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Development of Lower Rio Grande River Water Quality Transportation Numerical Model for Bi-National River Management

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DEVELOPMENT OF LOWER RIO GRANDE RIVER WATER QUALITY TRANSPORTATION NUMERICAL MODEL FOR BI-NATIONAL RIVER MANAGEMENT

A Thesis

by

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ABSTRACT

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Traditionally, water quality modelling has focused on modelling individual water bodies. However, water quality management problems must be analyzed at the larger scale to include influences from various water bodies that are interconnected. This paper provides a study on the hydrologic and quality transportation calculation by developing a hydrodynamic (unsteady state) channel routing model using a water-balanced approach. A one dimension Lagrangian river model was developed and applied to the 210 plus miles for the lower Rio Grande River Basin from the Falcon Dam to the head water of Brownsville that pours onto the Gulf of Mexico. This model can provide insight of on management options that can identify improvements of watershed health, flood potential, and agricultural impact of the Lower Rio Grande. The results of the modeling study exhibited variable responses of analysis of quality and temporal water transportation can assess the impact of seasonal changes within that water and their effect on possible contaminants. The resulting simulations can provide better management options that can reduce the impact of the agro-environment and wastewater effluents within the river for a better sustainable future.

DEDICATION

The completion of my master's degree would not have been possible without the love and support of my family and friends. My sister, Brenda Gonzalez, always supported me all while having a family of her own, my father, Matilde Gonzalez, making sure I'd pursuit goals higher than his own, and my bother-in-law, Ariel Moreno, for always helping me out whenever I'd needed it. A special dedication to my mother, Alicia Posada, and big brother, Leonardo Gonzalez, the only reason I am doing all of this, wherever both of you are, I hope I made you proud.

ACKNOWLEDGMENTS

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CHAPTER I

INTRODUCTION

The Lower Rio Grande River (LRG) is not only a barrier to another country, but is a main source of water for the LRGV of Texas and northern Mexico. A series of interconnected outflow waterways make up the LRG dynamic structure during flooding conditions. An outflow is an area along the main channel where water is diverted out of the system and through another stream channel. These outflows are stationed along the LRG and are positioned to maintain equilibrium for various flow conditions. The best way to study the hydraulics of LRG during flooding conditions in detail is by developing a hydrodynamic (unsteady state) channel routing model. By developing a hydrodynamic channel routing model and nutrient transportation model, many attributes of the LRG can be identified and used for management and planning purposes for local entities. The Lower Rio Grande Basin is comprised of the Falcon Dam, a dam on the Rio Grande between Starr County in the U.S. state of Texas and the city of Nueva Ciudad Guerrero in the Mexican state of Tamaulipas extends along the U.S./Mexico border, to the Gulf of Mexico. As the Rio Grande is the fifth largest river in North America, it forms an International Boundary between the United States and Mexico for a 1200 mile distance from its source in the Colorado. Its main source of water inflow are Río Conchos from Mexico, and the Pecos River from the United States. (USBR, 2013) The Amistad-Falcon Reservoir System contributes as a water resource for South Texas as assigned by the Texas Water Development

Board. The Falcon Reservoir is about 275 miles upstream of the Gulf of Mexico, providing the source of water for the Lower Rio Grande River of a drainage area of approximately 13,000 square miles, near Rio Grande City, Texas. The size of the Lower Rio Grande Basin is 54,000 square miles, of which 8,100 square miles of the section, or sub-basins, do not contribute any water flow to the River basin. The Falcon International Reservoir has storage for over 8.0 million acre-feet of water that is controlled by both the United States and Mexico, where it has a designated purpose of 2.25 million acre-feet for flood control purposes while 6.05 million acre-feet are reserved for water supply. (Carter et.2015), Seelke, Shedd, 2015)

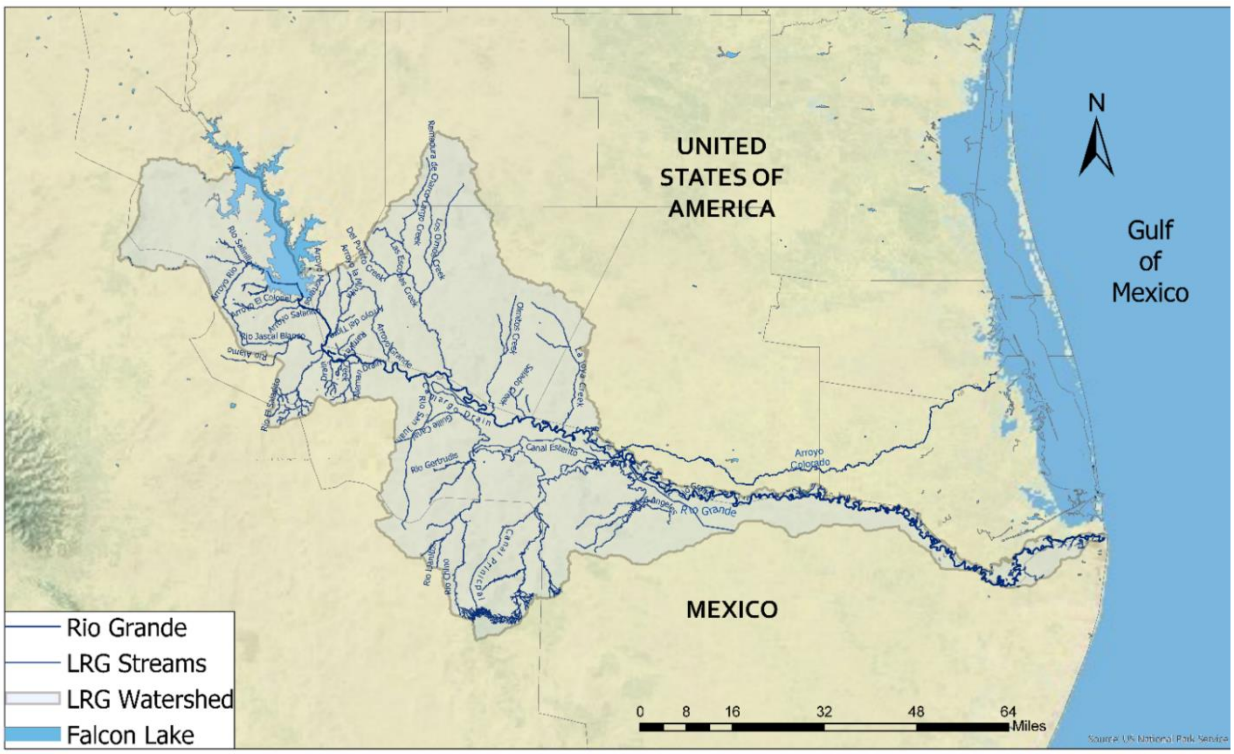

Figure 1 Lower Rio Grande watershed and tributaries

The United States and México collaborate in the preservation of the quantity and quality of the international river system, the Rio Grande/ Río Bravo. Both countries have established international treaties that govern the quantity of water each country must give and take as well as the joint standards for the quality of the river, which is important for the people and wildlife that use the water. This is why the federal and state environmental agencies in both the U.S. and Mexico are participating in recent years on a binational study for the Lower Rio Grande/Río Bravo called the Watershed Initiative, a binational pilot project to develop a plan to restore and protect the quality of the Rio Grande/Río Bravo.

The extend of the current initiative focuses on the Rio Grande River below Falcón Reservoir to the Gulf of Mexico, in order to create plans that will protect the watersheds surrounding them. In order to monitor the overall quality of the water it is necessary to understand both the pollution sources and the pollution travel throughout the river, which involves modeling the river. This model must be created with the standards and equations that are acceptable for both of the countries; this would involve the need of a model that is able to quantify the volume and quality of the river. This binational study will then need to include the consideration for a variability of unsteady-flows that would consider the low and high flow conditions that a river might experience. Although steady-state models are used frequently for point sources, stationary sources of pollution such as wastewater treatment plants that produce a constant flow of contaminated water, such models rarely account for non-point sources of pollution that are not attributable to a single source. This study will develop an estimation of the non-point source pollution that enters the Rio Grande/Río Bravo below Falcón Reservoir on a unsteady-state basis in order to assist in the development of the Initiative's water quality of model of pollution attributable to non-point sources to address the agro-environmental impacts within the Lower Rio Grande.

Development of a numerical model would build fundamental insights about the effect of a critical hydraulic control on nutrient concentrations, where the various flows would be a feature to study as the flow of the water of normalized conditions, along with high flow conditions. Under the critical flows, nutrient concentrations would not vary drastically as their effect of sink/advection, advection would stabilize compared to a high velocity mass transportation, and would be influenced by the surrounding area and atmospheric conditions (Etzold, S, et. al., 2010) Normalized flows will study the overall travel time along with the dispersion influence of different water velocities that influence the mixing of nutrient that affect the concentrations along the river. The interrelationship between the nutrient concentration, dispersion, water temperature, and time affect both the nutrient transportation and biological make-up of the water, as the relationship between nitrogen, orthophosphate and algae concentrations, as algae can multiply quickly in waterways with an overabundance of nitrogen and orthophosphate (Brunn, 2012).

The current agricultural setting for the Lower Rio Grande demands and uses water with the Rio Grande River, from which quality and hydraulic interrelationships have not been extensively studied. This bring a need to find the potential and impacted quality of the water resource within the river in order to the impact of the agricultural community within the river, a necessity for both its production and effects of nutrient loadings within the river. The effects for the water basin can be seen on various conditional aspects a growing population and need for agriculture. Changes in surface flows and land use conditions have direct effect on the downstream in the form of floods and/or water quality deterioration. Human interferences from a growing population and the changes in seasonal temperature/conditions could lead to temporal variations such as water quantity and quality. This issue is amongst the most important aspect for a bi-national river, where the ecological conditions affect the different management systems the both countries individually manage affects their respective economies (Mroczkowski, M., 1997). The complexity here on lies on the management method of the river both countries, where the overall water impact can be studied, water can be shared, and both can benefit. This complex relation creates a need to create a mathematical method and tool to analyze the information, compute related interrelation processes, and investigate the potential impacts that would create an informational decision on the way the river can be managed.

Using a one-dimensional river analysis program of Hydraulic Engineering Center River Analysis System (HEC-RAS), developed by the US Department of Defense, Army Corps of Engineers, a numerical model can compute steady and unsteady flow hydraulics, heat budget, water sink/advection, and nutrient dispersion to use as a tool to study the transportation of nutrients within the reach. The model solves the one-dimensional advection-dispersion equation water quality model implementing the principle of mass conservation using a control volume approach with a fully implemented heat energy budget (Lowney, 2010)

1.1 Background

Due to the increment of human interference as a source of water and other developments in Colorado, New Mexico and West Texas, the Rio Grande runs dry South of El Paso during much of the year. Lower Rio Grande Basin's climate is semi-dry that brings a somewhat barren condition to support vegetation. The estimated amount of precipitation that does fall within that reaches the Rio Grande is about four percent, where any runoff provided only caused by a temporary excess watershed loss of infiltration and evaporation during heavy rainfall. (USBR, 2013) The contribution of heavy precipitation are generally caused by storms and tropical occurrences creates various storm hydrographs to work with, but the rainfall amounts are lowered the farther away the travel from the Gulf of Mexico.

The complexity of accounting the social, economic, and environmental aspects into a modeling framework is a big feat, but the evaluation of hydraulic and quality impacts of such model far outweighs the work needed to be done. Management of the binational river can bring in advantages to both countries where policies and treaties can be created based on the watershed hydraulic patterns and water quality. The relationship between the daily total precipitation, the wastewater discharge, and nutrient loadings provided by inflows to the large cities and communities can be integrated in order to monitor and forecast. A model that accounts for scientific quantifications that is based on hydraulic, temporal, and at a spatial scale can identify a simple wastewater management solution rather than spot and one time sampling of the river and effluents.

The importance of assessing the binational quality problem must be highly regarded, where if the biological makeup of the water were to be greatly deteriorated; bacterial, high water temporal changes, high nutrient concentrations can affect the fish and people in contact with the water. As mentioned beforehand, the excess agricultural impact of the Lower Rio Grande Valley and growing population creates large amounts of discharge of waste material into a river. This is why modeling the river's hydraulics and river quality could address the management problem in which it can provide planning for amount and distribution of water pollutants. Modeling the river's characteristics involves the changes of water volume, transportation and advection of pollutants, heat exchange between the river and the atmosphere that affect the biochemical reactions, and the overall flocculation of quality parameters. Mathematically, the processes involved in the previously described aspects, mainly consist of a hydraulic model used for advection and dispersion, temporal model that computes the river temperature, and the biochemical effect from the hydraulics and temperature changes. The challenges involved in creating such model are in recreating the physical aspects that are computationally sound and institutionally realistic in order to be used as a decision model for analyzing and evaluating as a water management tool. Such model that is used for water resources management takes advantage of distributed hydrologic simulation modeling along with a coordinated decision model (McDonnell, et al. 2014). With a coordinated model allows the modeler to integrate the intrinsic actual hydraulic computations in order to create a decision making tool and coordination of individual aspects, such as that of quality transportation. In such a case, if the creation of operation of multiple wastewater facilities and their effluent needs a coordinated, a tool can be designed to improve coordination of effluent performance associated with operations.

To understand the complex interactions of these factors and make informed decisions regarding stream ecosystem management, natural resource managers can use computer simulations to water transportation. Regression models have the advantage of being computationally simple and applicable to locations where streamflow data is available. While regression modeling can be used effectively to predict water flows at discrete locations, they have problems when trying to project empirical relationships into the future or to locations where measurements were not actually made (Liu, L., & Xu, Z., 2015). This level of predictive capability calls for a deterministic model that represents the processes influencing water flow in a realistic manner. In order to understand the influences upon the water flow, a water-balance between the main stem of the river and tributaries and irrigation channels diversions must be applied. With the use of drainage canals that were obtained from a digital elevation model (DEM) was obtained from the United States Geological Survey for automated GIS (Geographic Information System) and the canals delineations were obtained. River sections were obtained and identified to obtain the cross-sectional structure that would be the basis for the geometric files.

Table 1: Breached Banks cross-sections in LRG

Beginning RS of Breached Location	End RS of Breached Location	Country of Breach
Falcon Dam (RS 416280)	Rio Grande City (RS 346000)	U.S. & Mexico
Los Ebanos (RS 299820.1)	Anzalduas Dam (RS 238300)	U.S. & Mexico
Anzalduas Dam (RS 238300)	Retamal Dam (RS 175925)	U.S. & Mexico
Gateway Bridge (RS 45425.97)	Gateway Bridge (RS 45412.9)	U.S. & Mexico
Matamoros, MX (RS 35536.7)	Matamoros, MX (RS 35021.6)	Mexico
Brownsville (RS 13633.78)	End of Reach (RS 414.206)	U.S. & Mexico

Spatial variable data for the lower Rio Grande and its floodplain include a wide array of topographical, geomorphological, hydrographical data sets. The available data includes detailed digital terrain models (DEM), topographic mapping, field survey data such as river cross sections. These data bases have been incorporated into the 1-D data input files. HEC-RAS has the flood routing capability to account for spatial variation and as more detailed floodplain data sets become available, the model resolution and accuracy will improve.

Steady and unsteady state flow modeling can help establish a modeling stream system endpoints, i.e., upstream and downstream. Water surface profile computations begin upstream for subcritical flow or downstream for supercritical flow (Brunner, 2000). Soluble dye or chemical, tracers have been commonly used in stream tracer investigations (Hubbard et al. 1982; Jobson 1996, 1997). Since the mid-1960s, numerous dye tracer studies have been performed on streams in the United States for travel time studies. For example, in a study of travel-times, Jobson (1997) analyzed tracer data from nearly a thousand sub reaches of United States streams. However, the values used with these methodologies can be uncalibrated estimates for travel time studies (Hubbard et al. 1982).The IBWC-US Section occasionally measures current velocities in the Lower Rio Grande/Rio Bravo using Acoustic Doppler Current Profilers, but these measurements are scattered and infrequent can provide only snapshots of velocity at single points in the river at random flow conditions. Nevertheless this data could be used to perform some level of hydraulic calibration for travel time studies, but according to TCEQ (2015), reliable data of this type is either lacking within frequent years, or data has not been an official statement on their reliability.

1.2 Modeling Purpose and Objective

The main objective of this study is to contribute to a better understanding on the hydrodynamics of the river and implement a model that computes nutrition transportation that can be used as management strategy for future waste load management for the lower Rio Grande. This may fall into various strategies such as promoting elevation stability, alignment stability, maintaining channel capacity, and managing water supply to reaches based on the association between a hydraulic and hydrologic model for a comprehensible model for flow to estimate travel time and implement nutrient loading to forecast transportation along the river. To identify reaches with the highest potential to incorporate these strategies a one-dimensional (1-D) hydrologic model. This study will focus on the 1D model in which the channel adjustments are made in the vertical with no change in width or channel alignment done by calibration for flow to estimate travel time of the Lower Rio Grande using one dimensional channel dynamic routing model.

CHAPTER II

MODELING PLAN

The determination of travel times, streamflow velocities, and a transportation of nutrition that consider longitudinal dispersion rates for a reach is necessary for various unsteady streamflow conditions. Predicting the effect of a mass transportation on the downstream water quality is a complex problem. The accurate modeling of travel time requires accurate modeling of transport that can be obtained by various methodologies such as: a Lagrangian model and Eulerian models, but the often suffer from numerical diffusion. Devkota and Imberger (2009) reviewed various Lagrangian and semi-Lagrangian models (Fischer, 1972, Manson et al., 2001). The drawbacks of these models were that these were not coupled with the Lagrangian flow and transport; instead they used an externally supplied reach average velocity field at fixed Eulerian grid points to drive the pollutants further and faster downstream of the river. While others have studied the possibility of using velocity-prediction equations where the main drive is using the mean river velocity as variable to calculate the travel time, but have been inaccurate at with velocities (Graf 1986; Jobson 1997). Predicting the effect of a pollutant spill may be dependent on the ability to predict the speed of movement downstream and the rate of longitudinal mixing. An optimal way to study the effect of mixing and distribution is to obtain the time of travel for a hydraulic output. However the results may vary with the use only limited to a flow condition that exists within the margin of an existent flow condition. This study plan to consider the use of extrapolating the travel time of water from the Rio Grande River from a high to low within flow bank.

The use of a one-dimensional dynamic channel routing and the development of the numerical model would build fundamental insights about the effect of a hydraulic control on nutrient concentrations disperse, where the flow would be a feature to study as the flow of the water of a normal condition would not flush out the concentrations of nutrients to study the effect of water transportation. With the use of a one dimensional model there would be an inclusion of a channel morphology, where the cross-sectional river mean velocity would be the factor that controls the travel time. Unfortunately the estimation of a mean cross-section velocity within a long reach has been studied before as being a difficult feat, where the measurement of travel time through a river is usually limited to various techniques, instead of dye injection being the most prevalent (Kilpatrick and Wilson, 1989). The (USGS) has conducted various travel time studies where there has been various equation have been proposed for the prediction of velocities, but all of having a poor prediction accuracy (Jobson, 1996). At the existent river discharge, the travel time study tries to give an accurate measurement for the average reach water velocity, but because the velocity varies there has to be an extrapolation of velocity from flow to another. Within this study we will explore the possibility of applying the principals of geometric morphology and the uniform unsteady flow distribution to predict the water velocity of a varying discharges. This would include an analysis of the flow data to determine streamflow velocities and longitudinal dispersion rates, and comparisons of the data to estimates from the transportation study developed Texas Commission of Environmental Quality.

2.1 Hydrologic Modeling Plan

In this study the development of a numerical model was used to build fundamental insights about the effect of a critical hydrologic control on nutrient concentrations, where the flow would be a feature to study as the flow of the water of a normal condition would not flush out the concentrations of nutrients to study the effect of water transportation. Using a one-dimensional river analysis program of Hydraulic Engineering Center River Analysis System (HEC-RAS), the use of one-dimensional advection-dispersion equation water model implementing the principle of mass conservation using a control volume approach. (HEC-RAS, 2010). The use for the hydrologic approaches the use of the principle of conservation of mass as a change in volume of water over the channel reach with a linear approach to discharge with the storage-continuity equation. This would have the need to determine the hydrologic parameters of recorded data for the dates of simulation (January 2006 to December 2010) of both upstream and downstream sections of the river.

Observed inflow and outflow hydrographs can be used to compute channel storage by an inverse process of flood routing. When both inflow and outflow are known, the change in storage can be computed, and from that a storage vs. outflow function can be developed. In order to have a water balance volume and flow changes must be estimated accurately for the reach, that is why a calibration can be done to the hydraulic parameters, as flow velocities are generally higher at higher flows. This can be done the inclusion of tributary inflow and outflow must also be accounted for in this calculation. The inflow and outflow hydrographs can also be used to compute routing criteria through a process of iteration in which an initial set of routing criteria is assumed, the inflow hydrograph is routed, and the results are evaluated. The process is repeated if necessary until a suitable fit of the routed and observed hydrograph is obtained.

