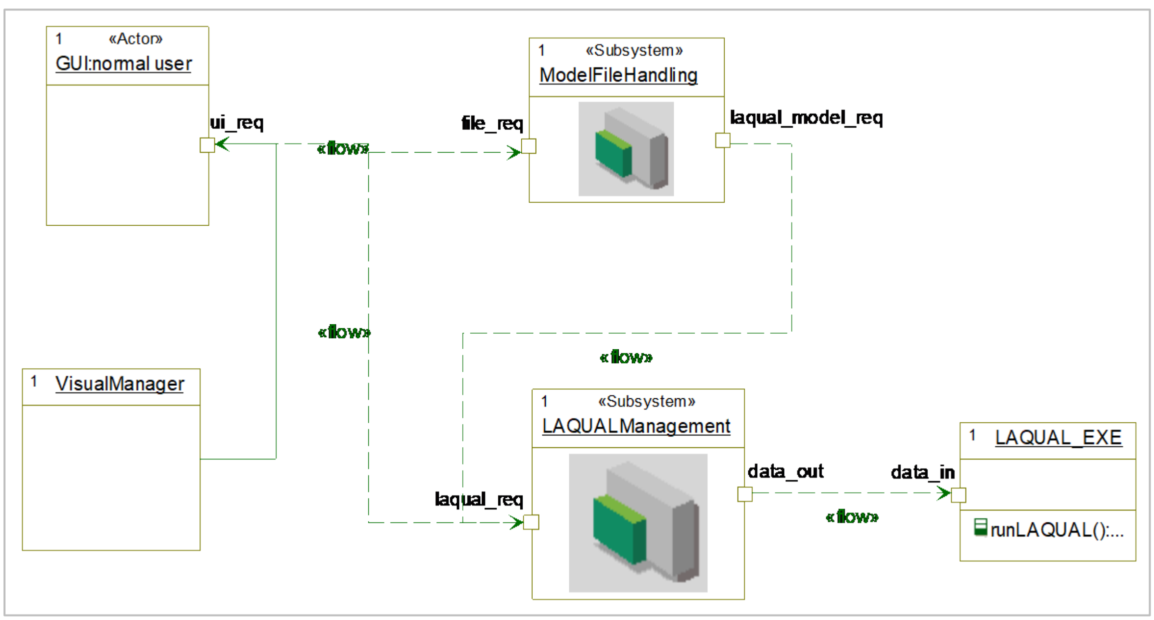
LAQUAL_model_req - populates the DSS GUI with information persisted in LA-QUAL model

Data_out - generates a valid LA-QUAL input file

Data_in - reads the LA-QUAL input file and executes LA-QUAL



(a)



(b)

Figure 1(a) Overall system architectural diagram; (b) structure diagram of system components.

Section 4. System Domain Design

4.1 System Domain Chart

The system domain chart is provided in the structural diagram given in Figure 1. Only one system domain is involved in this DSS.

4.2 System Domains

The system domains associated with the LRGWQIDSS are described below.

4.2.1 Domain DSS

Figure 2, below, provides a graphical representation of the overall LRGWQIDSS domain.

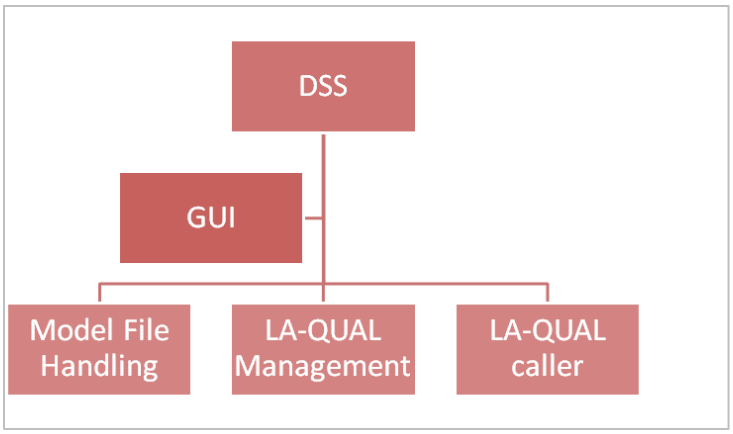


Figure 2. Overall system domain picture.

