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COLLABORATIVE MODELING TO EVALUATE WATER MANAGEMENT SCENARIOS IN THE RIO GRANDE BASIN[1]

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ABSTRACT: This article describes the collaborative modeling process and the resulting water resources planning model developed to evaluate water management scenarios in the transboundary Rio Grande basin. The Rio Grande is a severely water stressed basin that faces numerous management challenges as it crosses numerous jurisdictional boundaries. A collaborative process was undertaken to identify and model water management scenarios to improve water supply for stakeholders, the environment, and international obligations of water delivery from Mexico to the United States. A transparent and open process of data collection, model building, and scenario development was completed by a project steering committee composed of university, nongovernmental, and governmental experts from both countries. The outcome of the process was a planning model described in this article, with data and operations that were agreed on by water planning officials in each country. Water management scenarios were created from stakeholder input and were modeled and evaluated for effectiveness with the planning model.

(KEY TERMS: Rio Grande; decision support systems; planning; geographic information system; water resources management.)

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INTRODUCTION

Efficient water management requires collaboration among authorities and stakeholders to achieve common goals with regards to limited water resources. Usually, the existing water management is tested against alternative management scenarios to evaluate if it meets the goals specified or if there are alternative scenarios that might improve the water supply for stakeholders, environmental, and system requirements. A clear and transparent process for creating and testing these management scenarios is necessary to ensure the participation of stakeholders and policy makers. The *Shared Vision* technique provides a framework for the water planning process through the incorporation of traditional methodologies, organized public participation, and the use of collaborative modeling in the creation of an integrated decision support tool (Cardwell *et al.*, 2008). *Collaborative modeling* involves the participation of stakeholders in all parts of the modeling process; this approach is useful to

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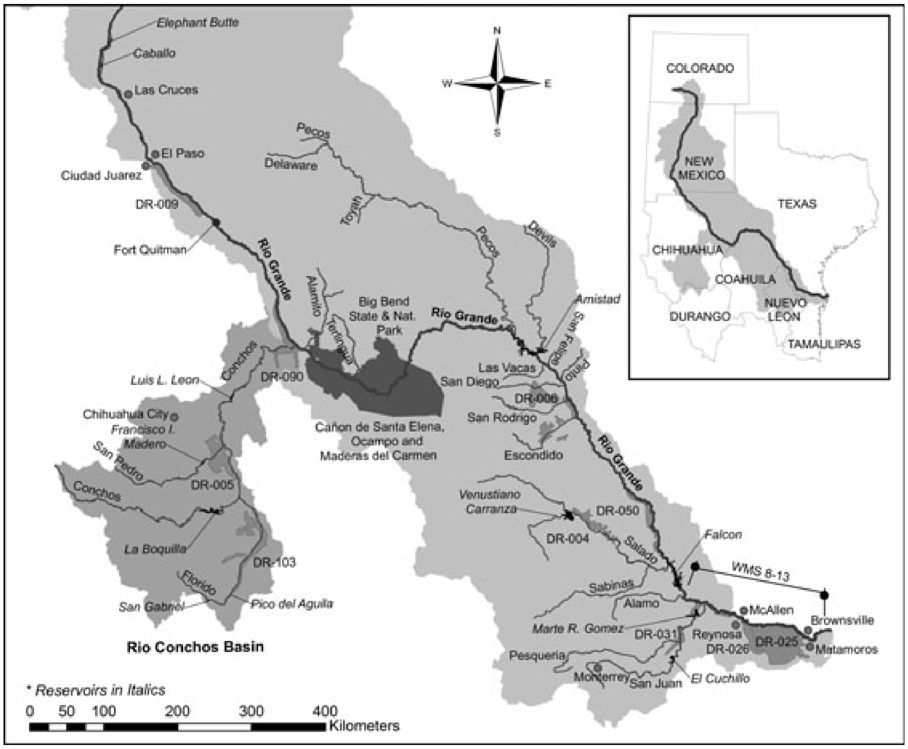


FIGURE 1. Rio Grande Basin.

ensure cooperation, transparency, credibility, and understanding of the basin and the problems to be addressed (Cardwell and Langsdale, 2011).

Collaborative modeling in a large-scale transboundary basin can be more difficult due to the size of the basin and the numerous jurisdictional boundaries that the river crosses. The Rio Grande is considered one of the most water stressed basins in the world (WWF, 2007) and increasing population with prolonged droughts is placing additional strain on an already water scarce basin. The Rio Grande basin comprises an area of 557,722 km^2 and forms 2,034 km of the border between the United States (U.S.) and Mexico (Figure 1) (Patiño-Gomez *et al.*, 2007). The objective of this study is to describe the collaborative modeling process used to (1) construct a water resources planning model that considers the Rio Grande basin as a whole entity, (2) define and evaluate scenarios, and (3) develop a methodology for the analysis of results.

BACKGROUND

The Rio Grande is the fifth longest river in North America flowing 2,892 km from its headwaters to the Gulf of Mexico. In 2010, the estimated population was 10.5 million people, 17% in the U.S. and 83% in Mexico. Currently, municipal demands account for 14% of the total water demands in the basin, whereas irrigation accounts for 86%. Mexico irrigates approximately 366,000 ha (CONAGUA, 2010), whereas the U.S. irrigates about 402,000 ha. The drought of 1994-2007 made evident the water management problems in the basin: (1) over allocation of water rights, more water is withdrawn than the water naturally produced in the basin (CONAGUA, 2008a; Sandoval-Solis and McKinney, 2011); (2) low water use efficiencies (IBWC, 2003); (3) uncoordinated water management between agencies and countries (IBWC, 2001, 2002); and (4) nonexistent policies to supply water to the environment (Blankinship, 2005).

In 2002, the Physical Assessment Project (PAP) was launched as an umbrella project to provide answers to the problems described above. The goal of this project was to examine physically feasible policies to improve the water management for the whole basin; the PAP was oriented to all the people involved in the water planning and management of the basin including stakeholders, water managers, technical personnel, decision makers, and environmentalists. Three main tasks were undertaken: (1) constructing an integrated georeferenced database, (2) building a water resources planning model to test water management scenarios, and (3) defining these scenarios through consultation with stakeholders and authorities (PAP, 2002). The first years of the PAP (2002-2006) were focused in the construction of a binational Hydrologic Information System (HIS) (Patiño-Gomez and McKinney, 2005;

Patiño-Gomez *et al.*, 2007). In 2005, the framework of the planning model was defined for the purpose of analyzing scenarios to improve the water management of the basin (PAP, 2005b). In the subsequent years (2005-2011), the PAP was devoted to examining alternative strategies to improve the water management in the basin, within the existing laws and treaties (PAP, 2005a). The PAP adopted a whole-basin and bottom-up planning approach to propose solutions and include stakeholders in the process.