2.2 Nutrient Qualitative Modeling Plan

Development of a numerical model would build fundamental insights about the effect of a critical hydraulic control on nutrient concentrations, where the dominant flow would be a feature to study as the flow of the water of a normal condition would not flush out the concentrations of nutrients to study the effect of nutrient transportation. Under the critical flows, nutrient concentrations would not vary drastically as their effect of sink/advection, advection would stabilize compared to a high velocity mass transportation, and would be influenced by the surrounding area and atmospheric conditions (Buchmann, et. al. 2010). The interrelationship between the nutrient concentration, dispersion, water temperature, and time affect both the nutrient transportation and biological make-up of the water, as the relationship between nitrogen, orthophosphate and algae concentrations, as algae can multiply quickly in waterways with an overabundance of nitrogen and orthophosphate (Brunn, 2012). The numerical model can compute steady and unsteady flow hydraulics, heat budget, water sink/advection, and nutrient dispersion to use as a tool to study the transportation of nutrients within the reach. The model solves the one-dimensional advection-dispersion equation water quality model implementing the principle of mass conservation using a control volume approach with a fully implemented heat energy budget (Lowney, 2010). By introducing the nutrient parameters into the system, the model takes into account rate constants for physical and chemical reactions that control the sours and sink in advection dispersion as seen in the following equation:

$$\frac{\partial}{\partial t}(V\phi) = -\frac{\partial}{\partial x}(Q\phi)\Delta x + \frac{\partial}{\partial x}\left(\Gamma A \frac{\partial \phi}{\partial x}\right)\Delta x \pm S \tag{1}$$

where V is the volume of the water (m^3), ϕ is water temperature (^oC) or concentration (kg/m^3), Q is flow (m^3/s), Γ is independently defined dispersion coefficient (m2/ s), A is cross-sectional area (m^2), and S is source and sinks (kg/s).

The equation requires that if there is a source of mass at a location, the mass being introduced must be accounted for. All to which the nutrients are subjectable to the flow present at simulated time and heavily influenced by temperature changes within the water that affect their chemical properties. Before going any further, it is important to note that many, if not all of the records used for the quality transport model was obtained from the Texas Commission of Environmental Quality and their subsidiaries, with the exemption of weather data that were obtained from both the NOAA and Undergroundweather.com. The nutrient computation is designed to conduct aquatic water quality computation with simplified processes and minimum state variables. It simulates carbonaceous biological oxygen demand (CBOD), dissolved oxygen (DO), amplified nitrogen and phosphorus cycles, which resulted in organic nitrogen (OrgN), ammonia (NH4), nitrate (NO2), nitrite (NO3), organic phosphorus (OrgP), and total inorganic phosphorus (PO4), and algae (Alg) and benthic algae biomass as additional state variables. The model simulated Lower Rio Grande River critical inflow density distribution, and overall exchange of nutrients stimulated by the heat budget to study, compare, and calculate nutrient dispersion/distribution, spatial and temporal trends in modeled water quality constituents.

2.3 Data Acquisition

For an unsteady state modeling, a flow that will be applied to 201 miles reach of the Lower Rio Grande. Various dates of high flow times were chosen to seek the effect of nutrient transportation within the river. The goal of the project is to design a seasonal high flow hydrograph that will inundate selected areas of the floodplain in this reach. Through the information obtained by the International Boundary Water Commission (IBWC) the FLO-2D model provided a hydrograph of various high flow sates within the river that extends from Falcon Dam to Progresso. One flow hydrograph will be simulated while three other can be based as a control for a comparative flow to the simulated flow: 6 month average hydrograph located at Falcon Dam, Anzalduas, and Progresso.

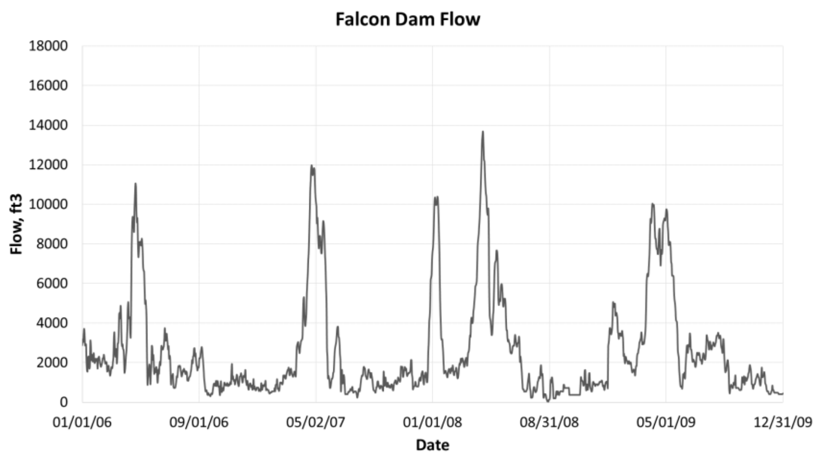

Figure 2 LRG River Flow Hydrograph at downstream of the Falcon Dam

It is important part of this project to have an implementation to existing data bases for a base control. In several locations along this reach, the water surface elevation may be foot below the top-of-bank. This channel bed response is difficult to predict because it depends on sediment supply as well as flow hydraulics. Generally, the volume of the water stored in the river at a given time is relatively minor compared to the total volume in the flood hydrograph. While the existing the model has relatively large grid elements, it is sufficiently detailed and accurate to conduct flood studies for a variety of projects such as levee design, river restoration, hydrograph routing, and flood inundation. The model will provide accurate estimates of in-channel discharge, area of inundation and water surface elevations. Estimated water losses include inflow and diversion flow from the channel and floodplain. This paper discusses model development, new components, calibration and applications.

The quality transport model implements the use of nearest meteorological station in order to model the water temperature changes over time (USACE, 2010). Weather data for the reach were assembled from a variety of surrounding gauge stations that were obtained online. The information collected from the National Weather Service and NOAA provides a general insight about the weather conditions for the model reach for the section of the Lower Rio Grande Valley, where the study section is located. The program requires a set of meteorological data must consist of: atmospheric pressure; air temperature; humidity; solar radiation; wind speed; and cloudiness, to provide the influence of outside sources to the water in net heat flux exchange between the atmosphere and the water. The projected area of heat will be exchange over an interface between the water and the outside atmosphere, the interface is contracted over the surface area of the water or a specific water cell surface area.

$$q_{net} = q_{sw} + q_{atm} - q_b + q_{h-} - q_1 \qquad (2)$$

where: q_{net} = Net heat flux; qsw = solar radiation (joules/m^2/sec), q_{atm} = atmospheric longwave radiation (joules/m^2/sec), q_b = back upwelling longwave radiation (joules/m^2/sec), q_h = sensible heat (joules/m^2/sec), q_l = latent heat (joules/m^2/sec) (USACE, 2010)

The Hydrologic Engineering Center recommends the use of nearest meteorological station in order to model the water temperature changes over time (USACE, 2010). Weather data for the reach were assembled from a variety of surrounding gauge stations that were obtained online and shown in **Fig.3-7.**

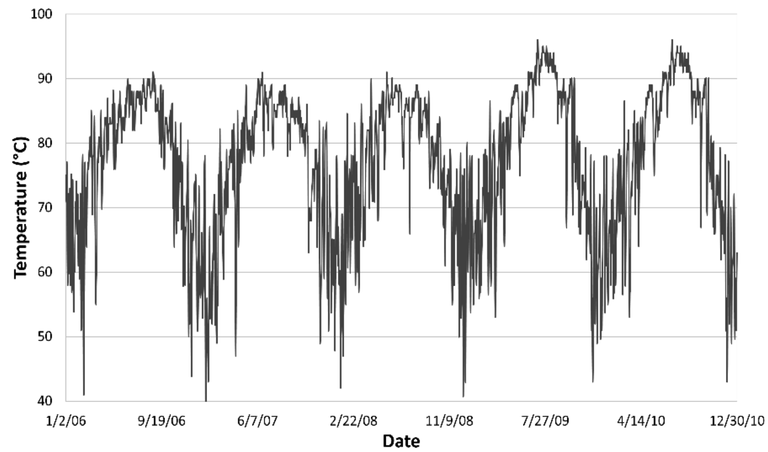

Figure 3 Time series of daily air temperature

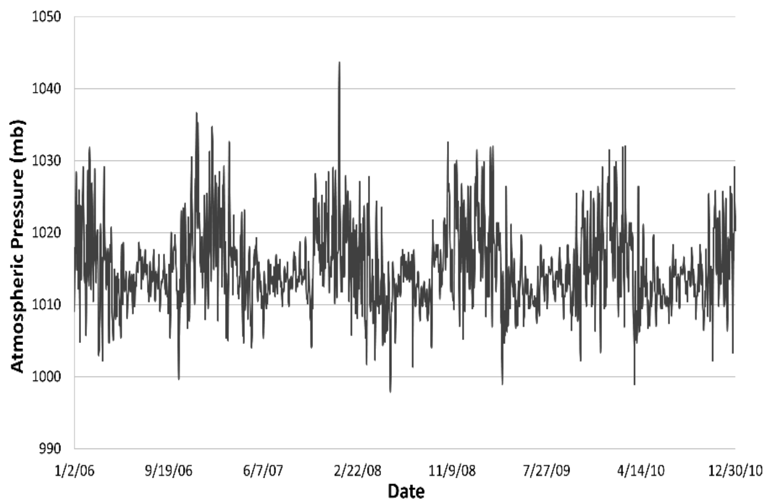

Figure 4 Time series of daily atmospheric pressure

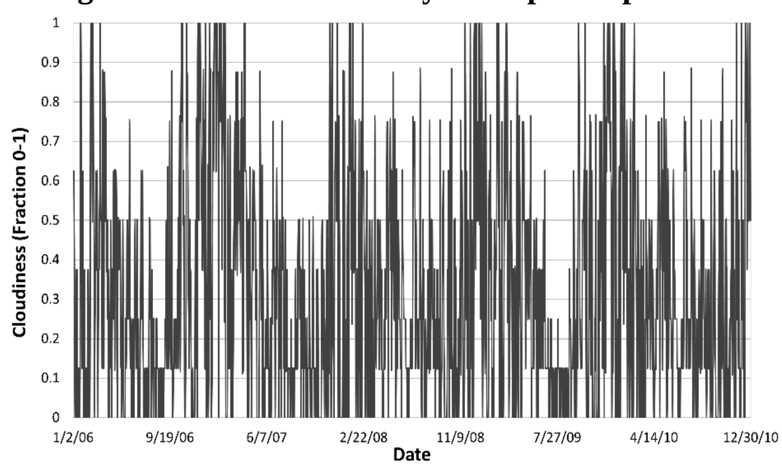

Figure 5 Time series of daily cloudiness

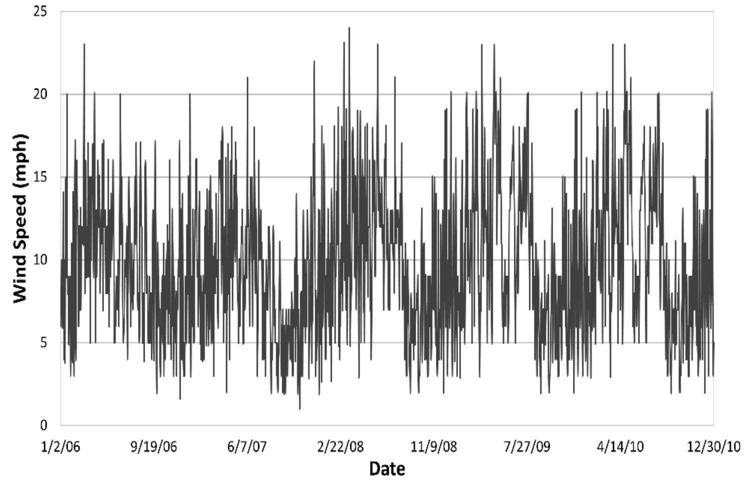

Figure 6 Time series of daily wind

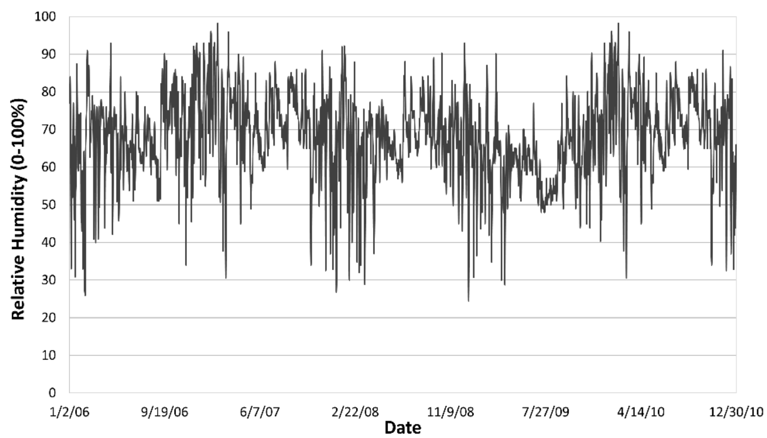

Figure 7 Time series of daily relative humidity

Atmospheric pressure is a strong function of elevation and varies with local meteorology, where it generally decreases with increasing altitude. The atmospheric pressure is entered as millibars (mb), with a span of six years. Air temperature is imputed in Celsius, is a measure of the hotness or coldness of the air. Humidity, is required input for the water temperature, imputed as relative humidity in percentage. Relative humidity is the ratio of moisture in the air to the maximum amount of moisture the air can hold. Solar radiation is the radiation received from the sun and emitted in the spectral wavelengths less than 4 microns. Solar radiation was available from a local weather station. Internal calculations are performed in W/m^2. Cloudiness, shown in the fraction of sky covered with clouds. An increase in cloudiness leads to a decrease in computed solar radiation and an increase in computer down welling longwave radiation. Wind speed, the measure the wind that is factored in with evaporation of water alongside with pressure. Wind is a necessary parameter for surface flux estimation. Collectively these results will projected and computed over an area of heat will be exchange over an interface between the water and the outside atmosphere.

CHAPTER III

HYDROLOGIC MODEL

The first order of the study for hydrologic modeling will be the creation of the river cross-sections in order to create the hydrodynamic channel routing modeling to perform a simulation of a life like hydrologic events, such as the hydraulics of a river, dam breach, or other natural disasters. It is a representation of the motion of water through a channel. The model recommends using a time period that starts at a low flow then gradually increasing to a peak flow then receding back to a smaller flow. This recommendation helps with keeping the model from going unstable and potentially causing errors in calculations. The time period for this study is January, 2006 through December, 2010. The study period was determined because of flooding in the surrounding areas of South Texas and northern Mexico along the LRG and the high flow rates that were measured during this time period. Geometric data from IBWC's 2003 study was used to develop the LRG reach from Falcon Dam, Texas stretching into Brownsville, Texas (as seen in figure 1 from left to right).

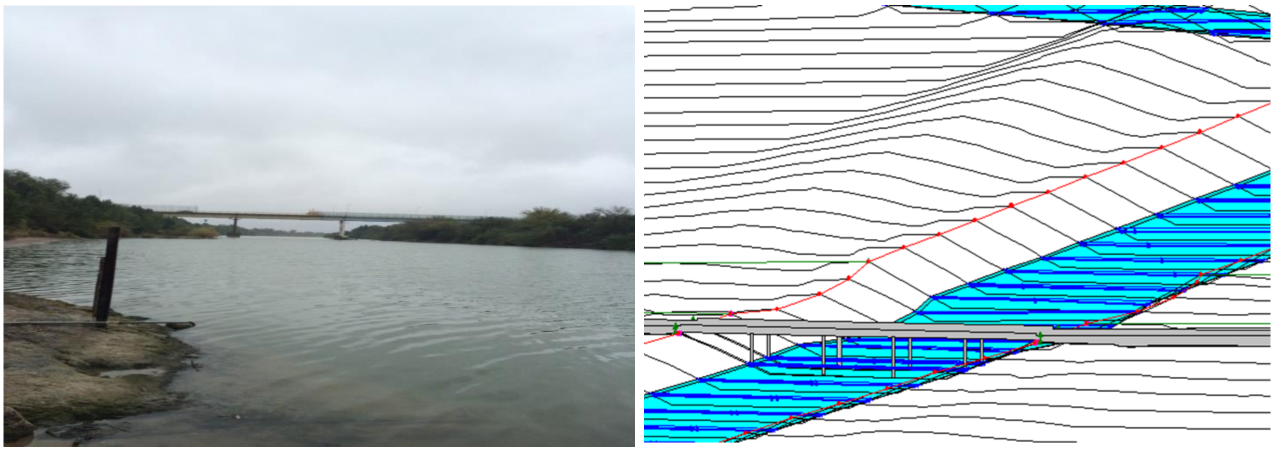

Figure 8 Rio Grande City International Bridge and its Cross-sectional representation in HEC-RAS

Cross-sectional information for the drainage canals were obtained from a digital elevation model (DEM) was obtained from the United States Geological Survey for automated GIS (Geographic Information System) and the canals delineations were obtained. River sections were obtained and identified to obtain the cross-sectional structure that would be the basis for the geometric files as previously seen in Table 1 for a total of 2042 cross-sections. Longitudinal segments with vertical layers in each segment obtained by the DEM data. Water surface elevations at each individual segment were to represent the overall distribution of water caused by the critical inflow of the upper-most section at a steady-state condition. During each individual normal profile computation, fundamental hydraulic properties of the flow, wetted area, average velocity, the Froude number for each cross-section are computed.

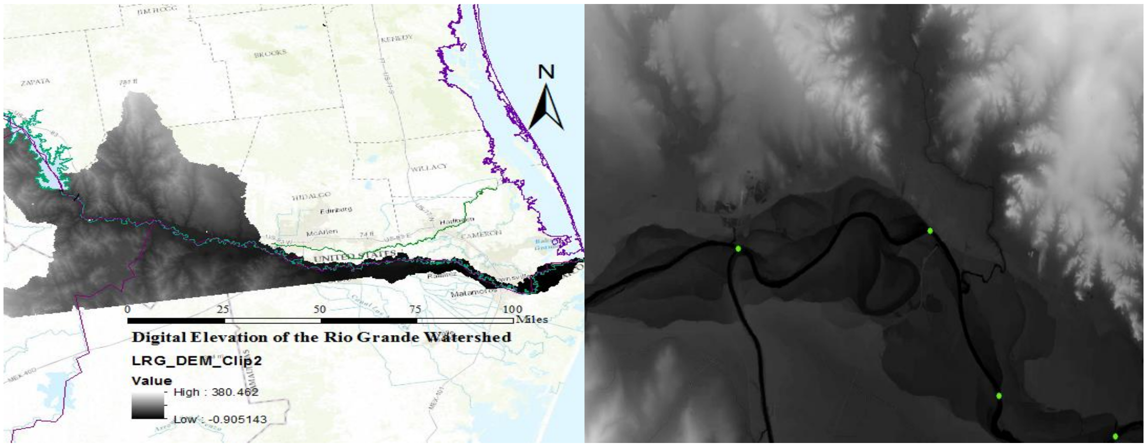

Figure 9 Rio Grande Watershed clipped over elevation model along with a close up within the river cross-section

3.1 Hydrologic Model Implementation

Dataset consisted of river morphology was provided information on the topography of the land surface and the gradient of the river, supplied information on the elevations, structures, and distances was acquired concurrent binational hydrography data set developed through a cooperative effort between the United States Geological Survey (USGS) and Mexico's Instituto Nacional de Estadística y Geografía e Informática (INEGI). The locations include major confluences of tributaries and drains to the river, major diversion points such as diversion dams, irrigation pumps, wastewater outfalls, historical and synoptic water quality monitoring stations, and flow gages. Major lateral structures were models for three locations; Anzalduas Canal, U.S. Floodway, and Mexican Floodway, along the LRG. The starting point of the upstream river station (RS) is labeled as 416280 where the ending of the most downstream RS is labeled 414.27as seen in **Fig. 1**.

Channel flow is simulated one-dimensionally with the channel geometry represented by either by natural shaped, rectangular or trapezoidal cross sections. Secondary currents, elevation in bends and vertical velocity distribution are computed by the channel component. Local flow hydraulics such as hydraulic jumps and flow around bridge piers are also not simulated with the model. The model does distinguish between subcritical and supercritical flow because the momentum equation is used and it has no restrictions when computing the transition between the flow regimes. Channel overbank flow is computed when the channel capacity is exceeded. An interface routine calculates the channel to floodplain discharge exchange including return flow to the channel. Once the flow overtops the channel, it will disperse to other overland grid elements based on topography, roughness and obstructions.