4.2.*1.1* The GUI of LRGWQIDSS

The GUI for the LRGWQIDSS provides an interface for the user to interact with the DSS.

4.2.*1.2* Model File Handling of the LRGWQIDSS

Model file handling - provides input-output support needed to manipulate LA-QUAL models

4.2.*1.3* LA-QUAL Management of DSS

LA-QUAL Management - provides support to generate valid LA-QUAL input files

4.2.*1.4* LA-QUAL Caller

Launches the external LA-QUAL program to run a user-generated LA-QUAL input file

Section 5. Data Design

This section describes the data contained in the data structures shared between design elements of the system design, including persistent/static data, transient/dynamic data, external interface data, and transformation of data.

5.1 Persistent/Static Data

5.1.1 Persistent/Static Data Store

Persistent or static data mean information that needs to be stored from disk or information that remain constants in a program. The persistent/static data store used by the DSS will be an XML file that maps the structure of the input to LA-QUAL. Internally, the data store will be an instance of LA-QUAL class, which is a data model encapsulating information content and structure of LA-QUAL input file. The watershed delineation file is an example of static data.

5.2 Transient/Dynamic Data

Transient data will be an in-memory data object that synchronizes with the user inputs from the GUI and is in a valid state at all times. The data object is an instance of the LA-QUAL class. This will be made possible by enforcing an error check each time a user changes parameter values through the GUI.

5.3 External Interface Data

The external interface's data design will reflect the modifiable portion of the LA-QUAL input. Examples include infrastructure features encapsulated in a scenario

5.4 Transformation of Data

Data transformation will be performed from GUI the form to the format required by the LA-QUAL input.

Section 6. User Interface Design

6.1 User Interface Design Overview

The GUI of the DSS orchestrates all user interactions associated with LA-QUAL modeling

6.2 User Interface Navigation Hierarchy

The diagram shown in Figure 3 depicts the navigation hierarchy and sequence of events/operations that originate from the GUI.