The PAP steering committee was comprised of eight institutions: two nongovernmental organizations (NGOs), two government research agencies, and four universities. Table 1 shows the PAP project partners integrated by the steering committee, water regulatory authorities, NGOs, and stakeholders (irrigation districts and cities) included in the collaborative process. Notice that environmental government agencies, such as Big Bend National Park, U.S. Fish and Wildlife, Natural Protected Areas Commission (CONANP, from the Spanish acronym), and National Institute of Ecology (INE, from the Spanish acronym) are located in the NGOs category because they act as environmental organizations due to their lack of power in the decision-making process.

The government agencies involved in the PAP do not have the ability to make decisions related to water allocation, laws, or treaties; however, they provide technical expertise and support during the planning process. In the Rio Grande basin, there are conflicts over exploring alternative water policies because most of them have impacts lying out of the legal or geographic boundaries and organizational missions of the local, state, federal, and international governmental institutions that propose a policy. The strength of the PAP was not being limited by the previous constraint; the PAP had the freedom to explore alternative scenarios providing an objective analysis of their effects. Government agencies felt represented in the PAP by the inclusion of the two governmental institutions. The role of the PAP in the planning process was to brief the parties involved (project partners) and build consensus by convincing all the parties of the relevance of the policies proposed. All of this based on nonpartisan and objectiveness for exploring scenarios. Sadoff and Grey (2005) suggest that cooperative regional assessment on international rivers may be undertaken without any agencies that have the authority or mandate to impose water management solutions to estimate the broadest range of potential projects and benefits with a basin-wide perspective.

COLLABORATIVE MODELING PROCESS

A water resources planning model for the Rio Grande basin was created through a collaborative

TABLE 1. Project Partners Included in the PAP: Steering Committee, Water Regulatory Authorities, NGOs, and Stakeholders (irrigation districts and cities).

	Location	United States	Mexico
Steering committee		The University of Texas	ITESM
		University of Arizona	UACJ
		USGS	IMTA
		NHI	WWF
Authorities		TCEQ	CONAGUA
		IBWC (U.S. Section)	IBWC (Mexican Section)
NGOs		The Nature Conservancy	Profauna
		Environmental Defense	Pronatura
		Big Bend National Park	CONANP
		U.S. Fish and Wildlife	INE
Irrigation districts*	Upper	Elephant Butte Irr. Dist.	DR-005 Delicias
		El Paso Wat. Irr. Distr. I	DR-009 Valle de Juarez
		Wat. Master Section 1	DR-090 Bajo Conchos
			DR-103 Rio Florido
	Lower	Wat. Master Sections 2-6	DR-050 Falcon Acuña
		Wat. Master Sections 7-13	DR-024 Bajo San Juan
			DR-025 Bajo Rio Bravo
Cities*	Upper	El Paso	Ciudad Juarez
			Chihuahua
	Lower	Presidio	Ojinaga
		Laredo	Nuevo Laredo
		McAllen	Reynosa
		Brownsville	Matamoros

*Stakeholders.

modeling process considering the participation of stakeholders and government officials of both countries. The participatory process was aimed at providing confidence and transparency regarding the planning model; it also helped to integrate ideas and concerns during the planning process by including the best available science and technology. The collaborative process began with data collection and continued through the model construction, scenario development, and outreach phases. Each step in this process is described in this section.

Binational Hydrologic Information System for the Rio Grande

As part of the collaborative process, it was important that the people involved in the planning process had access to and were aware of the data available. Because of this, a HIS was built for the Rio Grande to compile all the data available regarding hydrology, climatology, water quality, and infrastructure in the basin (Patiño-Gomez and McKinney, 2005; Patiño-Gomez *et al.*, 2007). The georeferenced database was used as the main source of information during the model construction and postprocessing of results. The database uses a standard Arc Hydro data model to organize data according to the basin principle (Maidment, 2002), which is the use of surface water hydrology (catchments, river network, control and monitoring points) to synthesize geospatial and temporal data. The geodatabase was the first step in establishing the necessary understanding of the basin as a whole, with spatial and temporal information provided by water authorities, government organizations, NGOs, and PAP steering committee institutions from the U.S. and Mexico.

Basin-Scale Planning Model

Personnel for the PAP steering committee built a water resources planning model to evaluate water management scenarios; the Rio Grande Water Evaluation and Planning (WEAP) model simulates the water allocation system, division of water between the U.S. and Mexico, infrastructure, surface water, and groundwater resources of both countries. For the Rio Grande, planning models have been built for dispute resolution (Tate, 2002), water availability (Brandes Co., 2004), and drought management (Vigerstol, 2002). The Rio Grande WEAP model was meant to aid in dispute resolution and management decision, as were the OASIS (Tate, 2002) and Stella (Vigerstol, 2002) models with two main differences: the modeling involved the participation of stakeholders during model construction and it was based on extensive calibration and validation. Several institutions participated in the construction and calibration of the model, the main institution in charge of model development was the University of Texas at Austin, assisted in the beginning by the Natural Heritage Institute (NHI). During the model construction, model calibration tasks and data exchange were frequent; the Mexican Water Technology Institute (IMTA, from the Spanish acronym) provided major inputs to the model calibration process and provided groundwater information for the Mexican side and the WWF provided environmental flow requirements in the Conchos basin.

In 2005, during a water summit organized by the International Boundary and Water Commission (IBWC) to compare river planning models, the WEAP model platform was chosen to simulate the water allocation system for the basin (McKinney and Purkey, 2005); it was selected from among other platforms because it is user friendly, has flexible modeling capabilities to characterize the Rio Grande basin, and is free to developing countries like Mexico. The WEAP model allows the representation of important institutional characteristics such as the division of water according to the Treaty of 1944, the water allocation system in Texas and in Mexico according to their respective regulations. Yates *et al.* (2005a, b) provide detailed descriptions of the WEAP model platform.

A series of training sessions were carried out along the basin for stakeholders, NGOs, and authorities to introduce the functioning and operation of the model: (1) at Ciudad Juarez in 2005 and El Paso, Texas in 2009 focused on IBWC staff, local stakeholders, and NGOs with materials including a tutorial for model construction in English and Spanish (Nicolau del Roure and McKinney, 2005); (2) at Cuernavaca in 2009 adding a reservoir operation tutorial, mostly for Mexican water authorities; and (3) at Mexico City in 2009 adding a tutorial for water quality modeling below Falcon Reservoir (Ingol-Blanco and McKinney, 2009). These tutorials were aimed at promoting the acceptance and use of the planning model.