The equation of motion is solved by computing the average flow velocity across a grid element boundary one direction at a time. Each velocity computation is essentially one-dimensional in nature and is solved independently of the other directions. The individual pressure, friction, convective and local acceleration components in the momentum equation are retained. More discussion of model solution and constitutive equations is presented in the study. The goal is to correlate a calibrated hydrologic the model to that of theory based, numerical calculation, and simplistic travel time calculation to predict the travel-time velocity.

The calculation of velocity used are used in sites adjacent to each other, so the travel time can be considered the time it takes for water to travel from each upstream sampling site to an adjacent downstream sampling site. The travel time, is calculated by taking the distance traveled and dividing it by the velocity of the river. The velocity of the river was not directly measured, but can be estimated from flow rate measurements using various equations based on control measured flows, and compared to model computations. The following relationship seems to be a generally accepted form for relating velocity to flow:

$$V = aQ^b \tag{3}$$

where is the velocity (m/s), are the coefficients, and Q is the flow (m3/s).

This relationship is used in the QUAL2E model (EPA, 1997) and has been adopted by several others (TCEQ, 2015). The watershed surrounding the river becomes one of determining parameters ("a" and "b") for the relationship. Several sources were examined that provide information from which parameters could be derived (W.E.Gates and Associates, 2007, EPA, 2007). Equation 2 relates the velocity of the river to the flow rate using two coefficients, a and b, to account for the hydraulic characteristics of the river. The method for deriving velocity-related coefficients "a" and Exponents "b" was used by a combination of the available stream geometry.

To derive these coefficients and exponents, we used a combination of available stream geometry flow, flow rating curve data, Manning's equation. With the river characteristics for this stretch Texas Commission of Environmental Quality (TCEQ, 2015), the river coefficients for the stretch of the Rio Grande were found to be a=0.0758 and b=0.5.60. The general average river flow of the sample that was taken was 116 cubic feet per second (cfs), or 4.7 cubic meters per second (m3/s) (TCEQ, 2015). The velocity is estimated as the coefficient a multiplied by the flow raised to the power of the coefficient b.

3.1.1 Initial and Boundary Conditions

The initial condition, for the boundary, one upstream and one downstream condition are required to solve the water equations for flow. The common upstream boundary conditions are either known depth or discharge both as a function of time:

$$y(x,0) = y^0(x) \text{ and } q(x,0) = Q^0 \tag{4}$$

For this particular simulation a stage-discharge relationship, or Q(h) as a single-valued function based on the relationship between the stage and discharge for the location of Brownsville station RS 414.206. The internal boundary condition used for the simulation were used only as either a flow through spillways, contributions through tributaries, or diversion of lateral structures**.**

For a fully functional model to achieve a realistic unsteady simulation would need to specify the exchanges between basin storage areas and the river flow, where surface water interactions can be quantified using exchanging storage models that describe surface water flow with an advection-dispersion equation, and incorporate storage zones to simulate water stored in low–velocity zones such as pools and storages (Runkel et al., 1998). The one-dimensional transport with inflows and storage is a common method that simulates systems where continuous and exchange between the stream and a storage zone in subsurface flows. In order to achieve the exchange of flows, two variables could be implemented: the cross-sectional storage area, or the exchange rate between the stream channel and the storage section (Runkel et al., 1998).

In the model, the main channel and flood plains of a river use two physical laws: the principle of conservation of mass continuity, and the principle of conservation of momentum bases on the principles presented by James A. Ligget from the book “Unsteady flow in Open Channels” (Brunner, 2010a). The model uses a control volume within a distance “x” measured along the channel, at the midpoint of the control volume, the flow and total flow area are denoted as Q(x,t) and AT, respectively. The total flow are is the sum of active area A and an off- channel storage area S (Brunner, 2010b).

The control volume is divided into a number of sections that moves with the mean flow velocity. The model can simulate the flow and lateral interactions between the main channel and flood plains. Devkota and Imberger (2009b) and (Brunner, 2010b) have described the modeling framework and the governing equations for flow and transport in open channels. The conservation of volume (incorporating the dams, inflows, storage, diversion or withdrawals), the longitudinal momentum, and the new position of the control volume. The rate of inflow to control volume, the rate of out flow, and the rate of storage change is given as

$$\frac{\partial}{\partial t}(AL) = [Q_{in} - Q_{out} \pm Q_{structure}] \tag{5}$$

$$\rho \frac{\partial A}{\partial t} \Delta x = \rho[(Q - \frac{\partial Q}{\partial x}\frac{\Delta x}{2}) - (Q + \frac{\partial Q}{\partial x}\frac{\Delta x}{2}) \pm Q_l] \tag{6}$$

Where Q_l is the lateral flow entering or leaving the control volume and ρ is the fluid density. Symplifying and dividing the change in distance and fluid density yields the form of the continuity equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} \pm q_l \tag{6}$$

Where q_1 is the lateral outflow or inflow per unit length.

3.1.2 Flow Boundary Conditions

By employing the numerical method, the time history of water depth and discharge can be computed for each point in the river. River stage observations collected during the years of 2006 to the 2010 flood were used to calibrate the 1-D model. Several simulations were carried out by using: the flow hydrograph observed at LRG upstream boundary condition of the Falcon Dam along with two other interflow locations, Anzalduas and Progresso, to the overall tendency of flows within the river as seen in **Fig. 2**. In order to apply the water balance the conditions for the final model did not include the internal flow condition, instead differences in gauge flows and recorded data for inflows/outflows were used to account for the water balance. At the downstream section where the information is known, such as a control section or a stage-hydrograph a stage-discharge relationship was created, or Q(h) as a single-valued function based on the relationship between the stage and discharge for the location of Brownsville station RS 414.206. The internal boundary condition used for the simulation were used only as either a flow through spillways, contributions through tributaries, or diversion of lateral structures as seen in the following figure**.**

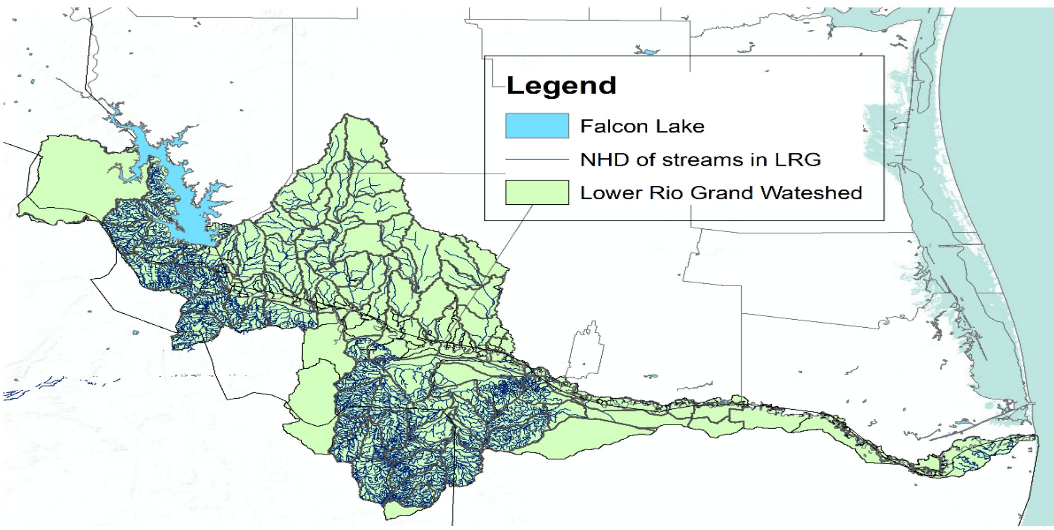

Figure 10 . Derived from USGS, GIS map of the Lower Rio Grande watershed and its tributaries

Common one-dimensional open channel flow models behave poorly in terms of flow distribution across a section in a natural meandering channel with vegetated flood plains (Martín-Vide, et. 2008). Therefore, model calibration remains a critical step in numerical modeling (Vidal, et. 2005). The model presented in this study is developed in a manner to enable multiple calibrating options with the goal of determining the most appropriate approach. The considered approaches are calibration with an implementation of contributed flow provided by the surrounded basins, or diverted flows provided by either diversion lateral weirs, or extracted water used by cities that were recorded by the International Boundary Water Commission (IBWC). The U.S. Geological Survey Has identified various sections along the LRG that contribute to the flow for the Rio Grande, as seen in **Fig. 10**, all of which were integrated into the model to account for all the water contributions. Although the simulations are conducted for the 5 years in the verification process, to retain clarity of all the considered methods, only segments of these results are presented. The criteria to evaluate the considered methods is the requirement of the calibration process, the physical justification of the considered approach as well as the results deviation from the measurements.

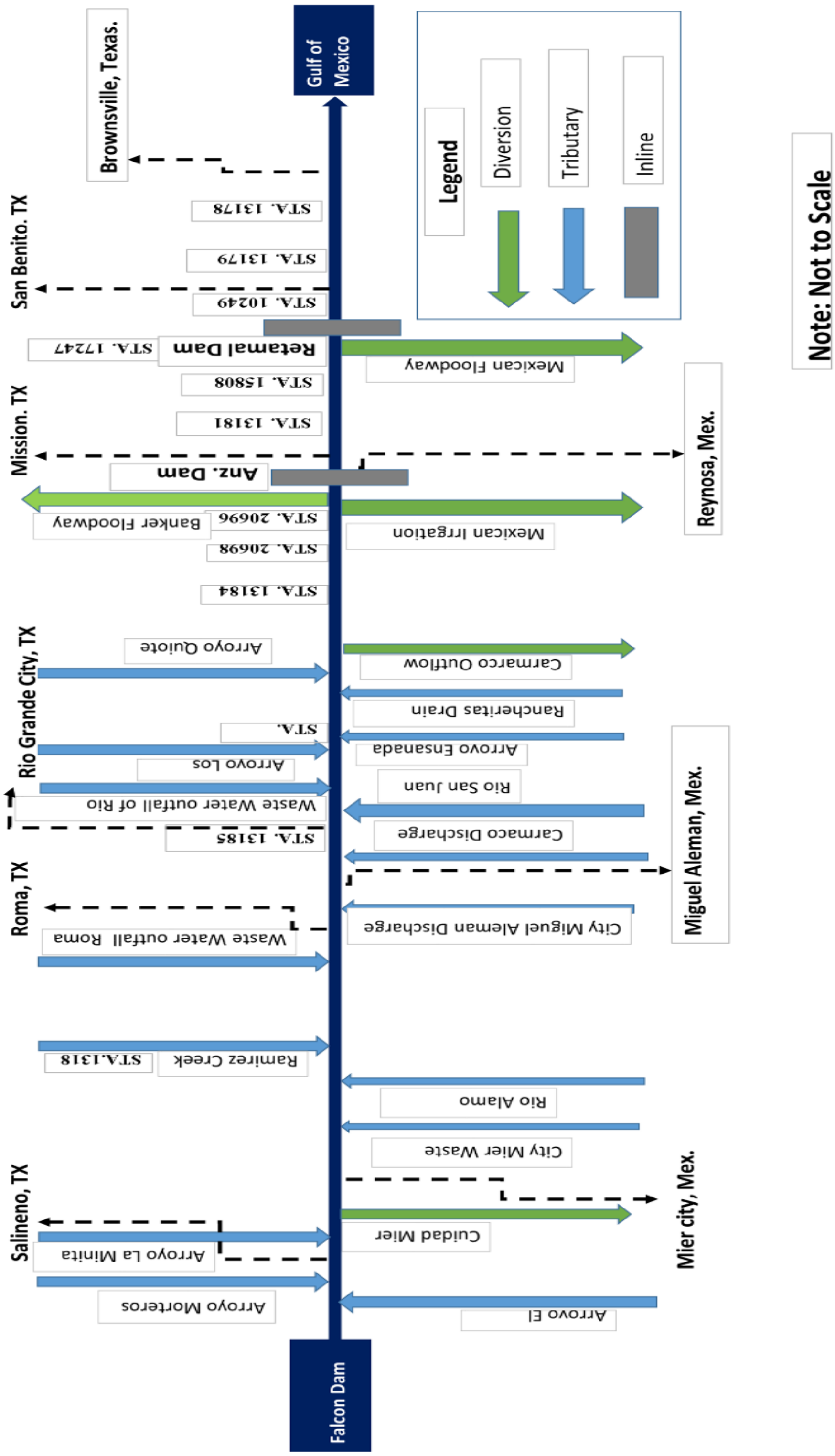

Figure 11 Identification of tributary inflows and river diversions within the model for the LRG.

3.1.3 Inflows and Diversions

Lateral inflows include the El Coronel, Arroyo Mortreros, Rio Alamo, Ramirez creek, Ciudad Miguel Aleman discharge, Arroyo Los Olmos, Rio San Juan, Arroyos La Minita and Los Negros; all of which are from both the U.S. and Mexico. The diversions included in the model consist of: Diversions of Cuidades Mier, Banker weir, Camargo outflow (Mexican Irrigation canal), and the Mexican Flood, these can be used as a calibration method in order to achieve a water balance.

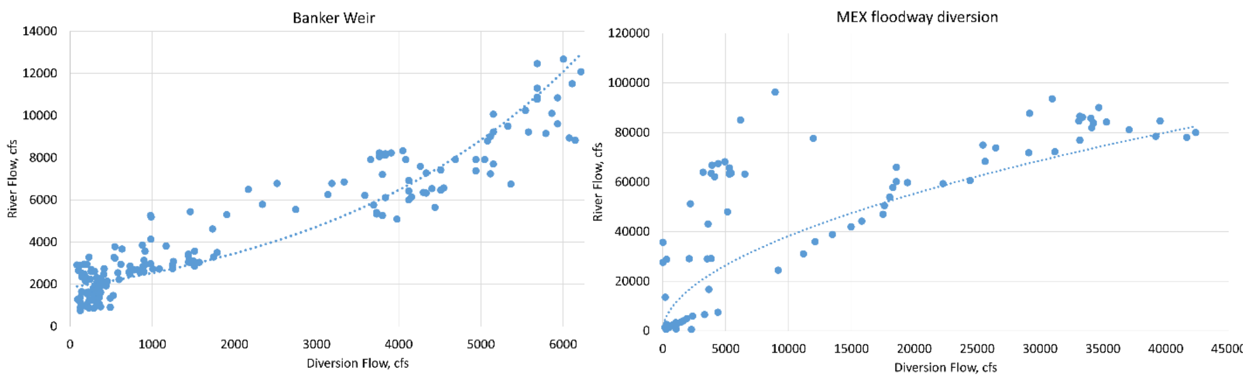

Figure 12 Relational Curves between river flow and diversions

The relation curves from which both diversion and inflows are derived were defined by the five year points for 2006-2010 years from flow measurements provided by the IBWC as seen in **Fig. 12**. The curves as defined by the points do not, however, cover the range required for all of the estimations of inflow. To extend the curves, at both the high and low ends, mean monthly inflow for the five years was computed for the relation of diversion relation to the river flow. The use of relational curves as a calibrating method was used as a methodology used in making estimates of inflow, the report presents considerable data on drainage basins and on streamflow patterns. (Bue, 1968) presented its relation curves as reference with only a limited number of values.

3.2 Steady Non-Uniform Flow.

The model was validated for a 10-day steady state flow for approximately 257 mile reach from the Falcon Dam to the downstream section pouring into the Gulf of Mexico. The point and diffuse inflows to the river showing the location of the inflows and the steady state flow rate. The upstream boundary condition, the flow from the Falcon Dam, was 6038.81 ft^3/s and a rating curve comparative of stage and flow at the downstream boundary. Comparison between the simulated and the measured steady state discharges are presented in **Fig. 12**. The results show great agreement between the field data and the model result, with the only difference being in the first few miles in Rio Grande City of the reach where the errors reached approximately 10%, which can be attributed to the diversion of water through the specified tributary of Table 2. The steady state simulations show that the system appears to be dominated by the diversions, as the flow decreases from 5155.941 ft.^3/s to approximately 1737.4 ft.^3/s, which is caused by the inclusion of the Anzalduas Dam and water diversion through irrigation canals located at the dam. The implication of this for modeling was that particular attention must be paid to the diversion boundary conditions.

Table 2: Contributions and Diversion of LRG Reach and Proportional Flow Contribution

Tributary Contributions	Length (m)	Proportion	Station
Arroyo Morteros	7509.05	0.16	R.S. 408931
Arroyo La Minita	15698.01	0.34	R.S. 397764.8
Ramirez Creek	10507.49	0.23	R.S. 384182.3
Arroyo Los Negros	4615.54	0.1	R.S. 381590.1
Arroyo eEl Coronel	8354.00	0.18	R.S. 405122
Diversions	**Length (m)**	**Proportion**	**Station**
Ciudad Mier Extract	195463.59	0.36	392743.50
Ciudad Miguel Aleman	354739.7	0.64	349277.10

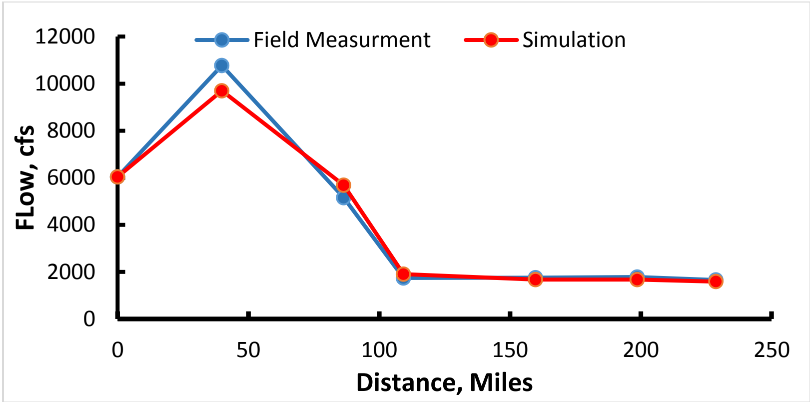

Figure 13 Comparison of field data and predicted simulation result for steady state flow.

3.2.1 Preliminary Unsteady Flow Results

First, the model was simulated for the Rio Grande River flow for the reach from the Falcon Dam to the downstream into the Gulf of Mexico for a 365-day simulation from January 01, 2007 to December 31, 2007 (**Fig. 14**) with flow recordings and tributary inflows provided by IBWC. The time step of the model was 6 minutes. The channel distances were varied between 100 ft and 3 miles.

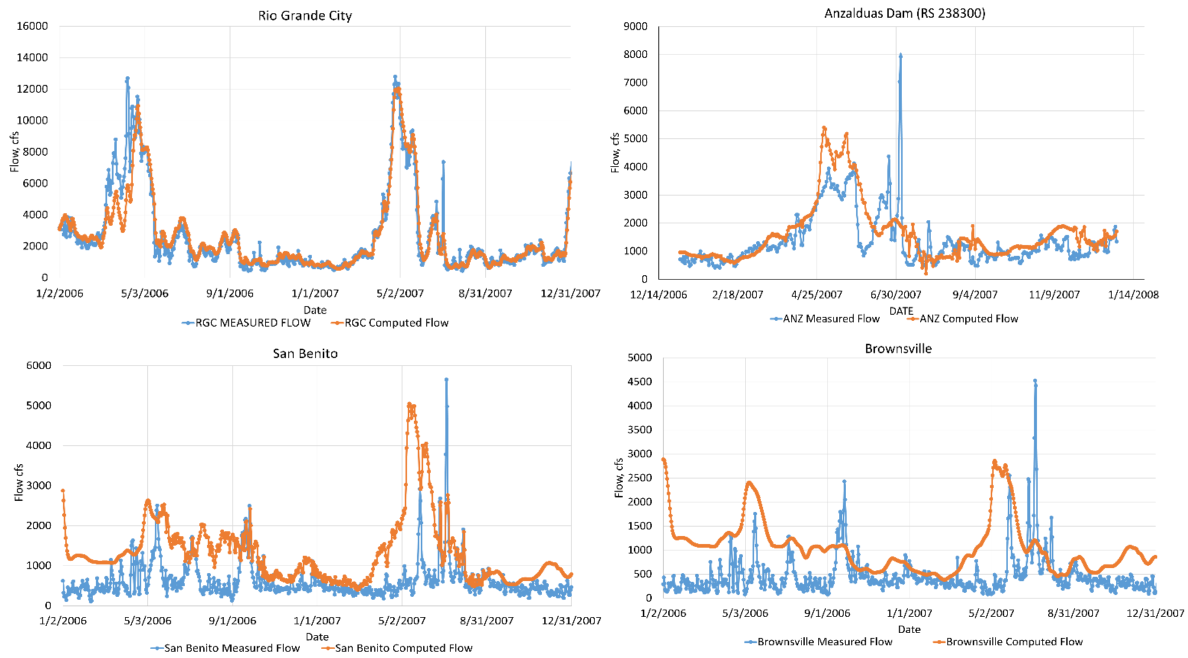

Figure 14 Preliminary Flow Computation comparison between measured flow with given lateral flows provided by IBWC and flow simulation of stations Rio Grande City (RS 346000), Anzalduas Dam (RS 238300), San Benito (RS 35536.7), and Brownsville (RS 13633.78)

As seen in **Fig. 14**, the initial flow simulation has a considerable amount of error, that is because the initial model only has the attributed upper and lower boundary conditions, but when we implement the attributed changes found from steady state, where the diversion of water changes the flow for the reach, there can be calibration model attempt, for the water contributions and water diversions for the reach. They were used for the creation of a rating curve for lateral structures, where if the river's water elevation hit the elevation of the lateral structure, that water would be diverted by a certain amount, or the alternative would be for river flow comparison to that of recorded diversion flows for a specific lateral structure.