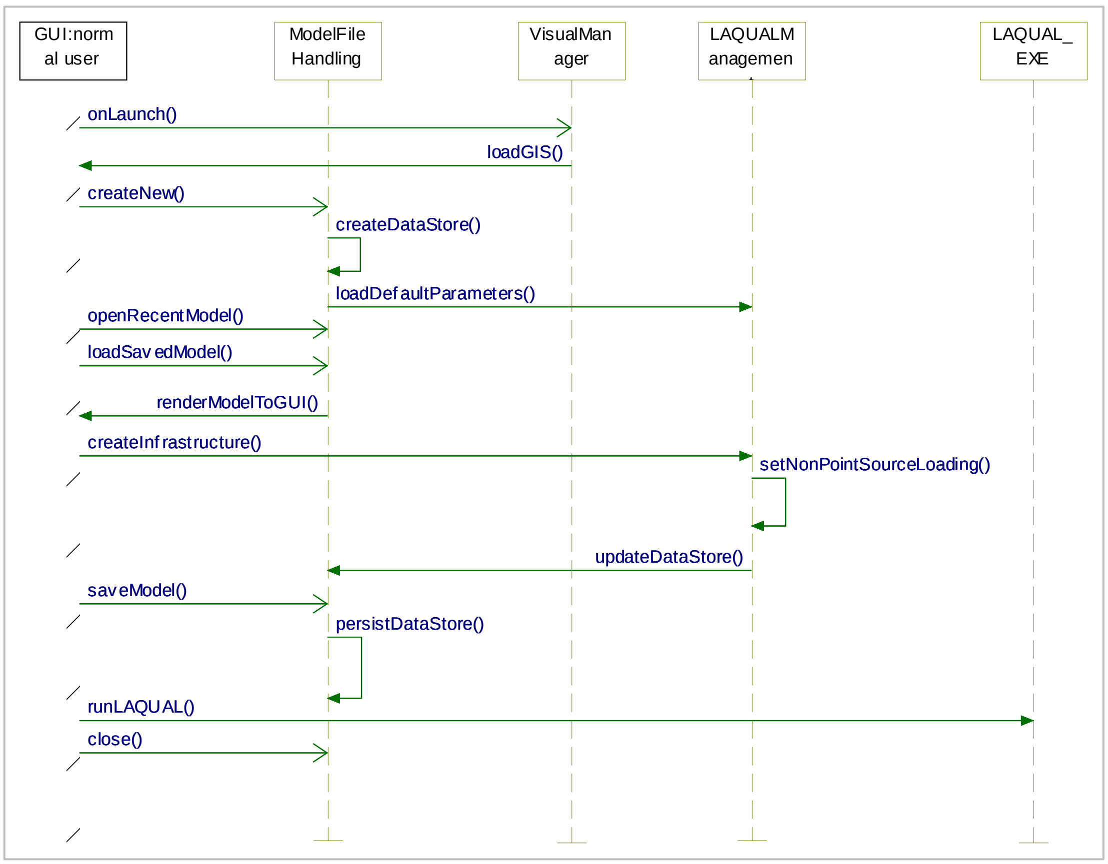


Figure 3. Sequence diagram of the DSS

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6.3 User Function Categories (or Use Cases)

This section documents each category of user function or use case addressed by the DSS GUI.

6.3.*1* Function (or Use Case)*: Model File handlers*

This group of functions supports the save/create/load activities associated with the LA-QUAL model.

6.3.*2* Function (or Use Case)*: Map handlers*

This group of functions supports the map display.

6.3.*3* Function (or Use Case)*: Scenario handlers*

This group of functions supports specification of point and nonpoint sources in a scenario.

6.3.*4* Function (or Use Case)*: Run handlers*

This group of functions supports launch of the external LA-QUAL executable.

Section 7. Other Interfaces

The DSS will be stand-alone software. The DSS interacts with LA-QUAL through the input file for LA-QUAL.

Section 8. Other Design Features

N/A

Section 9. Requirements Traceability Matrix

A Requirements Traceability Matrix indicates the traceability of the requirements documented in the SyRS document to the design elements documented in the SyDD. Table 1 provides a Requirements Traceability Matrix for major requirements listed in the SyRS document. A detailed functional requirement traceability list is given in SyRS document.

Table 1. Requirements traceability matrix between SyRS and SyDD (only the top-level requirements are listed).

Requirements		**Design Elements**
3.2.1	Model file handling	ModelFileHandler
3.2.2	GIS file handling	VisualManager
3.2.3	LA-QUAL handling	LA-QUAL Management

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Section 10. References

Document No.	Document Title	Date	Author
	LA-QUAL User's manual	2010	B. Wiland
	R. Lynch's Master's Thesis	2012	R. Lynch
	LRGWQI Terms of Reference	2013	IBWC

IBWC, 2013. Terms of reference. United States-Mexico Joint Cooperative Actions in the Lower Rio Grande/Río Bravo River Basin.

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Section 11. Glossary

Data Dictionary: provides discrete information describing the contents, format, and structure of a database or data system and the relationship between its elements

Data Object: An instance of a data structure or class

DSS: Decision support system

Event Handler: In computer programming, an event handler is a callback subroutine that handles inputs received in a program (e.g., GUI). Each event is a piece of application-level information from the underlying framework, typically a GUI.

GUI: Graphic user interface

LA-QUAL: A one-dimensional steady-state water quality modeling software package developed by the Watershed Support Division of the Louisiana Department of Environmental Quality

LA-QUAL Class: A class that encapsulates necessary data structures for LA-QUAL input file

LRGWQI: Lower Rio Grande/Río Bravo Water Quality Initiative

Python: A platform-independent, high-level programming language

SyDD: System design document

SyRS: System requirement document

System Domain: A group of modules/functions that collectively define and implement attributes and behaviors of a system. A system domain can interface with other domains and may consist of subdomains.

XML: Extensible Markup Language

TCEQ: Texas Commission on Environmental Quality

Section 12. Revision History

Identify changes to the System Design Description.

Version	Date	Name	Description

Section 13. Appendices

NA

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