Workshops were an important public venue to demonstrate to participants the operation of the model, to show transparency regarding input data and the assumptions embedded in the model, and to prove the adequacy of the model. Workshops were held to explain the operation and algorithms used to represent the water allocation system of the basin and receive feedback from stakeholders and authorities regarding the basin representation, input data, system operation, and undocumented empirical rules used to allocate water. A total of six workshops were held: (1) at Cd. Juarez and Cuernavaca in 2006; (2) at Cuernavaca, Mexico City, Monterrey, and El Paso, Texas in 2009; and (3) at Riverside, California in 2010.

The model has been subject to extensive calibration, validation, sensitivity analysis, and testing. Model examinations were carried out in workshops or during meetings with key system operators, academics, or stakeholders, who know how the system operates so they can ask penetrating questions and challenge assumptions and data. Computed reservoir storage and streamflows were compared against historical records to demonstrate that the model adequately represents the system. Goodness-of-fit coefficients, such as the Nash-Sutcliffe coefficient of efficiency and index of agreement (Legates and McCabe, 1999), were used to quantify how well the model represents the historic basic operation. These meetings helped the project gain credibility with stakeholders, government institutions, and the scientific community.

One important tool used in the collaborative process was the establishment of an ftp website used as the main mechanism to share information and files among project partners and the Rio Grande water community. This tool ensured the transparency and accessibility to data and information by over 50 participants. Tutorials, reports, related project documents, the HIS, and updates of the model were available through this portal. During workshops and training sessions, participants were encouraged to join the ftp website because the participants were representative of the water community of the basin (Table 1). Participants were asked to provide the information of other important people related with the water planning process; information about the PAP was sent electronically to this expanded community regardless of being responsive or unresponsive.

The PAP communication scheme was based on four actions: (1) the Rio Grande website to communicate events and documents with the public (PAP, Rio Grande-Rio Bravo, Designing a Common Future, Accessed July 2012, http://www.riogrande-riobravo.org); (2) the ftp website to share information and files between PAP partners and people involved in the planning process; (3) electronic communications through emails providing a quick update to project partners and the expanded water community; and (4) in-person events such as meetings, workshops, and training sessions to present results and receive feedback.

Definition of Scenarios, Meta-scenarios, and Outreach

In 2002, during a workshop, a group of scientists, academics, and professionals representing governmental research institutions, NGOs, and universities from the U.S. and Mexico (PAP, 2005a) gathered around the PAP. Ideas for scenarios were discussed by the project partners and participants (PAP, 2002). After this workshop, several meetings and field trips were held to identify water management challenges and possible solutions for the Rio Grande. From 2002 to 2006, 33 scenarios were defined based on consultations with project partners (PAP, 2006). These scenarios are strategies that interviewees were willing to implement themselves to improve their water supply.

In the first phase of the scenario analysis (2006-2009), every scenario that had sufficient scientific or official data to be modeled was developed; more than 20 scenarios were modeled and evaluated. The evaluation consisted of determining their physical feasibility and quantifying the water supply benefits and drawbacks that each scenario provided to water users, environmental and system requirements. Each scenario was compared with a baseline scenario. Several scenarios were eliminated because they were not physically feasible or they caused harm to other water users, international obligations, or environmental requirements.

In 2009, results from the first phase were presented to stakeholders for their feedback. In June 2009, results were presented to the IBWC in Ciudad Juarez, Mexico; the U.S. and Mexican IBWC commissioners attended this meeting where the planning model and scenarios' results were discussed. In August 2009, results were presented to the Rio Bravo Basin Council in Monterrey, Mexico; this organization defines the water management policies for the Rio Grande on the Mexican side. In October 2009, results were presented to the Texas Commission on Environmental Quality (TCEQ); the Commission Chair and staff were briefed regarding the results of the scenarios analyzed. Also, results of scenarios that improve the delivery of environmental flows were presented to NGOs. Several meetings were organized to present the model and results to stakeholders from both countries.

Based on these interactions and results, two winning scenarios, called Meta-scenarios, were defined based on the analysis of results. Meta-scenarios are combinations of individual scenarios aimed at improving the water supply for stakeholders, environmental, and system requirements. Meta-scenarios were designed by the PAP steering committee using the analysis of results (see the section Analysis of Scenarios) and the feedback from project partners (PAP, 2009). In the second phase of the scenario analysis (2010-2011), two Meta-scenarios were modeled and evaluated: Long-term and Short-term scenarios. A second round of presentations took place to report the results of the Meta-scenarios to all the people involved in the water management of the basin (2010-2011). Moreover, a methodology was developed to evaluate the performance of each scenario for water users, groups of water users, regions, and for the whole basin.

RIO GRANDE PLANNING MODEL

One of the major outcomes of the collaborative model process was the water resources planning model. The *Rio Grande WEAP model* was a task of the PAP: "constructing a basin-wide model to identify physically feasible strategies to improve the water management for the whole basin (PAP, 2005a)." The model calculates the balance between inflows, change in reservoir and aquifer storage, evaporation losses in reservoirs, delivery to water demands, return flows, and flows from Elephant Butte Reservoir in New Mexico to the Gulf of Mexico. The model is a monthly time-step simulation model that replicates a 60-year period of hydrologic conditions from October 1940 to September 2000. The 60-year period contains the record drought of 1948-1957, the drought of 1961-1965, and the beginning of the extended drought of 1994-2007. The model considers the main tributaries of the Rio Grande in the U.S. and Mexico. Table 2 is a summary of the water demands considered in the model. Surface water rights for municipal (14%), irrigation (86%), and other (<1%) are 7,385 million m^3/yr, this amount is slightly larger than the naturalized flow (described below) in the basin which is 7,343 million m^3/yr, on average (Sandoval-Solis and McKinney, 2011). Stakeholders, government agencies, and NGOs provided the input data for naturalized flows, storage capacities, storage-elevation curves, evaporation losses in reservoirs, and streamflow data through the HIS (Brandes Co., 2004; Patiño-Gomez *et al.*, 2007; CONAGUA, 2008a). Extensive details of the model are contained in Danner *et al.* (2006).

TABLE 2. Water Demands Considered in the Rio Grande Model.