3.3 Calibration of Unsteady-State Hydrologic Model

Calibration can be considered a continuous process where the input parameters that control modeled processes are adjusted during calibration to obtain better agreement between model output and actual observations. For this study, model iterations were made to improve predictions with, prior to calibration, initial boundary conditions were established for discharge, geometric and hydraulic parameters. The streamflow boundary conditions were established using the actual daily-value discharge hydrograph for the Rio Grande River below the Falcon Dam streamgage as the upstream boundary condition and a stage-discharge rating for daily-value streamflow from the Brownsville, Texas as the downstream boundary condition **(Fig. 1)**, with the addition of IBWC recorded lateral flows to 4 specific locations. As previously mentioned, instantaneous and daily-mean discharges files and stage-discharge-rating curves were retrieved or developed. Each file was tested in the model and the simulation result that yielded the best hydraulic performance (matching normal stage elevations) was selected. For the hydraulic boundary conditions, the initial Manning's n values were modified during calibration based on examination of cross section bed movement. Various periods from January 2006 to December 2009 had recorded two to three storm events each year and were used for model calibration and evaluation.

The model was calibrated by manually adjusting the Manning's n values to minimize the differences between the predicted and observed as flow hydrographs at Rio Grande City (RS 346000), Anzalduas Dam (RS 238300), San Benito (RS 35536.7), and Brownsville (RS 13633.78). The initial Manning's n values were determined in reference to Chow (1959). The following sections shows the calibration parameters for the lateral flow (contribution and diversion) and calibration of Manning's n. The average Manning's n for all cross sections was

0.034, ranging from .03 (level beds) to .6 (very rough bedrock and boulders near channel banks and just downstream of each dam). In general, gate openings for Anzalduas Dam and the Retamal Dam were acquired from real life measured hourly gate operations and averaged for every 6 hour changes. Internal boundaries for the dams were set using time-series of gate openings.

3.3.1 Lateral Inflows and Diversions

As mentioned before the lateral inflows are the Ciudad Mier Extract from Mexico (R. S. 397200), Arroyos La Minita and Los Negros (R. S. 384182.3 & 381590.1) and Diversions of Cuidades Mier and Miguel Aleman (R. S. Rio Alamo Diverted to Banker weir (R.S. 239870),and the Mexican Flood way (R.S. 179820.54) were used as a calibration method.

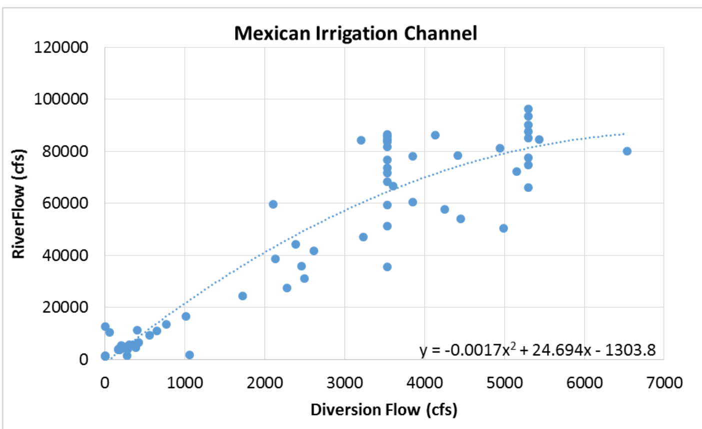

Figure 15 Relational Curve for the Mexican irrigation Diversion

For the purposes of automation, relational points between inflow/outflow within channel flows converted into equations by fitting a line through the table values in logarithmic space as seen for this study. Streamflow records for the 5-year period show that the patterns of streamflow around diversion areas can vary considerably from year to year. The use of a relational curve can be made as a calibration parameter where the estimates of inflow at inflow/diversion sections are estimates of total surface inflow to the river, which theoretically would equal the inflow to the river if adjustments were made for all diversions as on **Figures 12 and 15**. During very low months when evaporation and precipitation might be significant items in the water budget, adjustments can be estimated on basis water being pumped out by the cities, in fact records show (TCEQ, 2015) that water extracts from cities are more common during the dry seasons.

Groundwater inflow is largely an unknown quantity, as no comprehensive estimate of it has ever been made. Groundwater inflow consists of two main components: (1) direct seepage from water-table aquifers, and (2) upward leakage into the river from artesian aquifers lying beneath it. The U.S. Geological Survey has estimated the upward leakage to be within river waters between 50 to 250 cfs,(although they vary considerably from river to river) qualifying the estimate as possibly being in error by an order of magnitude but has made no estimate of the direct seepage (E. G. Otton, 1967). The attributed changes found from steady state, where the diversion of water changes the flow for the reach, was used for a pre-calibrated model attempt for the water contributions and water diversions for the reach, with flow recordings and tributary inflows provided by IBWC are. With further reviews for further model calibration, changes in diversion can be made to both allow further diversion of water during storm events and vice versa, obtain realistic results of minimal extraction during low flow events, as long as they agree with the relational curves.

3.3.2 Calibration of the Model using Manning's Roughness Coefficient

Using the flows for years 2006 through 2009 there were attempts for calibration of the model through the Manning's roughness coefficient; by using the coefficient to establish a "standard 'n'" for a flow event at one section of length for the lower Rio Grande River from the Falcon dam to Brownsville (reach end). Due to the long length of the reach and having various changes in slope, dams, bridges, and various types of industrial/natural sections along the river that taking single n value for simulation of flow in the whole reach would not be best approach. There was a calibration of the Manning's roughness coefficient for a point using the storm data and then different values have been used to justify their use for a simulation of flow in the study reach. Various single values used in calibration by the recommended guidelines for river morphology for whole reach for floods of years 2006 through 2009 that are shown in Table 3. The table 4, also, shows the flow duration and data for various gauging stations for calibration.

Table 3: Manning's Roughness Coefficients for Natural Streams, Chow (1959).

ROUGHNESS COEFFICIENT 'n' FOR MANNING EQUATION				
		n Value		
Line No.	Type and Description of Conduits	Minimum	Design	Maximum
	Natural Streams			
28	(a) Clean, straight bank, full stage, no rifts or deep pools	0.025		0.033
29	(b) Same as (a) above but some weeds and stones	0.030		0.040
30	(c) Winding, some pools and shoals, clean	0.035		0.050
31	(d) Same as (c), lower stages, more ineffective			
	slopes and sections	0.040		0.055
32	(e) Same as (c), some weeds and stones	0.033		0.045
33	(f) Same as (d), stony sections	0.045		0.060
34	(g) Sluggish river reaches, rather weedy or with			
	very deep pools	0.050		0.080
35	(h) Very weedy reaches	0.075		0.150

Table 4 Flow duration, Manning's n and gauge station used for calibration.

Flow Year	Roughness Coeffient Manning's 'n'	Storm Events	Guage Station used for Calibration
2006-09	0.03, 0.032, 0.034, & 0.04	15	RGC, ANZ DAM, San Benito, & Brownsville

The model of the lower Rio Grande River has been used to simulate the stages for different single roughness coefficients for floods 2006 through 2009. Different values of Manning's n have been used, as shown in Table 3, in order to achieve a correlation between the measured flow and the simulated flow. The simulated stage hydrographs were compared with observed stage hydrograph at Rio Grande City (RS 346000), Anzalduas Dam (RS 238300), San Benito (RS 35536.7), and Brownsville (RS 13633.78) stations. Simulation periods used for floods of various storm events are also shown on the Table 4.

3.3.3 Performance Determination Parameters

In the research of 1-dimensional models of different architectures there were various performance analysis of the models based on either the percent error for evaluation (PBIAS) or mean squared error (MSE) was performed, for this research the latter would be used. For this reason, visual inspection of time-series plots of measured and predicted DO was performed. Quantitative representation by implementing the quantifiable measurement of percent error for evaluation as:

$$PBIAS = \frac{\sum_i (OV_i - MV_i)}{\sum_i OV_i} \times 100 \tag{8}$$

where OV_i = observed value at the i time step, MV_i = modeled value at the i time step, and *PBIAS* is percent error.

Root mean squared error (RMSE) has been used for comparison of simulated stage with observed flow for various Manning's 'n' listed in Table 3. RMSE can be defined as:

$$RMSE = \sqrt{\frac{\sum_i^n (Q_o - Q_s)^2}{n}} \tag{9}$$

where Q_o = observed water flow in cubic ft. per second, Q_s = observed water flow in cubic ft per second and n = total no. of reference data points. Comparison of observed and simulated flow hydrographs using storm events found from 2006 through 2009 are shown on Table 4.

There were various attempts to create a simulation based on the varying ‘n’ numbers, from which individual Manning’s n numbers were used for the entire reach, while those with the most prevalent RMSE were kept for their specific section were used. From Table 5, RMSE flow comparison of various roughness coefficients, we can observe that it’s not necessarily the best option to place a single value of Manning’s ‘n’ represents the whole reach that in order to create a better performing model. For example, n = .032 creates a greater performance at the Anzalduas Dam (RS 238300) while for a n = .030 gives better performance at San Benito (RS 35536.7). Similarly, Brownsville (R.S. 4963.44) of n= .04 creates a better performance than the n = .030 that gave Anzalduas Dam (RS 238300) a better performance. And so, with the river that has various topographical features along the reach, two dams that interfere progressive flow, and expansion as it pours into the gulf, in can be assessed that no single value of ‘n’ can be chosen for the entire reach, instead a combination of the various n’s can be applied to the simulated reach in order to achieve a greater performance.

Table 5: RMSE Different Roughness Coefficients Affecting Flow Computational Accuracy at Stations.

Station no.	Change in time (Days)	n	∑R.M.S. Discharge
Rio Grande City (RS 346000)	1.000	**0.030**	414.52
		0.032	71.54
		0.034	106.68
		0.036	79.38
		0.040	109.75
Anzalduas Dam (RS 238300)	1.000	**0.030**	570.68
		0.032	71.20
		0.034	130.32
		0.036	365.80
		0.040	322.66
San Benito (RS 107700)	1.000	**0.030**	93.08
		0.032	134.23
		0.034	90.98
		0.036	202.97
		0.040	178.17
Brownsville (RS 49634.44)	1.000	**0.030**	104.40
		0.032	119.62
		0.034	81.92
		0.036	188.66
		0.040	68.72

According to their respective performance outcome, the combination of roughness coefficients of n=.0032/0.036 were used up to and between stations of Rio Grande City (R.S. 346000) and Anzalduas Dam (RS 238300). Meanwhile the variations of n=0.03/0.034/0.036/0.04 were used for the stations below Anzalduas Dam (RS 238300) at San Benito and Brownsville. Their respective station performance compared to measurements of flow can be seen on **Fig. 16**.

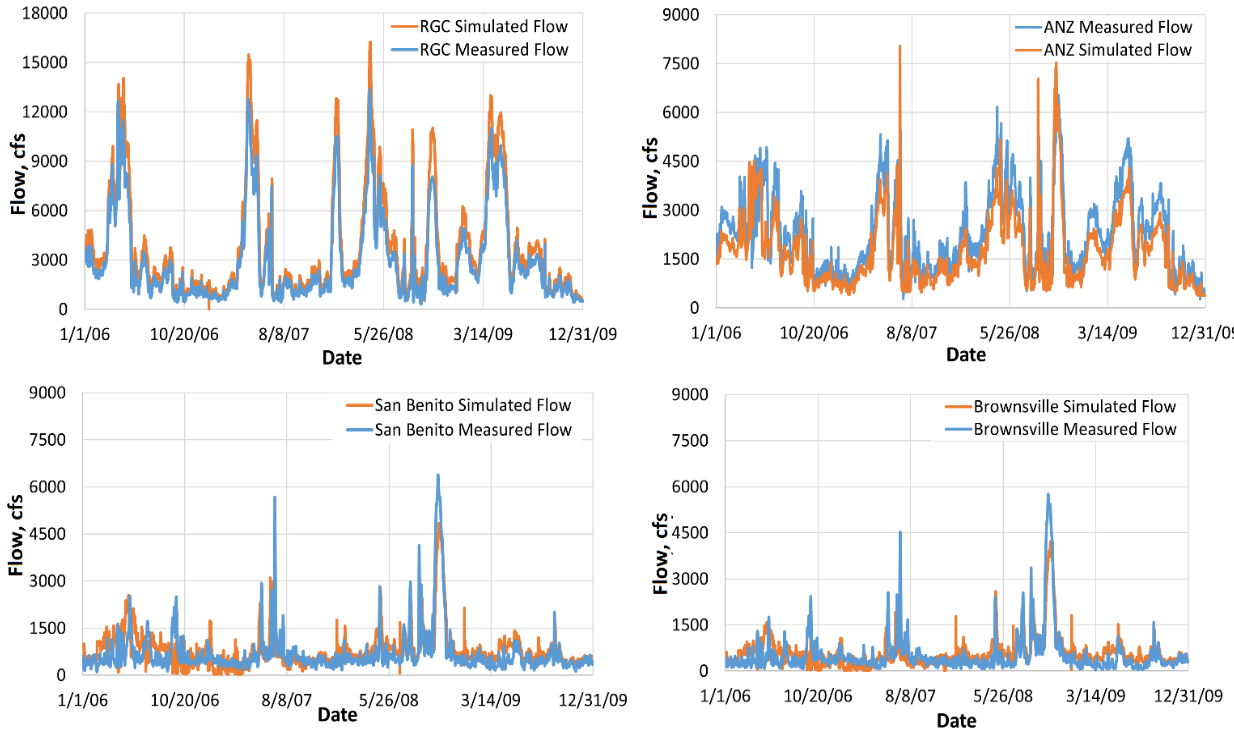

Figure 16 Calibrated Computed Flow Comparison between measured flow and Roughness Coefficient calibrated flow simulation with tributary inflow and diversion accounted of stations Rio Grande City (RS 346000), Anzalduas Dam (RS 238300), San Benito (RS 35536.7), and Brownsville (RS 13633.78)

The calibrated model based model has been used to simulate the storm event in 2006. The comparison of observed and simulated flows at Rio Grande City (RS 346000), Anzalduas Dam (RS 238300), San Benito (RS 35536.7), and Brownsville (RS 13633.78). Also, the RMSE has been computed to compare the performance of model in flow to their respective measurements for all the gauging stations are shown in Table 5. The results seem to agree with the dispersion of various ‘n’ numbers throughout the reach, where in fact the only station that would need to vary by some standard is station 107700, where the RMSE was its highest at 93.08. This anomaly could be factored as an unpredictable factor such as the operation variability of Anzalduas gate operation, where the simulation compared to the measured flows vary from time to time.

Having opted for a manning calibrations, the results can be compared to the observations. In **Fig. 17** the observed versus peak flow was graphed from 14 independent storm events over the periods of 2006-2010 throughout the simulated period for the Anzalduas station. The high peak discharges were reproduced reasonably well, but estimations were slightly worse for small floods where some points which were far from the 1:1 line. This can be attributed to the independent use of gate operation at the Anzalduas Dam, where based on judgement, the gates might close to let water run off at lateral structures, while the model does account for this issue as a diversion rating curve, the operating gates remain open in the model based on historical data obtained from the dam operators.

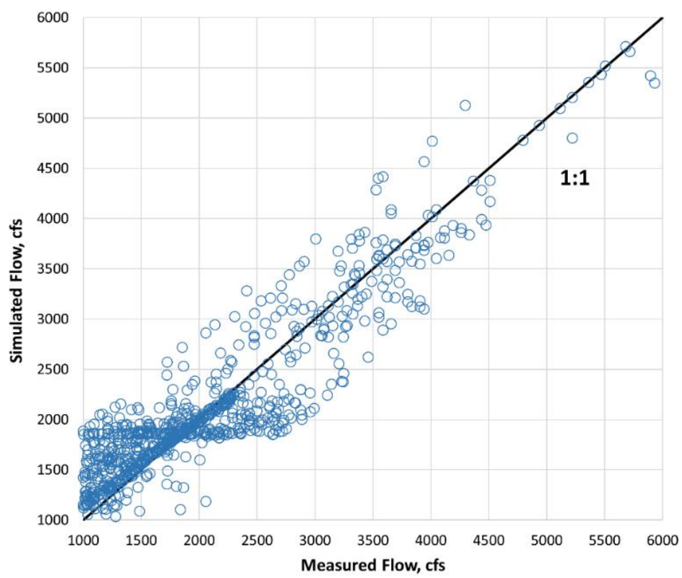

Figure 17 Comparison between measured flow and simulated calibrated flow for Anzalduas Dam

3.4 River Travel Time Estimation

After we obtained a combination of calibrated parameters n, the calibrated value of n is within the general range for natural river channels, but n also carries the uncertainty of R^2 of 0.81 as seen in **Fig. 17,** therefore, the ranges of calibrated n factors carry an influence that represent a quality that mirrors the real roughness of the channel. The simulated hydrograph and observed hydrograph were used to find the travel times for the sub-watershed area, where the flow measurements between the two cross sections was derived using the difference of the gauging stations. This simulated hydrograph was similar in shape to the flood wave at the upstream cross section, but with a larger peak amplitude volume and with various points of varying differences of discharge values.

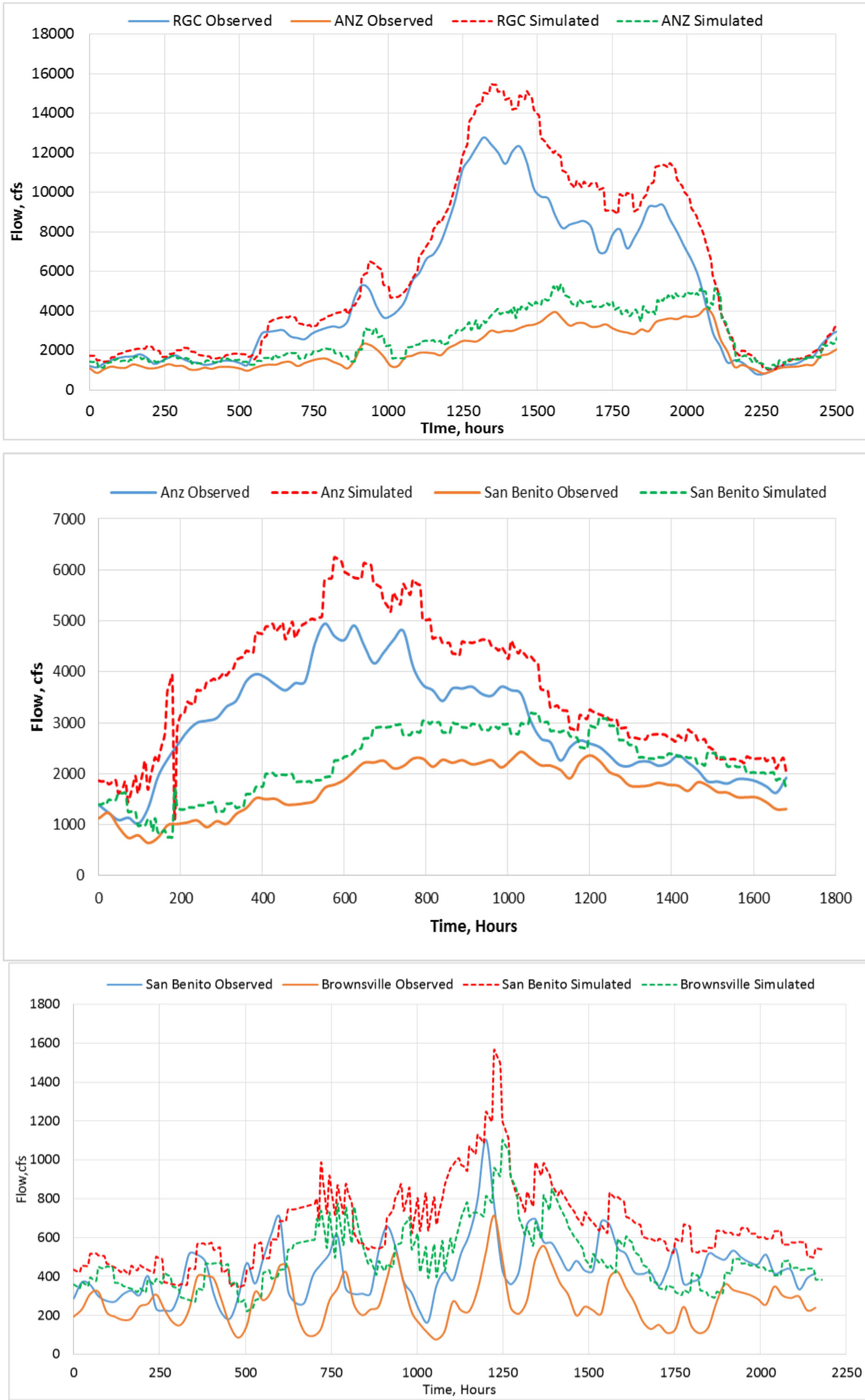

Figure 18 Observed and simulated flood waves. (a) Storm event that encompasses 75 percentile flow for the 4 year period between 2006-2009 of which the river bed roughness was calibrated; (b) Storm event that encompasses 50 percentile flow for the 4 year period between 2006-2009; (c) Storm event that encompasses 25 percentile flow for the 4 year period between 2006-2009

In these applications, the simulated hydrographs match our expectations, as illustrated by the **Fig. 18**. The downstream flow peaks were dominated by the upstream flow peaks, as they strongly influenced by the outflow diversions generated by the irrigations canals and the lateral structures assigned as spillways between the two cross sections (**Figures 18b and 18c**). Our simulation shows differences of the flows between the two cross sections, from Rio Grande City (RGC) to Anzalduas (ANZ) stations, and Anzalduas stations to San Benito station, and San Benito to Brownsville. With such a large time slot four years (2006-2010), we compared a total of 45 storm events that encompass different flow variations of the historical flow data, that is, obtain flows of 75%, 50%, 25% of the peak flow, in order to find the differences in travel time at variations of flow for the river model.