Water Use	Demands	Mexico	United States
Municipal	Number	21	23
	(million m^3/yr)	731	283*
Irrigation	Number	39	53
	(million m^3/yr)	3,939	2,374*
Other	Number	1	20
	(million m^3/yr)	47	11*
Groundwater	Number	35	21
	(million m^3/yr)	1,663	2,840†
Total	Number	96	120
	(million m^3/yr)	6,380	5,509

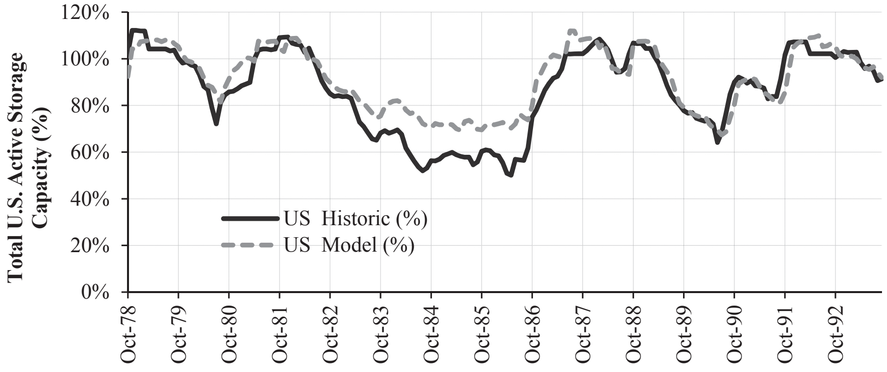
*70% of the full allocation demand. The current allocation is 62% of the full allocation.

†This value represents an upper bound on aquifer withdrawal by these water demands.

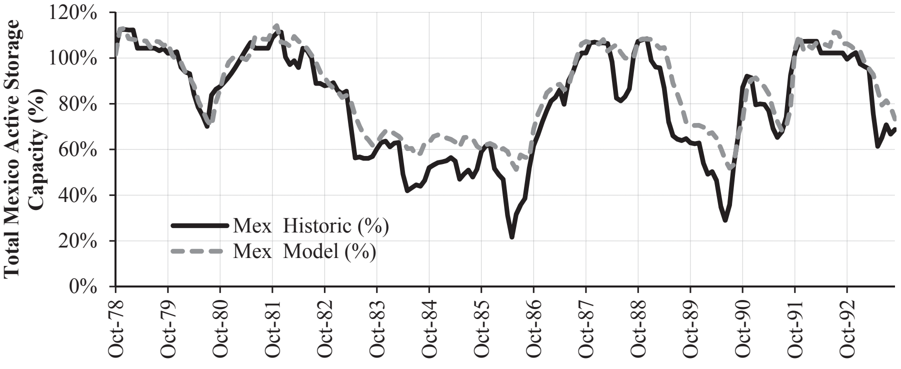
The model simulates the complex water allocation system of the basin; stakeholders and water authorities provided their knowledge, experience, documentation, and empirical rules to set the operational *logic* that governs the water allocation in the model. Several sets of rules were programmed to define the allocation system, priorities, and constraints associated with each regulation. Four main rule sets were included in the model: (1) Texas Watermaster Rules to allocate water in the U.S.; (2) Mexican CONAGUA rules to allocate water in Mexico; (3) the 1944 U.S.-Mexico Treaty rules for dividing the water between the U.S. and Mexico; and (4) the rules to account for the water stored for each country in the international Amistad and Falcon Reservoirs.

A hydrologic break in the Rio Grande occurs between El Paso and Fort Quitman, Texas where there is often little or no water in that reach (Teasley and McKinney, 2005). This hydrologic break creates a disconnect where water management decisions made upstream from El Paso have little effect on the Rio Grande mainstem at the confluence with the Rio Conchos. The convention of 1906 and the Rio Grande Compact regulate the water allocation upstream of Fort Quitman (IBWC, 1906; TCEQ, 1938). Water is allocated using the prior appropriation rule from Fort Quitman to Amistad and based on the water use and the type of water right from Amistad to the Gulf (TCEQ, 2006). In Mexico, water is allocated according to its permitted water users (CONAGUA, 2008b). All the water that reaches the Rio Grande and the gains along the mainstream are allocated to each country according to the Treaty of 1944 (IBWC, 1944). All these allocation rules were programmed in the model, as increased interaction with stakeholders occurred; the model was improved to better represent water allocation logic in the basin.

Naturalized flows are the main input to the model; they represent the streamflows that hypothetically would have occurred in the river in the absence of human activities. Before 2008, naturalized flow data were available for the whole basin only from U.S.-derived data sources (Brandes Co., 2004), and results presented to Mexican authorities using U.S. data were not always fully accepted; the validity of the results were disputed several times. In 2008, Mexican water authorities published a set of naturalized flows for rivers in Mexican territory and along the mainstem of the Rio Grande (CONAGUA, 2008a). These data were annual flows, whereas the model needed monthly flows. Two actions were taken to prove the credibility of the planning model to Mexican water authorities. First, both sets of naturalized flows were analyzed to determine if they are statistically similar



a) U.S. storage in the international reservoirs Amistad and Falcon



b) Mexican storage in the international reservoirs Amistad and Falcon

FIGURE 2. Combined Storage for Each Country at the International Reservoirs, Model *vs.* Historic Scenario.

or different using a Wilcoxon rank sum statistical test. The results showed that in 21 of 27 (78%) control points along the river the time series are similar; this analysis was documented, a memorandum was sent to stakeholders and authorities showing the comparison of both datasets (Sandoval-Solis *et al.*, 2010); however, the results from the model were still not fully accepted and Mexican water authorities wanted to see their data used in the model. Second, the annual time series of the Mexican naturalized flows were disaggregated using the monthly distribution from the U.S. naturalized flows, and this hybrid monthly time series was used in the model for rivers originating in Mexico. This resulted in a positive resolution to the difference over naturalized flow input data. Results from the model did not change significantly, verifying that both series are similar; nevertheless, Mexican authorities were more comfortable knowing that their information was being used in the model. These actions provided credibility to the collaborative modeling process, showing the willingness of the parties to collaborate and overcome technical obstacles, as well as demonstrating the robustness of the model.

A breakthrough happened when the model performed similar to historic records due to the calibration. In the U.S., historic data for water supplies and diversions from reservoirs are public (IBWC; Rio Grande Historical Mean Daily Discharge, Accessed February 2012, http://www.ibwc.state.gov/Water_Data/histflo1.htm); however, in Mexico these data were not public until 2008 (CONAGUA, 2008a), CONAGUA shared this data with the PAP. A *Historic* scenario was built using the historic data to compare the model results with the historical records. The good performance of the model is the result of a close collaboration with stakeholders and authorities to understand the details of water management in the basin, all those hours spent talking about unwritten rules to operate reservoirs paid off when the model behaved similar to reality (Figure 2). To ensure that the modeling process remained transparent, documentation was created for the model and testing process (Danner *et al.*, 2006).

SCENARIOS FOR THE RIO GRANDE

The scenarios analyzed in the PAP were derived from consultations regarding opportunities to improve the water management in the Rio Grande. Figure 3 shows the scenario analysis framework (pyramid) and the participatory process (oval) established with stakeholders, water regulatory authorities, and NGOs (Table 1). The PAP benefited from this participatory process; in 2006 the HIS was the first binational repository of hydrologic information; in 2010 the Rio Grande WEAP model was the first model calibrated for the basin that was presented and debated in both countries; and the scenarios proposed included ideas and feedback from a broad number of people directly involved in the water management of the basin. The collaborative modeling and scenarios analysis presented here is the last phase of the PAP effort to design strategies to improve the water management in the Rio Grande basin.

The *Baseline* scenario considers the current regulations to allocate water in the system, the water demands fixed at 2004 volumes for Mexico and 70% of the full allocation demand for the U.S.; these assumptions were derived from consultations with stakeholders and authorities. The 2004 water right volumes for Mexican water demands were used for two reasons; first these volumes represent the maximum water diversion legally allowed and second, after 2004 two policies to conserve water were implemented and stakeholders wanted to know their impact. The 70% of the full allocation demand for U.S. water users was assumed because this was the maximum water allocation after the drought of 1994-2007. This percentage has been reduced to 62% in recent years (Sandoval-Solis, 2011). The *Current* scenario considers the policies already implemented in the basin after 2004 (Upper: I, III; and Lower: V) and the current regulation. The policies of the Current scenario were evaluated to quantify the benefits and drawbacks that each of these policies provided to the system.

In this article a subset of 12 of the more than 20 modeled scenarios is presented, they were selected because they include the policies considered in the Current and Meta-scenarios (described later in this section). The 12 scenarios presented in this article consist of the Baseline scenario plus individual scenarios or simple combinations for the upper (I, II, III, IV, I+II, III+IV) and lower Rio Grande (I, III, V, I+III, III Shared), as shown in Table 3 (Phases 1 and 2) and Figure 3. The scenario descriptions are as follows:

1. Reduction in water demand through a buyback of water rights; *Upper*, this policy was implemented in two irrigation districts, DR-005 and DR-090, in the Rio Conchos basin by the Mexican Ministry of Agriculture (Sandoval-Solis *et al.*, 2011b); *Lower,* it is proposed for DR-025 Bajo Rio Bravo.
2. Conjunctive use of surface water and groundwater sources through an in-lieu groundwater banking technique (Sandoval-Solis *et al.*, 2011c).
3. Increased water use efficiency through improvements in infrastructure and irrigation methods; *Upper*, this policy was implemented in three irrigation districts in the Rio Conchos, DR-005, DR-090, and DR-103, through Minute 309 (IBWC, 2003; Sandoval-Solis and McKinney, 2010); *Lower,* it is proposed for DR-025 using the same conservation methods as in the upper basin. The *III Shared* scenario proposes to share the water savings, investment, operation, and maintenance cost between the irrigation districts DR-025 and Water Master Section 13 (WMS 8-13).
4. Environmental flows to improve the riparian and aquatic ecosystems in the basin, intentional release of water from La Boquilla and Francisco I. Madero Reservoirs to meet environmental requirements in the Rio Conchos basin (Sandoval-Solis and McKinney, 2009).

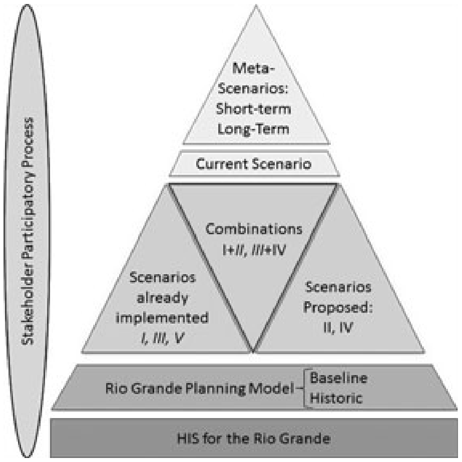


FIGURE 3. Collaborative Modeling Framework.

TABLE 3. Phases of the Scenarios Analysis.

			Location	
Phase	Analysis	Policy	Upper	Lower
1	Individual	*Baseline*	No action	No action
		Scenarios	*I*, II, *III*, IV	I, III, *V*
2	Combined	*Baseline*	No Action	No Action
		Scenarios	*I*+II, *III*+IV	I+III, III Shared
3	Meta-scenarios	*Current*	*I, III*	*V*
		Short-term	*I*+II, *III*+IV	I
		Long-term*	I**	III Shared

Note: Scenarios in *italics* are the scenarios already implemented.
*Long-term scenario includes the policies of the Short-term scenario.
**This scenario is proposed to be extention of what was already implemented.

5. Agricultural water demand reduction enforced in Texas as their water allocation was reduced from 70% to 62% of their full water rights allocation (Carlos Rubenstein, Commissioner, TCEQ, October 2009, personal communication).

A first set of scenarios was modeled (Table 3, Phase 1) to identify the benefits and drawbacks that each individual scenario provides to the system; they were compared with the Baseline scenario. Then individual scenarios were combined (Table 3, Phase 2) to identify arrangements of policies that provide benefits or mitigate negative effects of policies already implemented; results from these scenarios were documented and discussed with stakeholders in 2008 through workshops (Sandoval-Solis *et al.*, 2008). The outcome from these discussions and results analysis was the construction of two successful scenarios called *Meta-scenarios* (PAP, 2009). Meta-scenarios are scenarios integrating policies already implemented plus policies that improve the water management or counteract the negative effects of policies already implemented (Table 3 Phase 3), this was done through a professional synthesis analysis by the PAP steering committee. Through this process Short-term and Long-term Meta-scenarios were designed and proposed to improve water management in the basin (Figure 3). Meta-scenarios are compared against the Current scenario, these results were documented and presented to the Rio Grande water community in 2010 and 2011 in workshops. At this point, the economic, legal, and institutional analysis of the Short- and Long-term Meta-scenarios was developed and documented.