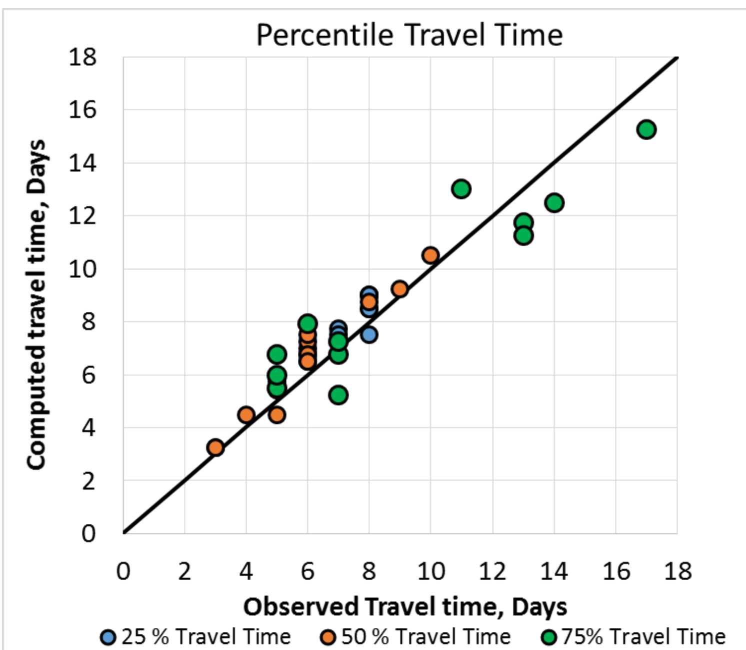

Figure 19 Travel time comparisons between observations from the gauge data and model simulation provided by the IBWC and the model simulation

3.5 Hydrologic Result Analysis

Our simulation shows that the travel time of the flood waves between various gauging stations for the entire reach varied throughout the change in flow where 25% constituted for an average of 800 to 1200 cfs.50% average of 4000 to 6000 cfs., and 75% average of 12,000 to 9,000 cfs, shown in **Fig. 19**. When taking the 25 % flow variation the travel times average about 7 to 8 days, this can be contributed, it seems that as an everyday flow where for the vast majority of the year the flow falls within this flow section. Next for the 50 % flow for a travel time calculation of an average of 5 to 6 days; for this spectrum of flow there is large margin of various travel times, this can be attributed to the variation of flow.

According to TCEQ (2015) the gate operations at the dams for Anzalduas Dam and Retamal dam (RS 238300 and RS 175925 respectively) are manually operated and their operation is independently judged based on the flow of the river. What this means for the results, as seen in **Fig. 19** , the travel times for this flow regime has a variation from 3 to 10 days due to the fact that when the river flow exceeds a certain flow (no recorded specification) that gates are closed in order to divert water into the lateral irrigation channels or the overflow dam. In order to mimic this diversion within the model, as explained in **section 3.1.3** ***Inflows and Diversions*** section, a relational curve between reach historical data of river flow and diversion flow was established at the dams, where is a certain flow (ranging from 2,000 to 10,000 cfs.) would divert an average of half water flow out into the irrigations channels. Which brings us to the flow regime of 75% of peak water flow, where simulated travel time does not represent the real observational data. Where the simulated travel time averaged 4 to 16 days, the observed travel time varied from 7 to 14 days. This anomaly could be traced to the operations of the gates, where the model depends on diversion curves; and it's limited, due the fact that the real gate operations closed at higher flows in order to prevent flooding downstream. The model itself does not close the gates in order to prevent instability due to the limitations of the models use of equations for conservation of volume, the longitudinal momentum, and the new position of the control volume that depends on constant flow from the upstream sections.

According to McDonnell et. (2014) there has to be a use of routine flow velocity in runoff routing model development in order to improve the understanding of hydrologic processes. There is variability on the use of water balance, river and watershed discharges, and flow velocities are not easy to measure or estimate. These flow discharges are dependent on temporary, spatial information for any given watershed, the channel condition, and weather conditions. With the conservation of volume and the use of the historical discharge data information and precipitation's influence on discharge can be used to obtain an idea on the river's travel time. This study approaches on methodology to utilize discharge data from tributaries, diversions, gauging stations in order to extract information about the flow waves in order to find travel times can and is feasible. This has the potential to be applied as a procedure to estimate flow velocity, water balance, and travel times.

3.6 Hydrologic Modeling Summary

The application of the travel time distribution formulation in the context of tributary and diversion outflows water interaction with the main water stem for the Rio Grande River. Through the medium of a distributed hydrologic modeling, we constructed the one dimensional, unsteady state hydrologic water flow model of the shallow, unconfined aquifer at the Lower Rio Grande watershed, in South Texas by using HEC-RAS. The distribution was characterized with a mean travel time of 6 to 8 days. We were able to find that the time scales over which one can expect to observe the surface water response to distributed along the watershed, were influenced both by dams and diverting/combining flows that vary along the watershed to be of the order of a week.

The determination of the time travel is due to the impact of various control variables on this distribution. The first variable that has to be considered is the variation for cross-sectional analysis for the model; an analysis of the GIS geometry can and does influence the velocity distributions as where the necessity of accurate representation of both river path lines and location of diversions/tributary inflows influence the flow. Secondly, the necessity of attributing the inflows to the main river flow is a representation of the watershed's water catchment due to precipitation that flows into the river.

The goal of attaining a water balance was achieved through the representation of storm event that provide water from the watersheds that provide flow waves along the river path-lines. The last control variable are the dams/lateral structures themselves; where their detainments and diversion of water attributed to the water balance. When one looks at a historical hydrograph of the river's flow, there are peak points of flow, where water is either detained. Where their representation in the model can achieve a similar result by recreating the gate operations that are present during a storm event that either detains or releases water through them that creates a similar hydrograph that can be compared to that of historical results. With the hydrologic results culminating into an acceptable result, there can be confidence in the model's ability to accurately represent the distribution of water through water balance. That is, if the water balance was achieved in order to recreate the distribution of water accurately, the distribution of nutrients within the water cells can be replicated as well.

CHAPTER IV

WATER QUALITY TRANSPORT MODELING

To begin the quality transport modeling, the water temperature modeling has to be established. The initial boundary conditions and water quality cells have to be computed by water cells conduct computations in between themselves at various degrees of stepwise time, where the cells' input depends on the output of the previously located upstream cell, to which the computational chain reaction leads up to its original input by the hydraulic boundary condition (Lowney, 2010). At any particular instant of time, the stream reach is capable of sustaining a particular water column temperature. Stream temperature change that results within a defined reach, where the temperature of a cell of water traversing the river reach enters the reach with a given temperature. If that temperature is greater than the energy balance is capable of supporting, the temperature will decrease accordingly to its surrounding meteorological conditions. Likewise if that temperature is less than energy balance is capable of supporting, the temperature will increase. Stream temperature change within a defined reach, is induced by the energy balance between the cell of water and the surrounding environment and transport of the cell through the reach. As the water cell traverses the longitudinal distance of a defined reach, energy processes stream temperature change. The water that enters the upstream portion of the reach is never exactly the temperature that is supported by the defined reach. And, as the water is transferred downstream, heat energy and hydraulic processes that are variable with time and space interact with the water cell and induce water temperature change (Brunner, 2010a).

4.1 The Variability of Temperature

The obtained recorded water temperature showcases yearly cycles with a short time scale variation as seen in **Fig. 18**. The temporal structure is an amplitude of temperature change throughout time that defines the variability that is shared by the stations. These records have various features such as a short to medium-term variation and a yearly cycle that is seen throughout the reach. Amplitude of the yearly cycle vary from year to year and between locations, this is seen most significantly on the Progresso station, particularly between 2006 to 2007 and there is a gradual yearly decrease from there on. After what seems to be a cold winter season (water temperature recorded to be 15°C), the summer season peak temperature is reduced thereafter on a variation scale of ± 2°C. Limited temporal records are available, but there are signs of shorter time scales variations between months. The largest variation seems to be emanating from yearly variations (on the order of 15°C at the locations in **Fig. 20**). Shorter time scale variations could be attributed to various combinations of local mixing, short-term atmospheric conditions, or local precipitation.

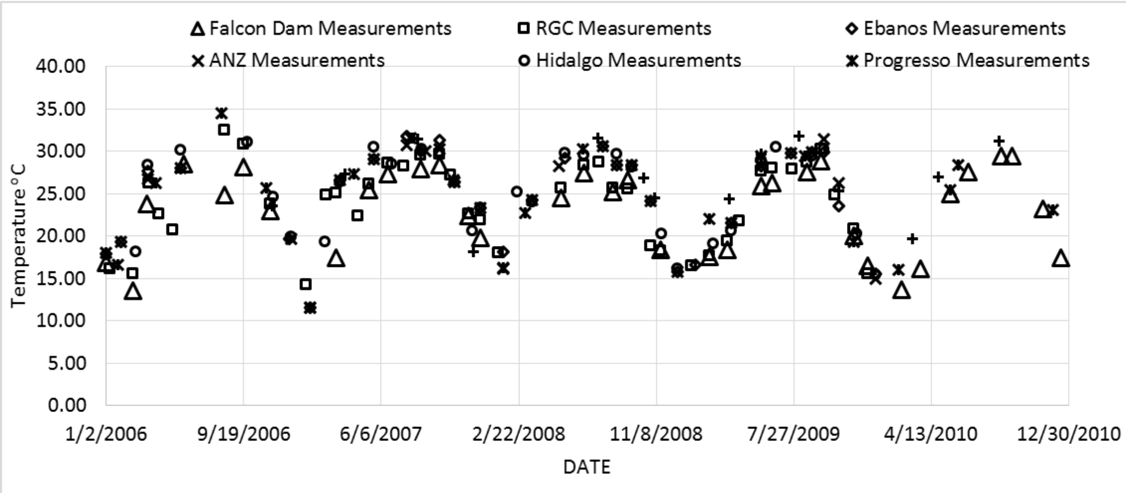

Figure 20 Observed water temperature (°C) for six gauging stationsalong the Lower Rio Grande River

The variably of temperature defined size of the computational cell has an effect on the time step and its computation time, in which case, increment of computational cell merges cross sections under one cell and has an effect of reduction of overall computational time, but reduction of quality computation for the range of cross sections under the cell. While reduction in computational cell specifies more cell per cross section**,** increasing quality computational range, but increasing the time step as there would be more cells to be computed. Once the boundary conditions and water quality cell constituents are dependent on the control of temperature calculation, the model needs to be specified on the range to interpolate results based on the nutrient date information.

The model used a heat budget formulation used by model is influenced mainly by the volume and surface area. Many water quality kinetic coefficients are temperature dependent. Water temperature computation has been implemented using a full energy budget approach. The source and sink term for temperature; i.e., the change in water temperature with respect to time due to heat exchange at the water surface, was computed as follows:

$$Heat = \frac{q_{nrt} \times A_s}{\rho_w \times C_{\rho w} \times V} \tag{10}$$

q_{net} = net heat flux at air-water interface w/m^2, ρ_w = density of water (1000 kg/m^3), C_{pw} = specific heat of water (4186 joules/ kg× Kelvin), A_s = surface area of computational cell (m^2), V = volume of wetted cell (m^3) (Lowney, 2010)

The heat exchange between the water and the atmosphere would vary on the intensity of heat (w/m^2) over time. The computed exchange of heat is defined by the surface area of the quality cell, and the amount of water within the cell, as the volume within the cell defines the amount of heat absorbed by the water. Quantification of changes of temperature over time has been limited to a set of temperatures that only correspond to measured dates. Considering that amount of water can influence for water temperature changes over time, calculations, according to the heat equation, can be slightly changed over by adjusting the surface area by slight decrease or increase, but the considerable amount of change cannot be made due to the fact that the Volume of water will be decreased somewhat proportionally, but in this case it the amount of heat concentrated in hoe cell can be limited to a small surface area.

In this application, it means there is a change in heat content (q_{net}) of the water over some time period, this implies that the temperature of the water (T) is changing over time, this is a result of the input of heat being either greater than ($dH/dt > 0$) or less than ($dH/dt < 0$) the losses of heat for this water cell. Calculating the effect of the adsorption of radiation of change of the temperature in the surface water is conducted by

$$\frac{\Delta(\mathrm{V}\times\rho_{w}\times\mathrm{C}_{\rho w}\times T)}{\Delta time}=q_{net}\times Area \quad (11)$$

The manipulation of equation 11 can calculate water temperature change. By using the net heat flux created by the meteorological information, application of size of individual cell lengths, and time rate, temperature can be calculated by using the various meteorological changes over time and the initial measurement of temperature to calculate the change of temperature over time (Yearsley, 2009).

As initial conditions for the heat equation we applied a various measurements that were taken from recorded data gathered by TCEQ: upper stream of 20 ft. below Falcon dam, Rio Grande City station, Anzalduas Dam Station, Progresso Bridge Station, and Brownsville lower station. These stations were chosen in order to create a linear interpolation between the measured temperature values, where temporal changes can be applied to any given station between measured stations (variables) in order for the model to apply the net heat exchange along the river flow.

4.1.1 Computational Surface Area

Although gauges to measure of temperature were not taken at an hourly nor daily rate throughout the monitoring stage of the study period, with the information that was obtained; the manipulation of equation 10 can calculate water temperature change. By using the net heat flux created by the meteorological information, application of size of individual cell lengths, and time rate, temperature can be calculated by using the various meteorological changes over time and the initial measurement of temperature to calculate the change of temperature over time. When the water quality model is created with the initial boundary conditions, water quality cells are initially established by the model as a roughly equally sized lengths exactly between cross section paired stations of the reach. The computational water cells conduct computations in between themselves at various degrees of stepwise time, where the cells' input depends on the output of the previously located upstream cell, to which the computational chain reaction leads up to its original input by the hydraulic boundary condition (Lowney, 2010).

The variably defined size of the computational cell has an effect on the time step and its computation time, in which case, increment of computational cell merges cross sections under one cell and has an effect of reduction of overall computational time, but reduction of quality computation for the range of cross sections under the cell. While reduction in computational cell specifies more cell per cross section, increasing quality computational range, but increasing the time step as there would be more cells to be computed. Once the boundary conditions and water quality cell constituents are dependent on the control of temperature calculation, the model needs to be specified on the range to interpolate results based on the nutrient date information. As seen in **Fig. 21**, the change in temperature was calculated by using an optimization method of different iterations where the surface area that absorbs the heat was calculated at different sizes for the upper stream and lower stream sections and compared to the measurements taken the sites in order to control and eliminate the absorption of excessive heat during computations. As equation 11 dictates, if the surface area were to be large enough, heat absorption would be minimal, and vice versa if the surface area is small enough, the heat absorption would be concentrated in a small area where it would warm up the water at a higher rate. Through different iterations for the calibrations process, it was found that a cell size of 300 ft. would be at an equilibrium state where the heat would not be excessive nor at a minimal heat absorption state.

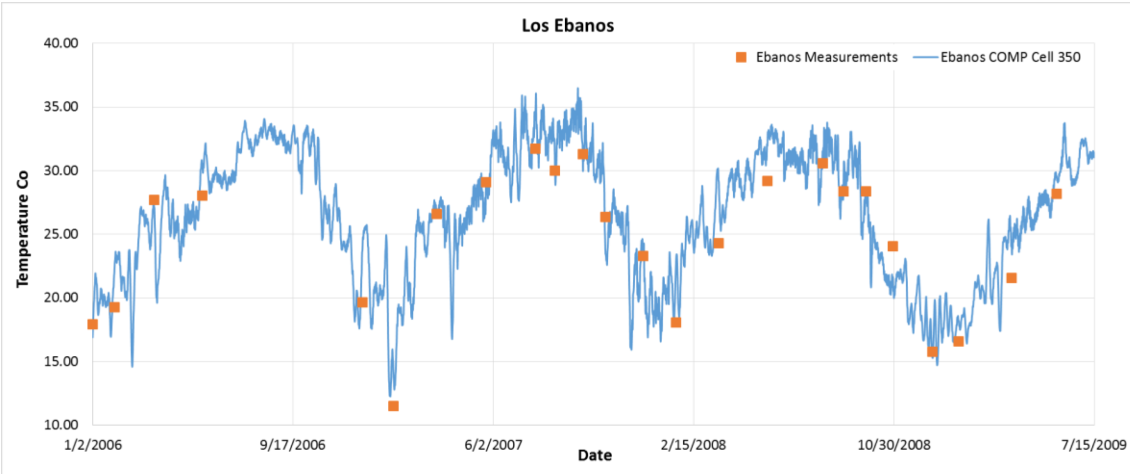

Figure 21 Time series of computed and measured daily water temperature for control section of Los Ebanos

4.2 Temperature Computational Results

As seen from the results in **Fig. 22**, the variably assigned quality cell surface area can create a regular ratio size between the surface air-water heat intake and the present volume of water to be at a 1:1 ratio; that is, control the intake of heat by adjusting the quality cell surface area to a size small enough that where there is small volume of water, the heat absorption, as indicated by equation **(**11**)**, would not intake excessive amount of heat over time. Using the methodology, temperate fluctuation can be calculated over changing time, by only using the beginning temperature input as calculations and then comparing them to other data used as observation as seen in **Fig. 22.** By using a sample correlation coefficient, that implies the linear equation describes the relationship between calculated water temperature and observed water temperature, the sample size indicates a correlation of about 0.897. This falls within an acceptable 10% margin of error, which means that we can continue on with the quality transport computation.