ANALYSIS OF SCENARIOS

Water supply for human water use (including agriculture), environmental requirements, and international obligations was analyzed in the PAP. Each stakeholder was evaluated using parameters called *performance criteria* that represented required or desired characteristics for their water supply; these criteria were defined during meetings, workshops, and conversations. Water users expressed a strong interest in a reliable water supply that recovers fast from deficits, and when deficits happen the average and worst-case deficit should be small; thus, the performance criteria selected for water users were reliability, resilience, vulnerability, and maximum deficit (Hashimoto *et al.*, 1982 and Sandoval-Solis *et al.*, 2011a). The selection of these desired characteristics is based on their empirical experience; historically their water supply varies from one year to another (not reliable); because of extended droughts the system does not recover fast (not resilient); and when there is a drought, the average and maximum deficit usually are large (high vulnerability and maximum deficit). The performance criteria selected for environmental requirements were the same as for water users.

Water authorities expressed a desire for the delivery of water from Mexico to the U.S. according to the Treaty of 1944 (*treaty obligations*) to be reliable, not vary much through time, and when deficits happen they should be small and must be paid as soon as possible. Thus, the performance criteria selected for treaty obligations were reliability, standard deviation, vulnerability, and resilience. Historically, the delivery of treaty obligations varies a lot from one year to another because it is supplied from six Mexican rivers of which four are unregulated. In addition to unreliable delivery, the system is in deficit about half of the time; when deficit happens, they tend to be large (high vulnerability); and the treaty deficit is not always paid in the immediate following cycle (low resilience) (Sandoval-Solis and McKinney, 2011). Presenting the performance criteria results to stakeholders and authorities improved the understanding of the benefits or drawbacks that each scenario may provide, given their preferred characteristics.

One of the challenges when analyzing scenarios in the Rio Grande is the basin size; there are plenty of water users to evaluate and thousands of performance criteria to compare. Whereas each stakeholder wanted to know the performance criteria results for each scenario, water authorities wanted to know concisely if a scenario improved the water management and by how much. These groups expressed the following questions: “Is there a method to summarize the results (performance criteria) for each stakeholder? Is it possible to have a single result for the whole basin? Where and who is receiving the benefits and drawbacks?” To address this problem, two indices were used to summarize the result: the Sustainability Index (SI) and the Sustainability by Group (SG) (Loucks, 1997; Sandoval-Solis *et al.*, 2011a).

Sustainability Index

The SI combines the performance criteria (C^i_m) of a stakeholder (1) into a single value from 0 to 1 by using a geometric average, Equation (1); this approach is used to consider each criterion as essential and indispensable. The criteria (C^i_m) included in Equation (1) must have a scale from 0 to 1, desirable criterion values tend to be 1, scaling and complements ($1 - C^i_m$) are applied prior to including them into Equation (1). Sandoval-Solis *et al.* (2011a) explain in detail the characteristics, scaling, and use of the SI. Equation (2) shows the SI for stakeholders considering the performance criteria of: reliability (Rel^i), resilience (Res^i), vulnerability (Vul^i), and maximum deficit (MaxDef^i).

$$\text{SI}^i = \left[\prod_{m=1}^{M} C_m^i\right]^{\frac{1}{M}} \tag{1}$$

$$\text{SI}^1 = [\text{Rel}^i \times \text{Res}^i \times (1 - \text{Vul}^i) \times (1 - \ \text{MaxDef}^i)]^{\frac{1}{4}} \tag{2}$$

Table 4 shows the performance criteria and SI of irrigation district 005 Delicias (DR-005), the largest water user in the basin, for the Baseline scenario and Scenario I that considers the reduction in its water demand due to buyback of water rights. Results show an improvement in the period of time its water demand is fully supplied (reliability), from 52% of the time in the Baseline scenario to 68% in Scenario I. The probability of recovery from a deficit (resilience) also improved, from a 24% chance (1 of 4 times) in the Baseline to 32% (1 of 3 times) in Scenario I. The average deficit (vulnerability) and maximum deficit did not change 53% and 99% of the water demand, respectively. Scenario I improves the reliability and resilience of DR-005′s water supply, but it has no effect on its vulnerability or maximum deficit. This is captured by the SI, improving from 16 to 18%, the four criteria have to improve to cause a significant change in its value; this is why each criterion is considered essential and indispensable. The slight increase in the SI shows that DR-005 will continue experiencing a 54% shortage on average (vulnerability) and a maximum deficit of 99% of its water demand.

Response to the SI was positive among stakeholders, NGOs, and water authorities. During workshops, the PAP steering committee explained the calculations of the SI. Participants recognized the value of the SI after analyzing the results of several scenarios.

TABLE 4. Performance Criteria and Sustainability Index, Baseline *vs.* Scenario I.

	DR-005	
	Baseline	**Scenario I**
Water demand (million m^3/yr)	942	850
Reliability (%)	52	68
Resilience (%)	24	32
Vulnerability (%)	53	54
Maximum deficit (%)	99	99
Sustainability Index (%)	16	18

The SI made it possible to discern which scenarios provided more benefits or worsening overall. The SI also allowed to track what performance criteria changed in each scenario analyzed. The SI makes the comparison of scenarios easier for each stakeholder, but still there are plenty of SIs to compare.

Sustainability by Group

The SG combines the SIs of a group of stakeholders (k) into one value using a weighted average. For the Rio Grande, the SG was weighted using annual water demand, Equations (3 and 4). The SG summarizes results by type of use, region, and for the whole basin; it helps to identify water management improvements at a glance.

$$\text{SG}^k = \sum_{i=1\in k}^{i=j\in k} \frac{\text{Water Demand}^i}{\text{Water Demand}^k} * \text{SI}^i \tag{3}$$

$$\text{Water Demand}^k = \sum_{i=1\in k}^{i=j\in k} \text{Water Demand}^i \tag{4}$$

Four water users groups are analyzed: (1) Rio Grande, this group includes all environmental and stakeholders' water demands and the treaty obligations; (2) U.S., it includes all U.S. water demands; (3) Mexico, it includes all water demands and the treaty obligations in Mexico; and (4) Environment, it includes environmental requirements in the Rio Conchos basin. Results for four scenarios are presented in Figure 4; Baseline scenario which is the system prior to 2004; the Current scenario which is today's system after three policies were implemented in the basin (Upper: I, III; and Lower: V); and two Metascenarios, the Short-term scenario which includes combination of policies that improves the system and

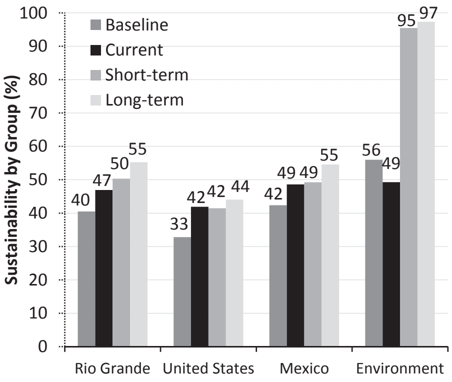


FIGURE 4. Sustainability by Group of Different Water Users.

the Long-term scenario which is increasing or extending policies of the short-term scenario into other regions.