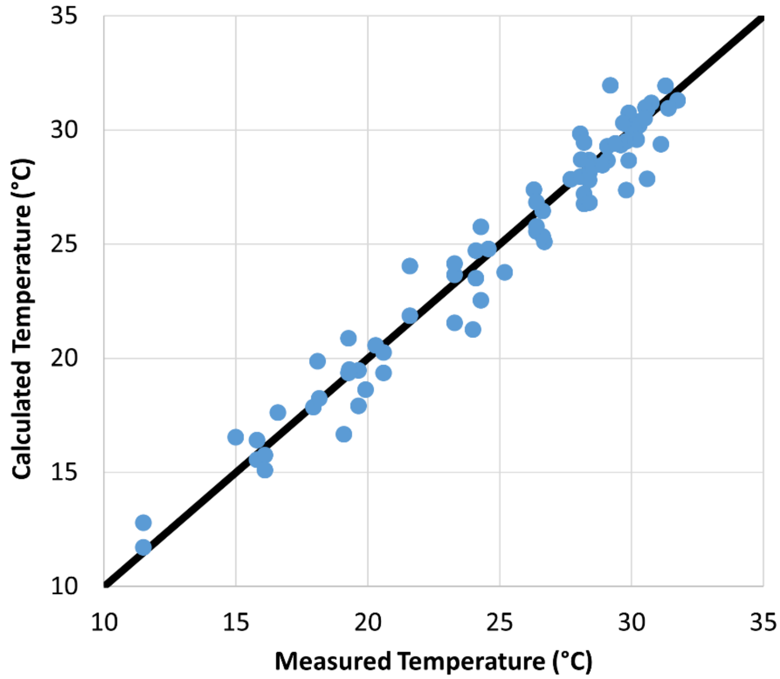

Figure 22 Comparison between measured temperature and simulated calibrated temperature for three locations of Rio Grande City, Anzalduas, and Progresso

According to the data obtained from the computations, the measurement data is resembled on the computations. PBIAS was conducted on various dates as specified graph showcases to find the errors, and taken from RGC, Los Ebanos, Hidalgo, Progresso, and Brownsville, as they are specifically spaced out enough to account for both the dependence of the input data from the source information and the computations derived from the input data don not collude with the computations. The results were compared to the measurements as seen in **Table 6**.

Table 6: PBIAS Comparison of Measured and Computed Water Temperatures

Water Temperature						
Stations	**Scenarios**	**3/30/2006**	**3/21/2007**	**5/20/2008**	**12/14/2009**	**9/14/2010**
Rio Grande City	Measurements (°F)	28.07	26.63	29.02	15.08	28.4
	Computations (°F)	29.01	27.02	30.04	16.78	27.23
	PBIAS (%)	**3.24%**	**1.44%**	**3.40%**	**10.13%**	**4.30%**
Los Ebanos	Measurements (°F)	27.47	26.06	28.40	14.76	27.79
	Computations (°F)	29.38	27.36	30.42	16.13	27.58
	PBIAS (%)	**6.50%**	**4.76%**	**6.65%**	**8.50%**	**0.79%**
Hidalgo	Measurements (°F)	28.4	26.4	29.8	16.1	27.56
	Computations (°F)	27.05	27.64	30.89	15.45	27.24
	PBIAS (%)	**5.00%**	**4.50%**	**3.54%**	**4.24%**	**1.18%**
Progresso	Measurements (°F)	29.59	28.35	30.21	16.75	27.89
	Computations (°F)	29.02	27.95	31.25	16.12	28.55
	PBIAS (%)	**1.98%**	**1.41%**	**3.33%**	**3.88%**	**2.30%**

The correlations are presented with the percent error for the modeled temperature and measured temperature was calculated to small degree of error. The results of this study support the use of a mass-balance modeling approach; in order to analyze and to quantify the source term described herein, results will be held up to the standards of both experimentation and modeling to that of the Environmental Protection Agency (EPA). The results is to demonstrate the potential bias and variability during modeling as in careful practices can still leave doubt. According to the EPA and “Peer Review of the Study Technical Plan for Human Health and Ecological Risk Assessment” (the general guidelines and regulations used by the EPA), section 3.3 Overview of Simulation Models: “any regulatory approved model that has had extensive, is reasonably updated to a modern standard of no more than 10 years…given that the simulated result’s margin of error (MOE) is less than 10 percent of the observed results… etc. acceptable with the condition and validation of peer review”. Following the guidelines set by the EPA the standards for an acceptable calibration will be implemented for the computations in this study.

Due to the varying numbers of data, the long measurement period, and the dense time interval, there are differences in the error percentage present, while the computed conditions of the year of 2006-2010 seem to correlate along the lines with the measurements (variability tends to be on the lower end of the spectrum with a less than 10% error margin), the long period of measurement for 2009 dos not correlate with the computations (6.9 % error for RGC, 9.4%). The improvement the computation methods were implemented by the use of varying cell sizes used in the computations, where the implementation considered the amount of water that can be influenced by water temperature changes over time, calculations, and the heat equation. The heat exchange that influences the temperature can be slightly changed over by adjusting the surface area by slight decrease or increase, but the considerable amount of change cannot be made due to the fact that the volume of water will be decreased somewhat proportionally, but in this case it the amount of heat concentrated in one cell can be limited to a small surface area. After various iterations with manual calculations of the heat equation where the cell size was calculated to different sizes and computational time steps, the best results for cell sizes that correlated to the observed results, was that of a 300 ft. cell length where this size was used into the computations.

Considering that an flow creates the same amount of volume of water throughout the river without the confinement and separation of cells, variably assigned quality cell surface area can create a regular ratio size between the surface air-water heat intake and the present volume of water to be at a 1:1 ratio; that is, control the intake of heat by adjusting the quality cell surface area to a size small enough that where there is small volume of water, the heat absorption, as indicated by the heat equation, would not intake excessive amount of heat over time (Yearsley, 2009). Using the methodology, temperate fluctuation can be calculated over changing time, by only using the beginning temperature input as calculations and then comparing them to other data used as observation as seen in **table 6**; all but only one date, (Brownsville, 5/27/2009, 9.4%) had reasonable results. With the margin of error correlates with the regulations set up by the EPA, we can move onto the nutrition transportation.

4.3 Model Computation Stability

The changes in temperature are seen along the span of the annual cycle with a shorter time scale variations. In order to measure the effect of temporal changes in the water, there needs to a computational interval for a minimum of a year cycle. Modeling choice to run an interval span of a year was initially chosen to correlate with the yearly seasonal effects, but there were limitations based on model sensitivity. The parameter values and assumptions of the model were subject to change and error, that is, the potential changes and errors and their impacts on conclusions to be drawn from the model. The model needs to be run under various assumptions; or computational time step. Too large a time step will cause numerical diffusion (attenuation of the peak) and also model instability. To small of a time step can also lead to model instability as well as very long computation times. For this model the modeled unsteady data was initially used (and previously shown) at a 40 minute computational time step. If it’s too large of a time step the program may go unstable, the derivatives of the unsteady flow equations in the model are calculated with respect to time and distance. If the hydraulic properties are changing rapidly with respect to time, then the program might go unstable. If it’s too small of a time step will cause the leading edge of the flood wave to steepen, possible to the point of oscillating and going unstable (Brunner, Gary W., 2010a).

Stability and accuracy can be achieved by selecting a time step that satisfies the Courant Condition (deAlmeida, 2012, Brunner, Gary W., 2010a), this is established by the model's internal equations:

$$C_r = V_w \frac{\Delta t}{\Delta x} \leq 1.0 \qquad \Delta t = \frac{\Delta x}{V_w} \tag{12}$$

For most rivers, the flood wave velocity is calculated more accurately by:

$$V_w = \frac{dQ}{dA} \tag{13}$$

An approximate flood wave velocity can be calculated as:

$$V_w = \frac{3}{2}\overline{V} \tag{14}$$

Where: V_w = The flood wave speed, which is normally greater than the average velocity, V = Average velocity of the flow, Δx = Distance between cross sections, Δt = computational time step, Q = flow rate, A = Flow area

For medium to large rivers the Courant condition may yield time steps that are too restrictive (i.e. a larger time step could be used and still maintain accuracy and stability) (deAlmeida, 2012). Using this as one assumption, unsteady data that was in temperature computations needed to be calculated based on the output of stability for unsteady state computations. Using the provided condition for the Courant Condition, the necessary computational time step was calculated based on the average distance, velocity, and known flow for three stations; Rio Grande City, Anzalduas, and Los Ebanos as seen in **Table 7.**

Table 7: Model Stability Computation of the Courant Number

Computational Time Step (min)	Velocity Avg. (ft./s)	Flood wave speed, (ft./s)	Channel Length, (ft.)	Courant Number
20 minutes	0.55	0.82	1200	**0.82**
	0.63	0.95	1305	**0.95**
	0.57	0.85	1156	**0.85**
30 minutes	0.55	0.82	1200	**1.23**
	0.63	0.95	1305	**1.31**
	0.57	0.85	1156	**1.33**

Based on the Courant Condition for the three stations, the recommended computational time-step is limited to a 20 minute time-step. This condition states that a time-step for around 20 minutes is necessary on order to impede an instability to occur for the calculations, that and the model's limitation on the order for computational time step is varied for either 40, 30, or 20 minutes (based on the closest Courant Condition recommendation). The decision to limit the time step to 20 min. is also based on another factor; the model's memory access limit.

4.3.1 Model Computational Internal Memory

Establishment of the computational time-step for 20 minutes for an unsteady state computation creates another assumption; the amount of memory created by the computational output. . Now if the time step is that of a 20-minute computation, over a span of 6 months (at average 30 days/month), that creates a total 12960 cycles of computational outputs. This output is written onto a memory file that will be used as a flow condition input for the temperature/quality transport model. Considering the amount of output cycles, this file is considerably large, as where the program is based on a 32 bit program can access only a certain amount of memory at one time (Gay 1984). This could be associated with a problem in logic such as that of the sensitivity analysis in computing. In computing logic there needs to be a finding if a set of premises entail a conclusion; the premises are the assumptions that are started in an argument, relative to computing, the inputs for the model and the output or conclusion arrived by using the argument that are needed to establish the conclusion.

If an argument is true, and based on the premises, the print is made (inputs, computational model, and output, respectively). All of this is relatively straight forward, but an issue arises based the arguments logic of computing, with the line of code provided, the line establishes the computation to have an infinite loop, or a large computational file. If a program file is large, say by 6 or 7 gigabits, then the program that would have to acquire the information is only limited to the amount of information that it could process at one time (Gay, C. 1984). Now, this does not particularly state that the model used in the computational time step behaves similarly, but in order to have the computational output, there has to be an argument based on the premises, or the computation and its time step used to calculate the inputs. The size of the computational time-step entails the computational output, which means that the size of the time step is the size of the output. Contextually to a line of code, if the line of code would provide a large size of the output any program running on that file would need to be able sustain that amount of size of an output. The model used for unsteady computations has limits place on the argument to process the premises, that is, the inputs are processed based on the input, process, and time step. Now if the time step is that of a 20-minute computation, over a span of 6 months (at average 30 days/month), that creates a total 12960 cycles of computational outputs. Based on a trial-and-error basis for the model, time frame, and the number of inputs (daily flow records) computation output has an average size of just below 4 gigabytes. The model used for the unsteady flow is based on a 32 bit processor where it can store 2^{32} different values, based on this information, the that a processor with 32-bit memory addresses can directly access at most 4 gigabytes of byte-addressable(Gay, C. 1984). Any more information storage causes an error for memory access based on the limitations of the program.

With this consideration for the program's limit on memory access, the input for the quality transport/temporal model was conducted at a 6 month interval in order to create the necessary amount of output memory of flow condition that would be accessible for the 32 bit program.

4.4 Preliminary Water Quality Transport Modeling Results

The overall objective for an initial preliminary model is to find the so called "initial flaws" within the objective model. In order to have some form of validation is to calibrate the quality model to the observed data, utilizing a set of model coefficients and parameter that are consistent with the observed data that are within the general ranges of values that could be scientifically acceptable. The use for the preliminary model is to utilize the set model coefficients initially used in order to create a guideline that could be used in the calibration process in order to create a consistent improvement across the spatial segments and consistent in time.

4.4.1 Kinetic Parameters

The water quality model is primarily controlled by kinetic rate constants specifying the rate of transformation of various components on the nitrogen and phosphorus cycles, as well as the dissolved oxygen and chlorophyll cycles. Kinetic rates, such as those specifying algal growth, respiration, and nitrification are collected in an input file. Kinetic parameter values used for the final calibration simulation, where several of these parameters were adjusted during the calibration phase of this modeling effort. These parameters include:

- Oxygen demand;
- Nutritional Dispersion
- Parameters controlling dissolved oxygen that include the decay rate, reaeration rates, and sediment demand in a water column;
- Parameters controlling the growth, respiration, and growth limitation of the algal biomass.

The general procedure would be to perform a set of iterative computations for the model that uses estimates of various coefficients and parameters. Comparisons are made between the model output and the observed data in order to obtain a qualitative assessment for the efficiency of the set of coefficients. This process will continue through the adjustments of the model parameter based on observational data, and their overall relation to one another (meteorologically, between nutrients, flow speed, etc.) until a reasonable reproduction of the observed data is attained or no further improvement is possible. Then after using the model's default nutrient parameters initial results were established as seen in **Fig.** 23

Figure 23 Preliminary computation for four locations of dissolved oxygen, where "CBRN" defines Preliminary Calibrated Result Number attempt

Initially there was a minor attempt to calibrate some of the nutrient parameter to see the overall effect of the model, where 4 different methods of dissolved oxygen were calibrated that dealt with reaeration and decay factors of dissolve oxygen. According to the data obtained from the preliminary computations, the measurement data is somewhat resembled on the computations. PBIAS was conducted on various dates as specified graph showcases to find the errors, and taken from Los Ebanos computations were compared to the measurements as seen in **Table 8.**

Table 8: PBIAS Comparison of Dissolved Oxygen between Measurements and Preliminary Results

Stations	Scenarios	1/30/2006	3/22/2006	5/23/2006	12/19/2006	5/23/2007
Rio Grande City	Measurements (mg/L)	7.12	8.2	7.7	6.78	6.23
	Computations (mg/L)	9.695	9.582	8.9	9.44	8.99
	PBIAS (%)	**26.56%**	**14.42%**	**13.48%**	**28.18%**	**30.70%**
Los Ebanos	Measurements (mg/L)	8.56	7.9	8.08	8.2	6.23
	Computations (mg/L)	9.85	8.81	9.02	9.35	8.77
	PBIAS (%)	**13.10%**	**10.33%**	**10.42%**	**12.30%**	**28.96%**
Hidalgo	Measurements (mg/L)	6.08	8.2	7.39	8.64	7.21
	Computations (mg/L)	10.07	8.7	8.64	9.67	8.57
	PBIAS (%)	**39.62%**	**5.75%**	**14.47%**	**10.65%**	**15.87%**

4.5 Calibration of Water Quality Transport Model

The correlations are presented with the percent error for the modeled dissolved oxygen (DO) and measured DO was calculated to varying degree of error; due to the varying numbers of data, the long measurement period, and the dense time interval, there are differences in the error percentage present; while the computed conditions of the year of 2006 seem to correlate along the lines with the measurements (variability tends to be on the lower end of the spectrum with a less than 20% error margin) , the long period of measurement for 2007 dos not correlate with the computations (30.7 % error for RGC, 28.9% for Los Ebanos). In order to improve the computation methods, there has to be a way to implement the changes to the environment surrounding the biological aspect for the nutrients (in this case DO), this can be achieved by considering the parameters used for DO computations.

4.5.1 Dissolved Oxygen Contributions to the Model

The concentration of DO reflects equilibrium between oxygen-producing processes and oxygen-consuming processes and depends on many factors such as temperature, oxygen depletion, sources of oxygen and other water quality parameters. Therefore it is very desirable to create a DO model of the Rio Grande so that water quality can be optimized throughout a time period. The water quality model is a very complicated as it requires more information of the river system. To solve the problem by developing a model that is capable of correlating a large number of input patterns with a resulting set of yields. Many descriptions of DO interaction in a reach of river with various other nutrients have been proposed since the study of Streeter and Phelps in 1925. The implication is the creation of various other mathematical model that relates algae, phosphorous, nitrate, and of course BOD interaction affects the quality in terms of DO. The effects of algae, which is their photosynthetic or respiratory activity, on DO levels is well documented (Marzolf, Erich R. et.al 1994). This indicated that the DO concentration could be used as a principal measure of water quality. The condition of a stream can be determined from a DO balance which includes all the sources and sinks of DO along the reach. The DO balance can indicate the purification capacity of the river that depends on its DO resources and its ability to replace the oxygen consumed in the oxidation of organic wastes. The oxygen source considered by Streeter and Phelps (Streeter, H. W et. al. 1925) was reaeration, or the physical absorption of oxygen from the atmosphere by the flowing stream. Streeter showed that the absorption of oxygen by rate of absorption is directly proportional to the saturation deficit.

Dissolved oxygen concentrations in rivers are controlled by many factors including atmospheric reaeration, biochemical oxygen demands (carbonaceous and nitrogenous), algal photosynthesis and respiration, temperature, and the other characteristics for the river stream.

Many of these factors are difficult, if not impossible, to accurately assess. Such examples include the fact that photosynthesis can produce large quantities of oxygen during the day if algae are present in the stream. On the other hand, nightly algal respiration creates an oxygen demand. Research efforts have attempted to fit functions to this factor, but with limited success (Heymans, 2001, Strickland, 1997). As with other researches, the available data about nutrients (in this case algae) may come limited, as algal quantities were not measured directly, but indirectly by that of chlorophyll-a as a byproduct for phytoplankton algae. Nevertheless, the DO has and is one of the best indicator for life within streams as seen by (Heymans, 2001, Strickland, 1997), with these studies in mind, we will proceed to use the DO as a calibration parameter.

4.5.2 Estimation of Reaeration Rate

Several estimations of the reaeration rate exist, which generally follow the equation

$$k_2 = Kv^a H^{-b} \tag{15}$$

where; K is a constant, v is the flow velocity (m/s), H is the hydraulic depth (m), a is a constant, and b is a constant.

The constants depend on the system to which the equation is applied, i.e. the flow velocity and the size of the stream or river. Different values are available in other literature. Various software have use the application where the constant range from a is between 0.75 to 0.93, while b is between 1.37 to 1.54; they apply them accordingly to the geometric shape for the river/stream. The following equation was derived on the basis of values used for the constant and variables used in published literature along with the popularly used qualitative water model WQMCAL (Jolánkai G. 1997):

$$k_2 = 2.148 v^{0.878} H^{-1.48} \tag{15}$$

Application of this expression will be repetitive at every iteration for a qualitative computation (at every 6 months) to account the average velocity within the channel. Due to both precipitation and the tendency within the study area (next to the Gulf of Mexico), of being prone to attract tropical storms, there are large amounts of flow variations throughout the years. For this matter where the reaeration expression is both dependent on velocity and depth (flow), the calculation for this constant will be recalculated every computation iteration.

4.5.3 Contributions of Algae Biomass to CBOD and DO

Within streams with significant algal biomass, the additions of DO and carbonaceous biochemical oxygen demand (CBOD) recycled from phytoplankton biomass could be considerable. When the preliminary model was used without the inclusion for chlorophyll-a, the modeling for both CBOD and DO was significantly larger or lower than the measured data. Since the river water samples contained the concentrations of phytoplankton found in the river, the results reflect two components of oxygen demand. The first is the demand created by oxidation of organic waste material and the second is the combined demand created by the respiration of living algae and oxidation of dead algae contained in the sample. Matching the model calculated CBOD with the measured values depends on the carbon to chlorophyll-a ratio, which is not usually independently measured and is therefore a parameter with great degree of uncertainty.

4.5.4 Algal Respiration

The use of chlorophyll is used as an indicator for the algal growth rate, as this is limited by light or nitrogen, so nutrient/light effects are multiplicative but nutrient/nutrient effects are alternate (Walker, 1981). The expression above is used to calculate local algal growth rates are listed in the model's User's Manual. The model specifies that the algal respiration rate controls the amount of oxygen that is consumed by algae, while it is assumed that the algae use ammonia and/or nitrate as a source of nitrogen. The effective concentration of available nitrogen is the sum of both concentrations and the algal growth rate are temperature dependent. These factors are used for calibration purposes according to the procedure explained in the User's Manual.

$$CHL = \alpha_0 A \tag{16}$$

where CHL is chlorophyll-a concentration (μ Chl-a L^{-1}), α_0 ratio of chlorophyll-a to algal biomass (μ Chl-a/mgA)

The input data for the model is offered in the format as algae, in this case the byproduct of chlorophyll-a would have to be converted using the expression previously mentioned, this is usually done by factors such as research provided by numerous researchers (Heymans, 2001, Strickland, 1997, Dalsgaard & Pauly, 1997, Walsh 1981, Bundy 2004). A consideration for the measurements that were provided for chlorophyll-a were in terms of weight, to which the conversion for chlorophyll-a to phytoplankton biomass for weight factors are provided in **table 9.** The necessity to provide various results were based on a number of conversion factors that were used due to the uncertainty and lack of study in the matter, that is the variability for algal reproduction is based on numerous factors (atmospheric, flow conditions, nutrient contents, etc.). It should be noted that those conversion factors literature themselves provide caution in regarding the appropriate conversion factor to convert phytoplankton organic carbon. For this reason various conversion factors were used during the calibration process in order to achieve the best results based on the recommendations on **table 9.**

Table 9 Phytoplankton Conversions and Comparisons.

Quantity	Reported Values	Reference
mg C: mg Chl	30	Strickland 1966
	30	Epply 1968
	30	Banse 1977
mg wet weight : mg C	32.26	Heymans 2001
	10	Dalsgaard 1997
	16	Walsh 1981

The chlorophyll-a conversion factor is somewhat an important calibration factor, along with the reaeration coefficient, as they have a factor on the overall sensitivity of the computations(Heymans, 2001). This is why it is important to have all available options ready at hand, in this case having multiple conversion factors. Quantifying the amount of chlorophyll-a alone is a task that requires either a filtration process or chemical testing that is not at all times available, and due to only a growing interest of quality for the Rio Grande in recent years, there are limited amount of measurements and/or sophisticated testing techniques to measure chlorophyll-a. Nevertheless, with the readily information that is available, the factor of chlorophyll-a is necessary as it provides a measure of the amount of active algal biomass present per area of stream bottom, or a measure of phytoplankton from a volume of water that uses oxygen. With the various conversion factors, the one that yields the best computations will be used.

4.5.5 Dispersion Coefficient

Nutrition dispersion might be another factor that influence the indicator of dissolve oxygen (as mentioned before) where the factors of kinetic rates, such as those specifying algal growth, respiration, and nitrification is affected by the mixing processes of solutes in porous media/aquifers. The hydrodynamic dispersion coefficient is a measure of their mixing process for modelling of dispersion in turbulent fluid flow, where this coefficient is dependent on flow rate and the dispersity factor, which can be determined by the effect the geometric shape and its effect on velocity has on the water (Auset & Keller, 2004).

For the mixing process, there is a combination of molecular and mechanical dispersion functions in nutrition mixing process (such of those for solutes), with the hydrodynamic dispersion coefficient it creates a way to sum both the mechanical and molecular dispersion. The spread of particles are spread over a large area and the concentration gradient are small, where the model determines the concentration by solving the advection-diffusion equation numerically. The model uses the advection-diffusion equation, where the dispersion is accurate only if the diffusing particles have been in the flow longer than a Lagrangian time scale, and they have to spread to cover a distance that is a size larger than the largest scales of the turbulent fluid flow (Fisher et al., 1979). This concept was established and worked on by various other research works (Smiles, Gardner, & Schulz, 1995; Chou, Wu, Zeng, & Chang, 2012), where they improved other characteristics, such as the use of the by-products of the spread covered distance and the geometry (velocity and wetted width) to combine them into an equation. Through the use of Eulerian framework and a set of partial-differential equations that has to be solved simultaneously with the advection-diffusion equation. The model itself recommends the use of the following equation for calculating the dispersion coefficient (Brunner, Gary W., 2010a) to be used for the calibration of dispersion rates:

$$D = m \times 0.011 \left(\frac{u^2 w^2}{y u^*} \right) \tag{17}$$

where: m is a user assigned multiplier (unitless), u is the face velocity (m/s), w is the average channel width (m), y is the average channel depth (m), and u^* us the shear velocity (m/s).

For the shear velocity, the equation is established as:

$$u^* = \sqrt{gdS} \tag{18}$$

where: g is the gravitational constant (9.81 m/s^2), d is average channel depth (m), and S is the friction slope (unitless).

During the calibration process and dispersion coefficient determination, the features of hydrodynamic dispersion, flow velocity, and dispersity were compared individually under the conditions of water flow for their corresponding computational time. The confluence of varying sites were a varying factor on the coefficient, where factors such as precipitation, varying flows, and diversions are an issue when calculation is needed. For this matter, computation for 6 months (as established beforehand) needed the coefficient to entail a variation of flow. Although a logical method to establish the flow velocity and dispersity would be to obtain an average for the six months, the method used was to use the velocities of the most dominant flow regime for the 6 month span. Both the flow velocity and the dispersity variables reflect the complex mechanism of hydrodynamic dispersion response to given impact factors. A predominant flow regime that is repeated more often than other would be used for the dispersion coefficient in order to account a base line of flow velocity and the dispersity variables that is representative of the computational time.

4.6 Quality Transportation

It is important to factor the evaluation and to quantify extent of nutrient loadings into the water placed in by the surrounding area, as most of the runoff comes from the agricultural and carried off by drainage ditches (EPA, 2010). Quantifying nutrient loadings from drainage ditches is limited to a few measurements that convey the surrounding water. The water quality sampling of the study vary in such nutrients as the nitrogen species; ammonia-nitrogen, nitrite and nitrate-nitrogen, total and dissolved phosphorus, dissolved oxygen, algae, and other water quality parameters.

Using a monthly input data, small time-step, the model computes the atmospheric warm/cold surface layer that affects both water temperature. Computed results will assess the kinetic processes and corresponding time rates of change of the concentration due to biochemical reactions and its dispersion factor. The kinetic process will be determined by the change in water temperature created by the heat budget which includes solar radiation, wind mixing, air temperature, cloud dispersion of solar radiation, humidity, and atmospheric pressure.

Computations of water mass transportation were modeled to compare the nutrient mass transport to that of surveyed results to initially obtain a control quality model. The river flow samples were collected at gauging sections to monitor water quality over the river reach. Field water quality parameters were monitored by using either multiprobe sonde, water sample collections and subsequent tests of it, that include parameters such as temperature, dissolved oxygen, conductivity, pH. While the nutrients were analyzed for nutrients of nitrate, nitrite, organic nitrogen and orthophosphate.

Water was tested for various nutrients were collected from every gauging sections were provided by the department of Texas Commission of Environmental Quality (TCEQ). Data is based on monitoring of the water quality parameters over the period of 5 years (2006-2010) on varying of monthly to quarterly (year) basis at various sites in the Lower Rio Grande River. The following are the parameters: temperature, dissolved oxygen, pH, salinity, turbidity, nitrite nitrogen, dissolved nitrate nitrogen, dissolved organic nitrogen, dissolved ammonium nitrogen, dissolved organic phosphorus, dissolved orthophosphate, carbonaceous biological oxygen demand, and algae. The chemicals were analyzed by equipment TCEQ used in their labs from the water samples. All of these parameters were collected on surveyed dates and used for modeling, with an indication of measured data, where that information will be used to be review the modeled quality transport in the canal and compared to that of real surveyed results Each applied nutrient has a biological impact on the water that relate to the quality of the water as well as their nutrient counterparts.

4.7 Water Quatlity Modeling Results

The water quality transport model will be implemented to compute the DO, carbonaceous biochemical oxygen demand, ammonium nitrate and algae biomass with a comparison of field measurements. This study will simulate the flow of the Lower Rio Grande River overall sections at a stepwise method section by section over time. This will allow the study of nutrient transportation to be simulated as an effect of accumulation over sections of the water that could help manage the use of tributary flows out, or into, of the water to soften the effect of nutrient loadings into the water. The critical hydraulic computation was correlated to correspond to specific date of nutrient observations to reflect that of regular mass and flow transportation. In order for fair and unbiased set of results, there will be a separation of inputs in between sections;

that is, having a set of variables and control stations. The input sections for qualiative information implemented for computations will be the source of inputs or the control, while the variables will be excluded from the applied set of inputs and studied and compared to the computations, or the variables. The stations that are identified in this study are as follows starting from the upstream sections to the downstream: Falcon Dam, Rio Grande City (RGC), Los Ebanos, Anzalduas, Hidalgo, Pharr, Progresso, San Benito, and Brownsville. The stations were picked as they are gauging stations and also are relatively evenly spaced out at about 20-30 miles apart. The control stations are RGC, Pharr, and Brownsville. While the variable stations are Los Ebanos, Anzalduas, Hidalgo, and Progresso.

An advantage of modeling at a normalized flow rate (yearly/seasonal) would be to correspond a nutrient observations to minimal accumulation of concentration over a distance within the reach. Management application can locate those sections of abnormal concentrations and address them than the otherwise option for high flow modeling that would transport nutrients farther downstream at a faster rate. The model is able to predict observed water quality concentration within the river. Observations of vigorous amount of measured data and, preferably, daily temperature readings were implemented into the model in order to close the gap in accurate results that could represent any concerns. As covered from the previous sections, this iteration of the model was updated to include the calibrated parameters that do in fact influence the overall computations for the nutrients. Special attention was placed on various parameters: reaeration parameter that dictates the ability of oxygen to be replenished within the river, the inclusion of the conversion of chlorophyll-a into algae in which is used as a degenerative factor in the rivers oxygen, and the dispersion factor which is the combination of molecular and mechanical dispersion functions in nutrition mixing process.

4.7.1 Modeling Plan

Different nutrient concentration situations of the river system, different flow possibilities, and at various ranges of a meteorological influence in water that were translated into various flow condition scenarios. Hydraulic computation was translated into nutrient mass transportation as a crucial element for the study. The plotted model results are outputted at a 12-hour cycle for the model output for each constituent and for each station, and the measured data was compared at corresponding dates for each simulated station. The compared results between observations and the model's computations are those of dissolved oxygen, algae, biological carbonaceous oxygen demand for the stations that were not used as the inputs.

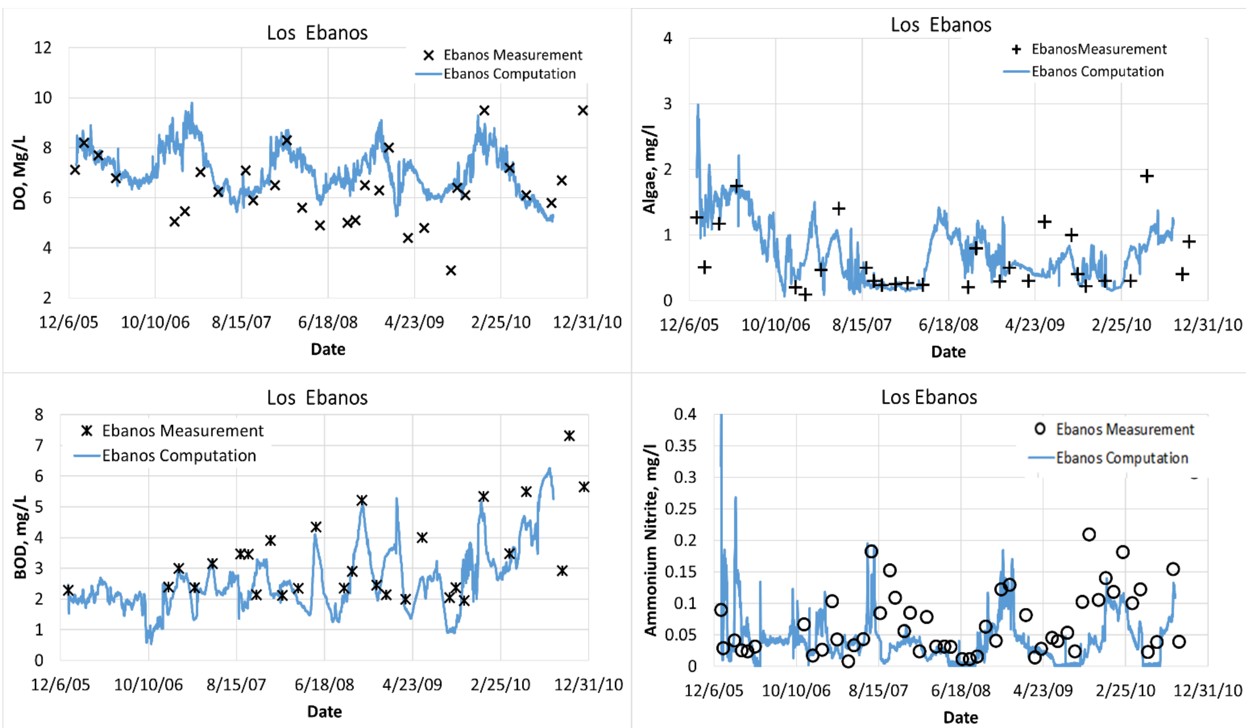

Figure 24 Los Ebanos comparison between observations and computations of DO, CBOD, algae, and ammonium nitrate.

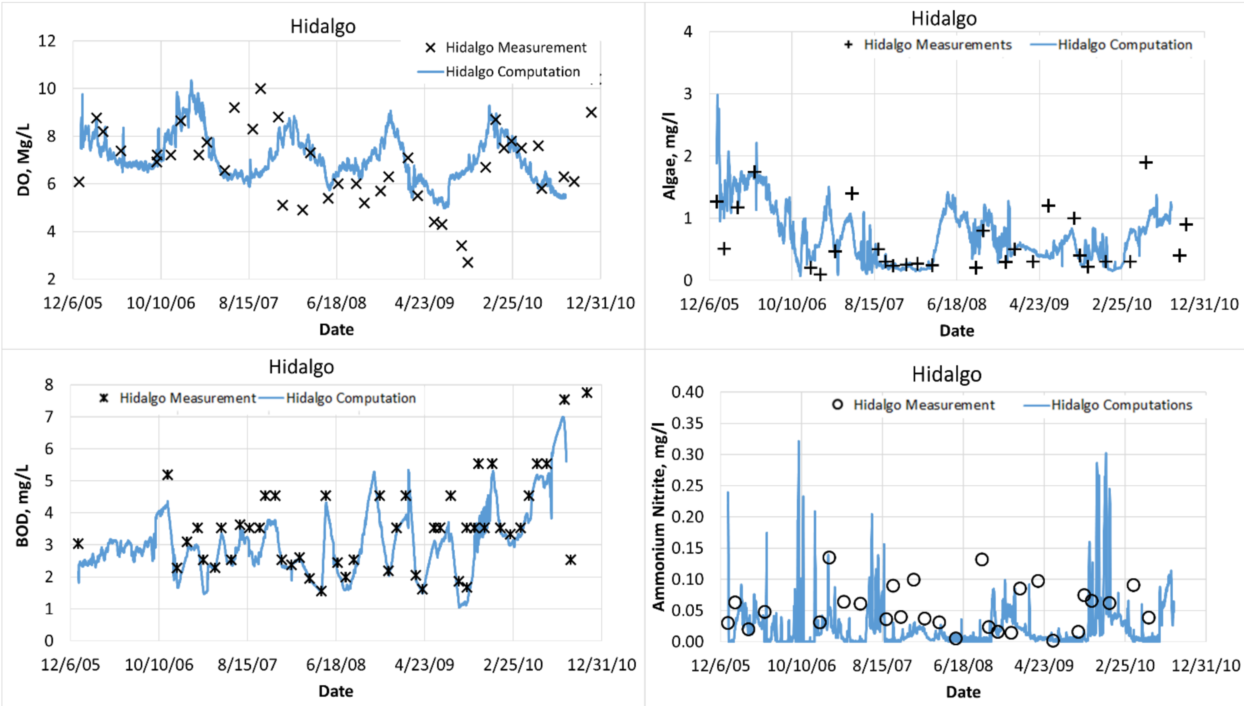

Figure 25 Hidalgo comparison between observations and computations of DO, CBOD, algae, and ammonium nitrate.

4.7.2 Dissolved Oxygen Computational Analysis

The nutrient computations of the five different dates were compared to the measurements, as seen in **table 10**, where the PBIAS for 3/30/2006, 3/21/2007, and 5/20/2008, 12/14/2009, 9/14/2010, where the sites of RGC, Los Ebanos, Hidalgo, and Progresso were compared to the observations for dissolved oxygen. This nutrient computation was expected to be the dominant feature from which the computation was to correlate strongly to the measurements, as this is the most extensively researched, calibrated, and abundant in observations measured. As seen by the table, the location for RGC fall within the acceptable margin of a PBIAS of 10 %, for the dates of 3/30/2006, 3/21/2007, and 5/20/2008, 12/14/2009, 9/14/2010 having 7.36%, 10.26%, 2.32%, 5.46%, 3.94% margin of error for the compared dates. Hidalgo has a margin of error of 6.5%, 1.3%, 7.8%, 0.32%, 5.5%, for the dates previously mentions, while Progresso only has a margin of error that varies between 4.6%-9.9% all of which fall below the 10% acceptable margin.

Table 10: PBIAS Comparison between Measurements and Calibrated Results for DO

Dissolved Oxygen						
Stations	**Scenarios**	**3/30/2006**	**3/21/2007**	**5/20/2008**	**12/14/2009**	**9/14/2010**
Rio Grande City	Measurements (mg/L)	7.12	7.18	6.23	10.4	4.2
	Computations (mg/L)	7.69	8.00	6.38	9.86	4.37
	PBIAS (%)	**7.36%**	**10.26%**	**2.32%**	**5.46%**	**3.94%**
Los Ebanos	Measurements (mg/L)	8.56	7.03	4.9	9.5	5.8
	Computations (mg/L)	7.95	8.58	5.75	8.62	5.12
	PBIAS (%)	**7.62%**	**18.07%**	**14.76%**	**10.16%**	**13.18%**
Hidalgo	Measurements (mg/L)	6.08	7.74	6.56	8.7	6.3
	Computations (mg/L)	6.50	7.84	6.08	8.75	5.97
	PBIAS (%)	**6.49%**	**1.33%**	**7.84%**	**0.62%**	**5.45%**
Progresso	Measurements (°F)	9.1	7.6	4.4	7.3	4.8
	Computations (°F)	8.43	8.00	4.80	8.10	4.59
	PBIAS (%)	**7.93%**	**4.97%**	**8.30%**	**9.90%**	**4.62%**

Stronger correlations with the for the modeled nutrient was expected for the calculated section of Los Ebanos, as this site is only a 20 miles downstream a control site and thus, creating a small percent error of to a small varying degree of error, but as seen by the table a different result was presented. The differential in qualitative comparison were varied from 7.62%to 18.1% error as presented on Table 10 for Lose Ebanos section. The quality transport computations was reviewed for the flow used as an accurate description of real flow conditions that reflect the advection of water based on the comparisons done and the informational accuracy for the calibration factors. Both of the parameters seemed to be accurate after 5 different iterations, along with a review of the input data. As seen within the Los Ebanos section, variation on the comparison, the margin of error seem to be the highest at this particular section, with a variation between 7.62%to 18.1% error. Although this is particular concerning, this anomaly could be from misinterpreted input parameters; maybe wrong historical information was provided from data sources, this idea can be proved from the next two sections. Let's take into consideration of stations of Hidalgo and Progresso, the margin of error is between 0.62% to 9.9%; analyzing these comparisons, we can take into account the calibration parameter of reaeration's computational effect. As mentioned in section 4.52, the reaeration effect is based on the velocity and area which in turn covers the overall cross-sectional length in between sections. This means that although, the Los Ebanos section had a bad computational concentration, the reaeration effect recuperates the oxygen levels within the water, as shown at the Hidalgo and Progresso stations.

4.7.3 Carbonaceous Biological Oxygen Demand Computational Analysis

The computations of CBOD can be taken as a way to investigate the environmental impact of water runoff across the Rio Grande River. Through quantification of our data, there is insight on the component concentration that will allow the computations to analyze the quality. This computation allows us to gain insight into the oxygen depletion that is caused by two important factors, the biological oxygen demand of aquatic life, and the actual dissolved oxygen. The latter, DO, would induce sight in the amount of waste being discharged, as the levels of DO are lower in waste, through-out the river. Thus, the DO at the river is lowered as soon as the waste is added into the stream. As covered in the previous section, there were some concerns due to the fact that a set of dissolved oxygen information might have been compromised for the RGC section. Considering that the dependence of CBOD lies on DO, the set of characteristics for DO would be transferred onto the CBOD. So let us consider the results: there were computations of the five different dates were compared to the measurements, as seen in **Table 11**, where the PBIAS for 3/30/2006, 3/21/2007, and 5/20/2008, 12/14/2009, 9/14/2010, where the sites of RGC, Los Ebanos, Hidalgo, Anzalduas, and Brownsville were compared to the observations.

Table 11: PBIAS Comparison between Measurements and Calibrated Results for CBOD

Carbonaceous Biological Oxygen Demand						
Stations	**Scenarios**	**3/30/2006**	**3/21/2007**	**5/20/2008**	**12/14/2009**	**9/14/2010**
Rio Grande City	Measurements (mg/L)	5.19	2.54	4.24	5.54	1.62
	Computations (mg/L)	4.77	2.32	4.19	5.25	1.50
	PBIAS (%)	**9.01%**	**9.47%**	**1.18%**	**5.39%**	**8.39%**
Los Ebanos	Measurements (mg/L)	2.38	2.37	4.35	5.34	2.54
	Computations (mg/L)	1.64	1.33	3.95	4.78	1.68
	PBIAS (%)	**45.05%**	**78.67%**	**9.97%**	**11.88%**	**51.01%**
Anzalduas	Measurements (mg/L)	1.77	1.18	3.00	1.18	1.50
	Computations (mg/L)	1.84	1.11	3.27	1.28	1.38
	PBIAS (%)	**3.74%**	**5.77%**	**8.26%**	**7.25%**	**9.13%**
Hidalgo	Measurements (°F)	4.11	1.87	1.29	1.31	1.99
	Computations (°F)	3.84	1.86	1.40	1.58	1.87
	PBIAS (%)	**7.03%**	**0.36%**	**8.22%**	**17.13%**	**6.74%**
Brownsville	Measurements (°F)	4.09	1.69	3.00	1.13	1.76
	Computations (°F)	4.70	1.66	1.28	1.10	1.63
	PBIAS (%)	**12.88%**	**1.78%**	**134.30%**	**2.65%**	**7.70%**

As seen by the table, the location for RGC fall within the acceptable margin of a PBIAS of 10 %, for the dates of margin of error between 1.18% - 9.47 % for the compared dates.