Results show improvements in the water management from the Baseline to the Current scenario for Rio Grande, Mexico, and U.S. water demand groups; nevertheless, the water management for the environment worsens. The policies implemented in the Current scenario are focused on improving human water supply without considering the environment. Buyback of water rights (Upper: I) has occurred in the upper basin, in DR-005 Delicias water savings are stored in the reservoirs to benefit this irrigation district, but this policy reduces the conveyance of water in the river affecting the environment. A water use efficiency program in DR-005 has been implemented (Upper: III), and water savings are delivered to the confluence of the Rio Conchos and the Rio Grande in December and January, this arbitrary pattern affects the environment by modifying the natural regime of the river.

META-SCENARIOS

Short-term scenario results show improvements in the water management with respect to the Current scenario; the proposed policies do not affect the water management in the U.S. or Mexico, but they do significantly improve the water supply for environmental purposes by 46%. Buyback of water rights (Lower: I) is proposed in the lower basin for DR-025 to retire water rights of irrigated land that is susceptible to salinity problems (Zatarain *et al.*, 2005). The delivery of water for environmental purposes, environmental flows (e-flows), (Upper: IV) does not affect human water users because normal e-flows are delivered when there is enough water in the reservoirs to fully supply stakeholders and drought e-flows are delivered when shortages are expected. Water savings due to increased water use efficiency (Upper: III) are delivered in an environmental pattern. Conjunctive use of surface and groundwater (Upper: II) provides a more reliable supply for DR-005. This scenario shows that the environment can be integrated in the water management of the basin without harming stakeholders; this is an important result as environmental requirements have been neglected because they are thought to harm anthropogenic water users. The Rio Grande group shows an overall improvement of 3%, with respect to the Current scenario.

The Long-term scenario includes the policies of the Short-term scenario plus two additional policies. In the upper basin, the buyback of water rights program is extended (Upper: I**, see Table 3) reducing the irrigated area of DR-005 from 90,000 ha to 50,000 ha; this policy compensates farmers who have water rights that are difficult to supply in drought conditions. In the upper basin, the scenario considers an increase in water use efficiency (Lower: III Shared) in DR-025 as well as sharing the investment and water savings with WMS 8-13. Results show improvements in water management in the U.S., Mexico, and the environment of 2, 6, and 48%, respectively, with respect to the Current scenario. The overall improvement for the Rio Grande of the Long-term scenario is 8% with respect to the Current scenario.

Figure 5 shows the SG of the Current scenario for different regions of the Rio Grande. Figure 6 shows the change in SG of the Long-term scenario compared with the Current scenario and it shows the subbasins that will be benefited from the Long-term Scenario (Meta-scenario B). The Rio Conchos basin is the region with more potential for improvement (Δ26%) followed by the regions located along the lower Rio Grande mainstem. Both figures show in a list, the overall performance of the Rio Grande, water users in the U.S., Mexico, and the environment. These figures show the versatility of the SG in the spatial display of result.

KEY FINDINGS

An important finding of the PAP was to demonstrate the feasibility of improving the environment, while, at the same time, not affecting and improving the water supply for stakeholders and treaty obligations (Sandoval-Solis, 2011). The Short-term and Long-term scenarios improve the water supply in the basin by reducing the water demands, improving water use efficiency, and promoting an integrated water resources management through groundwater banking and environmental flows. These results promoting integrated environmental and human water management have been presented to stakeholders and authorities along the basin.

Another important finding was the definition and use of the SI and SG. These indices allowed a systematic evaluation of scenarios for individual water users, groups of water users, regions, and for the whole basin (Sandoval-Solis *et al.*, 2011a). Results can be divided into three levels for different purposes and audiences (Table 5). In the first level, performance criteria are used to analyze in detail the effects of each scenario for water users, the environment, and treaty obligations. At the second level, the SI summarizes the performance criteria for each

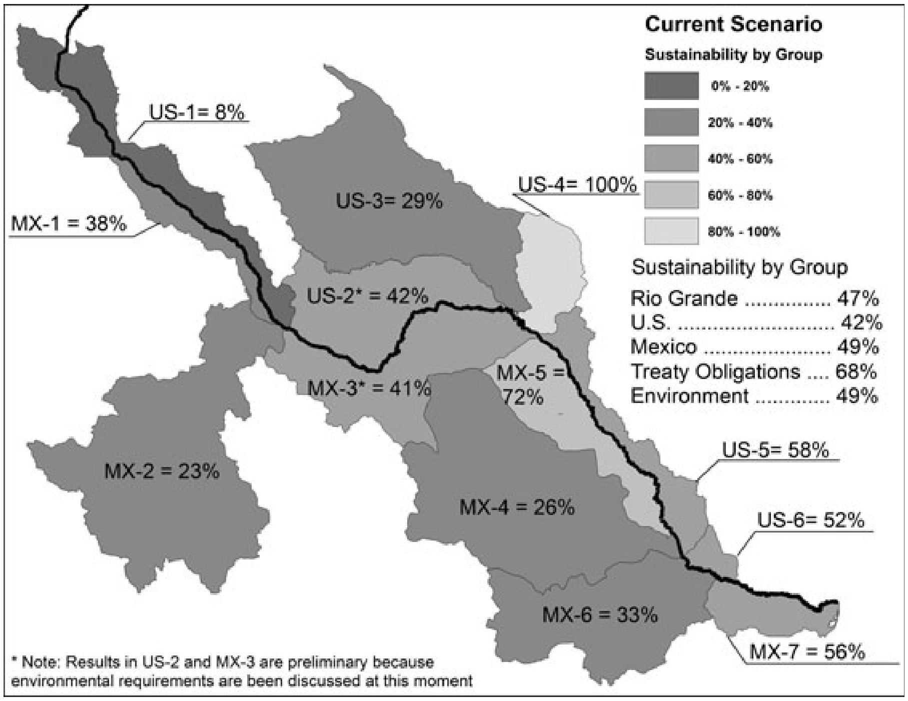


FIGURE 5. Sustainability by Group for Different Regions, Current Scenario.