Anzalduas had a PBIAS between 3.74-9.13%, while Hidalgo has a margin of error of between 0.36%-17.13%, this site has some concern for the set of computations which will be later explored. For the remaining site of Brownsville, the margin of error varied wildly; from 1.78% to 134.3%. The Brownsville site had an anomaly in its computations due to the fact that for the date of 5/20/2008 the margin of error is 134.3%, while the other date fall within a reasonable margin; this site was computed for various times at different computational cells but there were no changes seen to the anomaly. In this author's opinion, this could probably attributed to computational noise where the effects of finite precision destroy smoothness of the simulation output and complicate subsequent analysis. The station for Brownsville is only limited to up to 2-3 measurements per year, as water samples for CBOD for this site are smaller than the other sites presented in this study. It is important to factor the evaluation and to quantify extent of nutrient loadings into the water placed in by the surrounding area of all the sites, as most of the runoff comes from the agricultural and carried off by drainage ditches. The issue is that quantifying nutrient loadings from drainage ditches is limited to a few measurements that convey the river water site. In terms of random signal analysis the limited instrumentation of the water gives rise to several difficulties. The most severe difficulty is one of short-length data records of low signal/noise ratios in which the sampling frequency is poorly matched with the time constants of interest (2006-2010).

A further problem is that this study is restricted to the use of normal operating records. Our problem here is that given a set of empirical, noisy data, and, incidentally, a reasonable a prior knowledge of the DO-BOD interaction, there are enough samples of DO to justify the amount of it within the water, but in order to quantify the CBOD, there needs to be another establish method of fining the deterministic relations between the dynamics of an algal population and the DO and BOD. There have been various studies on the uncharacteristic of the average level of mathematical modelling activity in this subject area and it's an indication of the importance of describing water quality in terms of CBOD. The effects of algae, that is their photosynthetic/respiratory activity, on DO levels is well documented (O'Connor et. al.), but the same is not true for any possible interactions between algae and CBOD; furthermore, no dynamic model of river water quality has been verified against field data for the Lower Rio Grande River. As this is far greater than the reach of this study, the results will have to stand; as further time and resources can be applied to future studies that could help reduce the computational noise in this study.

Lastly there is the site for Los Ebanos, where the PBIAS was of 9.97% to 78.67%; this site was expected to vary widely for the reasons mentioned in the analysis for DO computations. Although this justifies the reason of why the Los Ebanos site had a widely varying degree of uncertainty, this doesn't explain the reasons of why the sections downstream of this location (Anzalduas, Hidalgo, and Brownsville as seen in **Table 11**) do not vary as much as that specific section. Although Los Ebanos is not a control site, the effects of the computational results must be transferred through to the other downstream sections as the model has the effect by being a Langrarian model. Well there are two factors on why the other downstream sections are not affected: one being is the fact that downstream of Los Ebanos is the control site of Anzalduas, where the information is taken into account for the computations at the Anzalduas site and used for the lower tier of the computations. The second has to do with the computational parameter of reaeration that affects the DO and CBOD, where the issue of distance, velocity, and time take into effect the overall reaeration of the water. The overall calculation for the reaeration can identify the baseline for conditions of abnormal environmental events when they occur. These conditions are the expected in normal environmental conditions for the body of water, including an expected range of values for each parameters established by substantial observation. Important factor that is considered is the amount of time the water spend traveling and the overall amount of wastewater within the water, where the DO depletion along the river are dependent on the sources of oxygen and the factors affecting oxygen depletion.

The influence of biological oxygen demand degradation on the water quality modeling can be explained by the characterization of the river's DO sag profile, it only considers that the first-order biological oxygen demand (BOD) degradation and atmospheric reaeration are the sink and source in a river, respectively, as seen in in equation 1. In the river water-quality calculation, the assumption may not always provide satisfactory simulation due to an inappropriate description of BOD degradation. There were various patterns of BOD degradation, where they were combined with the oxygen reaeration to simulation the DO sag profile in a river. To consider the correlation between the observations and the computations, with the possible comprised data set that Los Ebanos site, to the other downstream sections of Anzalduas, Hidalgo, and Brownsville where the margin of error varied from 0.36% to 17.8%; the use of the various data sets from the other control sites below the compromised data section were computed with the inclusion of interpolation from upstream sections to downstream sections.

For the calibration process (reaeration rates, decay, dispersion), the consideration of flow velocities, atmospheric conditions, and temperature are combined with input data, where before the computations occur, the transition of information from one section to another is linearly interpolated between control sites, with variable sites in-between them. When the model's computation starts, it then correlates the information between deoxygenating and reaeration rates, low flow areas, high sedimentation, atmospheric conditions, and other nutrients which then provides the computed factors to the variable sites. The oxygen deficit in water after exertion of CBOD decreases the farther away it is from the wastewater river junction; the higher the travel time value, t, away from wastewater site, the higher the travel time value is, the overall value of the oxygen demand is decreased. In this sense, this could explain the reason on why the computational values for the carbonaceous biological oxygen demand for the downstream sections (Anzalduas, Hidalgo, and Brownsville in **Table 11**) correlate with the observational data, despite the fact that the control site's input data for the Los Ebanos site (upper stream) could have been compromised. The overall computations of the model for CBOD appear to track the nutrient transportation and predict the biological changes created by the environments and concentration along the reach were modeled accurate level despite the possible compromised site. Considering the PBIAS, most of the results fell within a range of 10% of error for the majority of the sites, to which was attributed on a number of factors aforementioned. In order to make a more accurate model it is possible to include other factors such as a modification of the model that includes internal sources (such as photosynthesis) and sinks (BOD, background BOD, sediment oxygen demand, and other respiration) of DO. As that is beyond the scope of the study, the model shall stand and explored on a future study.

4.7.4 Algae Computational Analysis

The computation for algae, where the model specifies that the algal respiration rate controls the amount of oxygen that is consumed by algae, is showcased on **table 12.** The effective concentration of available the algal growth rate are temperature dependent, from which with the accurate computation for temperature, there was some assurance on the computational accuracy.

The model only allows one algae group to be defined and simulated (Lowney, 2010). Observed algal biomass was converted from chlorophyll a measurements, whereas the observed algal data are in units of Chl a concentration (mg/L). **Table 12** shows the final calibration results for simulated and observed algal concentrations at 5 stations for six years. Statistic indices of algal biomass indicate that the model performs well overall for the majority of the stations. Simulated concentrations are quite small during the winter time of the year until the temperature and light conditions are suitable for algal growth. Peak concentrations of algal biomass simulated for the summer (July-August) range from 5.0 mg/L to 7.5 mg/L. RGC was considered as a control site, where its overall accuracy for a low margin of error was from 0.84% to 17.8%; Los Ebanos varied from 3.59% to 67.35%; Anzalduas varied from 1.84% to 70.34%; Hidalgo had an MOE of 0.61% to 73.61%; and Brownsville went from 11.24% to 90.96%.

Table 12: PBIAS Comparison between Measurements and Calibrated Results for Algae

Algae						
Stations	**Scenarios**	**3/30/2006**	**3/21/2007**	**5/20/2008**	**12/14/2009**	**9/14/2010**
Rio Grande City	Measurements(mg/L)	0.72	0.45	1.78	0.29	1.30
	Computations (mg/L)	0.88	0.47	1.56	0.30	1.31
	PBIAS (%)	**17.87%**	**2.43%**	**14.21%**	**3.36%**	**0.84%**
Los Ebanos	Measurements (mg/L)	1.17	0.47	1.59	0.30	0.40
	Computations (mg/L)	1.21	0.50	1.28	0.32	1.23
	PBIAS (%)	**3.59%**	**5.89%**	**24.65%**	**5.69%**	**67.35%**
Anzalduas	Measurements (mg/L)	0.69	0.45	1.80	1.00	0.25
	Computations (mg/L)	0.55	0.46	1.71	1.03	0.84
	PBIAS (%)	**26.42%**	**1.84%**	**5.19%**	**3.18%**	**70.34%**
Hidalgo	Measurements (°F)	0.74	0.42	0.20	0.50	0.21
	Computations (°F)	1.57	0.48	0.77	0.50	0.80
	PBIAS (%)	**53.08%**	**12.72%**	**73.73%**	**0.61%**	**73.61%**
Brownsville	Measurements (°F)	1.98	0.50	0.57	0.27	0.60
	Computations (°F)	1.66	0.26	0.51	0.32	0.62
	PBIAS (%)	**19.32%**	**90.96%**	**11.24%**	**15.61%**	**3.60%**

The issue now stands on the fact that algal quantities were not measured directly, but indirectly by that of chlorophyll-a as a byproduct for phytoplankton algae. Using a different range of conversion factors, **Table 9**, the computational model used various conversion factors that depended on the recommendations by different studies (Heymans, 2001, Strickland, 1997, Dalsgaard & Pauly, 1997, Walsh 1981, Bundy 2004). There is another factor that is needed to factor in the algae; the growth of algae (phytoplankton) is governed mostly by the availability of the two main nutrients phosphorus, P, and nitrogen, N, plus light (Rechkow K.H. 1979). Keep in mind that the Lower Rio Grande has been only been studied for qualitative standards at a bi-national in only recent years. With the available data sets, provided by TCEQ, the collection of phosphorus and nitrogen were hardly available, with sample sizes sometimes limited to only 3 time a year and for only 3-4 sites along the river. The Dalsgaard & Pauly, 1997 study had a similar situation of where, due to limit data availability, the algal computation was derived from the CBOD, where it was lumped as avariable and made up of both algal and nonalgal biomass. In the model, CBOD and algae are separate state variables; so, it is necessary to either subtract algal effects from measured CBOD or add algal effects to modeled CBOD. Again, this process can be presented in a future study, where time and resources can be used to use the observed CBOD data and be converted into CBODu (effluent), then algal biomass consumption of oxygen subtracted for model comparison. Five-day carbonaceous biochemical oxygen demand concentrations can be used to define $CBOD_U$ inputs for the point sources because they are measured more frequently. Also, the discharge permits are defined in terms of CBOD5 (Smith et al. 2010). This is thought to be a way to relate two as point source inputs before the variable station from the upper section, use them a point source, and implement it into the model to monitor the changes along the river.

4.8 Summary of Quality Transport Transformational Model

This study explored the application of the travel time distribution formulation in the context of tributary and diversion outflows water interaction with the main water stem for the Rio Grande River in order to replicate the transportation of qualitative nutrients. Through the medium of a distributed hydrologic modeling, we constructed the one dimensional, unsteady state hydrological water flow model of the shallow, unconfined aquifer at the Lower Rio Grande watershed, in South Texas. The distribution was characterized with a mean travel time of 6 to 8 days. We were able to find that the time scales over which one can expect to observe the surface water response to distributed along the watershed, were influenced both by dams and diverting/combining flows that vary along the watershed to be of the order of a week. The determination of the time travel is due to the impact of various control variables on this distribution. The necessity of attributing the inflows to the main river flow is a representation of the watershed's water catchment due to precipitation that flows into the river was able to introduce the necessity of dispersion for qualitative terms. The goal of attaining a water balance was achieved through the representation of storm event that provide water from the watersheds that provide flow waves along the river path-lines. The last control variable are the dams/lateral structures themselves; where their detainments and diversion of water attributed to the water balance that the necessary ingredient for the quality transportation in which it creates a sort of backlog that accumulates the nutrients.

The water quality transportation model, simulates BOD, DO, simplified algae biomass in the river system. The hydraulic simulation produces hydraulic outputs at each specified time scale for use as input to the model. This integrated model was applied to the LRG where it was able to predict observed water quality concentration along the LRG. Moreover, the model reproduces temporal and spatial distributions of algae, CBOD, and DO against those of measurements. The model allows realistic predictions based on the combined effects of hydraulic, biological, and chemical processes on longitudinal variations in water quality. A greater degree of spatial resolution of water quality was obtained than would otherwise have been possible, due to the relatively complex hydraulics of the model.

CHAPTER V

CONCLUSION

A new water quality transportation model, was developed by using HEC-RAS. The numerical model simulates BOD, DO, simplified nitrogen and phosphorus cycles, and algae biomass for the Lower Rio Grande River. The model hydraulic simulation produces hydraulic outputs at each specified time scale for use as input to the qualitative model. This integrated model was applied to the Lower Rio Grande River in the southern Texas watershed. The model is able to predict observed water quality concentration along the river, moreover, the model reproduces temporal and spatial distributions of algae, CBOD, and DO that could allow realistic predictions based on the combined effects of hydraulic, biological, and chemical processes on longitudinal variations in water quality. A greater degree of spatial resolution of water quality was obtained than would otherwise have been possible, due to the relatively complex hydraulics of the model. This is the first application of a new water quality for the LRG. This tool expands the HEC-RAS modeling framework to achieve linking water quantity and quality modelling at basin scale. This model allows modelling of temperature, arbitrary constituents, dissolved oxygen and eutrophication processes. The main advantages of the model are the variety of constituents that can be modeled, the integration with the water management module and the integration of all the elements of a basin and their interdependences. Its integration in the environment provides easiness of use and of result display and analysis. This one basic model that has been used extensively, has demonstrated to be able to calculate the river water quality in which watershed for DO, algae, and BOD used for important pollution loading. There are limitations on its application as there has been a question as to whether the first-order assumption on the nutrients is appropriate. Therefore, this study is aimed at investigating the influence of various forms of nutrient loading along the river such as those with various concentration of those created by waste water flows.

The model created can help assess insight on the water quality and hydraulic management; the necessity factors of creating such model involved hydraulic, environmental factors, and complex spatial variability in order to have a variable response to the surface runoff and water quality to changing conditions. Temporal changes were integrated to the model, where analysis indicated the impact from the seasonal changes that have a biological effect on quality parameters. The impact of the temporal waters is significant as it creates the tool for management for potential agricultural runoff, wastewater, and drainage from growing populations. The tool can be used to plan the input from municipal wastewater to find the effect of degradation and/or quantity and quality of surface water bodies. With the development of the model that use mathematical techniques, it can be used to aid decision makers in creating cost-effective and environment-friendly plans for wastewater management.

This shows that the model can provide a real predictive capability and aid in assessing riverine water quality. The model is a simplified transportation nutrient model, where there were promising findings in the study where not only a normalized flow was established, but it shows that a qualitative model can be achieved with further exploration to nutrient calibration. This model can be a major advantage that it could demand less input data and computational effort, which makes it suitable for quick studies or for projects where there is limited data available. Because of its widespread use in flood analysis and other hydraulic studies, most large river systems, as well as many smaller rivers and streams in the US, have already been modeled with HEC-RAS. An existing river hydraulic model can quickly be adapted to model water quality. With this, the overall cost to those whom study it could be interested in water quality modeling is dramatically reduced.

The qualitative status of the Lower Rio Grande varied at different locations. For one, those stations that were above the influence of tributary flows, had a relative good condition, with DO levels varying between 7 – 10 mg/l, and BOD levels from 4-7 mg/l for RGC and Los Ebanos station. These qualitative parameters indicate that levels between 8 -9 mg/l for DO and 4-6 mg/l for BOD are in great condition that the general aquatic life can thrive. Other stations that were integrated with tributary flow had lower values for the qualitative parameters, like those stations below of Anzalduas had up to 6-8 mg/l for DO and 2-5 mg/l for BOD, where these levels are not threatening, but have a cause for concern. The assumptions for these lower levels comes from the fact of the Lower Rio Grande Valley's economic zone of agriculture and increments of concretization due to populations booms. Another issue could stem from the computational analysis for the site that stems from the Rio Grande City location, where the information gathered from the site could have been compromised to the wastewater treatment plant located at that location. This can come as a call of concern unless the site for water collection can be addressed, which brings us to the limitations of the model.

The computational model does have various limitations when it comes to the computing power of the software program. The modeling choice to run the hydrologic model at an interval span of a year was initially chosen to correlate with the yearly seasonal effects, but there were limitations based on model sensitivity. Numerical diffusion (attenuation of the peak) and model stability had a precedent to the derivatives of the unsteady flow equations in the model. There are calculations with respect to time and distance, where wave distribution, velocity calculation, and flow can be attenuated with respect the comparison to the control measurements. The issue that hydraulic properties change rapidly with respect to time, where the program might go unstable, might be improved to create a smaller time-step where calculations can be stable and more accurately represent the measurements in order to improve the hydraulic aspects needed for the proper used in the quality transportation model. In other words, if there is a smaller computational time-step, the mixing properties, velocity, and flow recordings from the unsteady state model can be recorded at an interval of 10 to 20 minutes that can capture the hydraulic properties changes from a smaller time-step. These computations can be transferred as the flow conditions for qualitative mixing in the transportation model. For the quality transportation model, the limits stems originally from the limits from the hydraulic model, but there are also limits due to the data information gathered. While the information was enough of a success to correlate the computations to the measurements, there is also room for improvements. For example, the qualitative information gathered for the RGC sited needs improvements in order assert a better conclusion for the site's qualitative status, while other sites (to be more specific sites below the Progresso station) had a limited amount of qualitative parameters.

Improvements to the model can be expanded to incorporate new contaminants and other water qualitative aspects, such as sediments, and other, to overcome current limitations. Also, it can be made to couple the water allocation simulation and the water quality simulation models in such a way that water quality will be also considered in the canal systems within the Rio Grande Valley. This new model can include the canal system with the main river, can improve various aspects of flow (tracking diversions and inflows along as backwater into the river), and attain information of what & how much of the qualitative parameters are going into & from the river. The implementation of greater diversions are also an important factor to improve the model for flooding events, where not only can this system gather information of the potential locations for flooding, but also see how the land surrounding the river might be affected by the potential floods. Qualitative aspect for the model with an expansion of the model with a diversion and tributary system of canal creates the need for qualitative parameters for them. Luckily, there are Texas programs that are expanding on informational gathering around the canal system in recent years, these plethora of information can greatly improve the model transportation.

Overall the model itself was found to be successful when compared to the measurements, although a verification process still needs to be done, the calibration of the model was a success. The margin of errors were gathered to be around the 10% error margin success established by the EPA, which means that further steps to improve the model can be done in order to follow the next step of verification. Further plans to create a canal system will be adapted into the model by another master's student, by taking this model as the framework. The inclusion of further information to this model opens up the potential to the verification process that was not possible during the course of this study. With the help of the improvements, all the scenarios previously defined, environmental, incremental, and dilution flows can be estimated for each alternative. These additional flows can be estimated under the water quality criteria for aquatic life where the dissolved oxygen is used as the critical constituent and hopefully verified. The overall variability of flow, concentrations, and temporal changes of the model accounts to all aspects of the river where the amount of qualitative loadings and volume changes overtime. The idea is to use the variability to obtain a tool that is able to consider the wastewater contamination that is affected by the seasonal changes. If used properly, the model can be used to plan for various aspects such as wastewater transportation that can be used not only monitored within a river that is as a water resource, but to account for nutrient loadings from wastes used within the agricultural community and for its bi-national management. The modeling efforts is just the initial phase from the end goal of being able to use the model to forecast the biophysical water quality that would be used to help dual nation management make decisions in exploring and create plans for managing the river-water system.

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BIOGRAPHICAL SKETCH

Jose Orvyl Gonzalez graduated from the University of Texas Pan American with a Bachelor Degree of Science in Civil Engineering on May 2015, and earned his Master of Science in Engineering Management degree from The University of Texas Rio Grande Valley on August 2017, with a focus in hydraulic systems and watershed management. Mr. Gonzalez is a member of a number of professional and student organizations including the Texas State Chapter of the American Society of Civil Engineers, Structural Engineers Association (ASCE) and Society of Hispanic Professional Engineers (SHPE). During the past two years, Jose participated in Bi-national River management internship/study spearheaded by the Texas Commission on Environmental Quality in which a current study of river and watershed management in quality within the Lower Rio Grande River. These experiences provided him with valuable experience and insight into the design, coordination, and construction of a variety of hydrologic and hydraulic modeling that provides insight in emergency, quality, water management. Jose will take the FE Exam this October and will obtain EIT status upon completion. In the short term, he looks forward to beginning work as hydraulic engineer to gain knowledge and practical experience in the hydraulic engineering profession and to obtain his license as a Professional Engineer (PE).

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