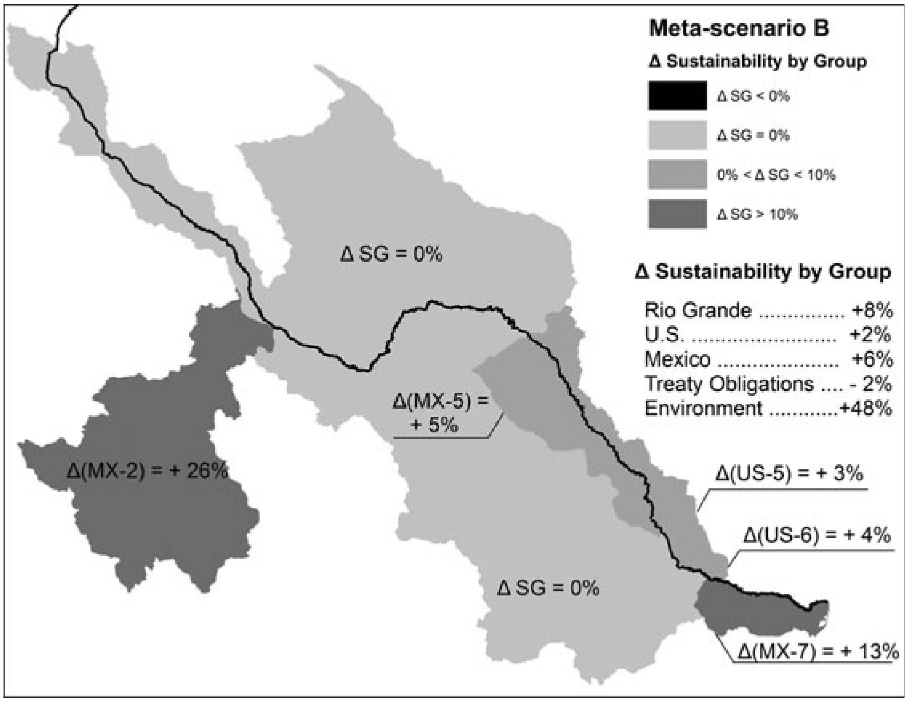


FIGURE 6. Change in Sustainability by Group for Different Regions, Long-Term Scenario.

stakeholder; at this level it is easier to compare different scenarios than at the performance criteria level. Results of the previous two levels are intended to inform water users and water operators. At the third level, the SG summarizes results of the SI; results are displayed according to water users groups, regions, and for the whole basin. At this level it is easier to compare different scenarios from the perspective of water users groups, regions, or the whole basin. Results from this level make it possible to

TABLE 5. Level of Information Obtained and for Whom They Are Oriented.

Level	Data Management	Results By	Oriented To
1	Performance criteria (C^i_{m})	Criteria	
		Reliability	Water users
		Resilience	Water operators
		Vulnerability	Stakeholders
		Maximum deficit	
		Standard deviation	
2	Sustainability Index (SI^i)	User	
		Water users	Decision makers
		Environment	Stakeholders
		System requirements	
3	Sustainability by Group (SG^k)	Group	
		Whole basin	Authorities
		Regions	Decision makers
		Type of use	Planners

identify areas of potential improvement and regions at risk. Results from this level are intended to inform water authorities, decision makers, and planners (Sandoval-Solis, 2011; Sandoval-Solis *et al.*, 2011a).

SUCCESSES

Evaluating the success of a project like this is very difficult. According to Loucks *et al.* (1981), a measure of success of any basin study resides in the answer to the following questions:

(1) “Did the study have a beneficial impact on the planning and decision-making process?” Yes, it did. For the planning process, the model developed will be used as the foundation for a future institutional water planning model of the basin. For the decision-making process, this project built awareness of potential benefits and hopes that this knowledge has a good impact on planning and decision making. The PAP balanced the interests of different groups (environmentalists, farmers, and municipalities) providing a better understanding of the basin.

(2) “Did the results of the study make the debate over the proper choice of alternatives more informed?” Yes, it did. Scenario results were presented to water users, scientists, and water authorities of both countries, they know which policies have a high likelihood of improving or worsening the performance of the system; the decision-making process will be more informed because of the collaborative modeling process.

(3) “Did it introduce competitive alternatives which otherwise could not have been considered?” Yes, it did. For instance, the Short- and Long-term scenarios provide strategies to reconcile environmental and anthropogenic water requirements; the PAP showed that the environment can be included as an integral part of the water management without harming stakeholders. This is an important result as environmental requirements have tended to be neglected in the Rio Grande basin because they are thought to harm human water users or it is believed that there is no water left for this purpose.

Based on these answers, the collaborative modeling promoted by the PAP was successful in enlightening the water planning and management of the Rio Grande.

FAILURES

There were several unintended failures during the process described here. The biggest failure was the lack of technical support at the right time during the negotiation of water regulation in the Rio Bravo Water Council, the organization in charge of defining rules for water allocation on the Mexican side of the basin. Despite the fact that stakeholders, NGOs, and most of the government institutions were convinced of the usefulness and accuracy of the Rio Grande WEAP model, the Mexican water authority, CONAGUA, was not completely convinced of the model and people from this agency have preference for a different modeling platform. Workshop and training sessions were provided to CONAGUA; however, when the basin council became aware of the existence of the Rio Grande WEAP model, it was too late; they had already taken the decision to use a different platform. However, given the documentation, calibration, and acceptance of the Rio Grande WEAP model, the new CONAGUA Rio Grande model is being built using the logic, structure, scenario analysis, and algorithms developed in the Rio Grande WEAP model. There are weaknesses already identified for this new model, the biggest one is that it will only consider the Mexican side of the basin, resulting in yet another Rio Grande model that is not integrated. Authorities and stakeholder have been briefed about the mutual dependence of water availability between the two countries, a change in U.S. water management affects Mexico’s water availability and vice versa (Sandoval-Solis *et al.*, 2011a), and still the basin council decided to build an incomplete planning model. Perhaps, this was a more political decision than a technical decision. The new model will be released by the end of 2012.

Reluctance to adopt a modeling platform is a sign of potential failure; the authors recommend developing exercises and workshops to show how to perform the same tasks in alternative platforms. This can help technicians understand the operation and logic of the unfamiliar platform; thus, reducing the aversion to it. However, there is still the chance that the technicians simply do not like the other platform and any attempt to convince them may be unsuccessful.

NEXT COLLABORATIVE PROCESSES IN THE RIO GRANDE

Since 2008, the PAP steering committee has been part of an independent scientific committee to estimate environmental flows in the Big Bend reach of the Rio Grande and to design policies that can provide these environmental requirements. The objective of this committee is to determine the amount of water necessary to support the riparian and aquatic ecosystems in this region, and to determine water management policies that can provide this water. The PAP is providing the support to design the water management policies given its expertise in the basin.

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