# Assessing the State of Water Resources Management Policies and Water Resources Planning Tools for the Rio Grande/Bravo

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## OVERVIEW

This project describes past and present water management objectives, policies, allocation practices and water uses, summarizes the state of water resources models that are available to explore Environmental Flows (EF), and outlines a methodology for developing a geodatabase that summarizes water-related elements in the basin and available water modeling tools.

In the Rio Grande Bravo Basin (RGB) there has been documented habitat degradation from channel narrowing, invasive species (saltcedar and giant cane) and near extinction of endemic aquatic species (e.g., silvery minnow). Water demands, supply, and allocations have been studied and modeled for the different reaches on the basin. However, there has been no effort to integrate the different available tools (rainfall-runoff models, river channel movement and sediment transport models, aquatic ecosystem models, and water resources management models), or to couple models developed for specific reaches into a more holistic watershed decision-support tool. This report outlines promising next steps to meet long term goals of improved decision support tools and modeling.

The collection of water resources models for the RBG Basin is examined for their management of EF to prioritize future research and monitoring needs for the development of further river system modeling tools. This body of work is especially focused on providing RGB-specific information relevant to the arid lands EF literature. A summary of existing and ongoing water management modeling efforts to identify available tools is presented in this report. The summary includes a description of model boundaries, spatial and temporal resolution, period of record, vector space (e.g., 1-dimensional, 2-dimensional…), driving equations, and model output of such tools. It also highlights models that include environmental or ecological processes along with agricultural, municipal, and industrial water management objectives. This model inventory identifies reaches that have modeling tools available as well as river segments without modeling support, where models should be developed to improve water management for human and environmental uses. Further, this research improves understanding of models with similar time steps, driving equations, assumptions, or modeled time periods and identify models that may be easily coupled for innovative and novel problem solving. Findings from this research show that there is a variety of models that can assist planning activities to implement environmental flows across the RGB. However, no models with the appropriate spatial extent and the necessary time-step exist for developing operational environmental flow targets in the basin.

After environmental targets are proposed, integrating environmental release into the water management framework of the multiple stakeholders on the basin will be complex. An adaptive management strategy should be implemented to allow for evaluation and correction of environmental releases. Recommendation from this report consist on moving from monthly planning models into weekly time-step models and operational models that mix surface water and hydraulic characteristics to account for other factors such as sediment concentration and water quality. Also, inundation plain and flow relationships, duration of floodplain inundation, water temperature, and flow recession are some of the parameters that should be addressed under an operational scenario, as they are not represented under the monthly time step and are relevant for fish spawning cues.

# BACKGROUND

The Rio Grande/Rio Bravo (RGB) is one of three large drainage basins in North America whose stream flow is divided between Mexico and the U.S. The RGB has two significant headwaters – the San Juan Mountains of Colorado and the Sierra Madre Occidental of Chihuahua (Figure 1). The downstream part of the RGB watershed has a sub-humid climate where there is greater annual rainfall that augments seasonal stream flow. As an exotic river, snowmelt from the San Juan Mountains and the precipitation-excess runoff from the Sierra Madre Occidental cross the semi-arid and arid Basin and Range before reaching the Gulf Coastal Plain. The northern branch of the RGB and the Rio Conchos join at La Junta de los Rios near Ojinaga, Chihuahua, and Presidio, Texas, to form the main stem river. Approximately 530 km further downstream, the Pecos River flows into the RGB. Further downstream, the Rio Salado and the Rio San Juan contribute stream flow from the south. Total watershed area is approximately 557,000 km$^2$ of which half is in the U.S. and half in Mexico; The RGB share ecosystems, communities, and water problems making it a truly bi-national river. The river forms the border between the two countries for approximately 2,034 km (Patiño-Gomez et al., 2007). Bi-national allocation of the RGB is defined by the Convention for the Equitable Distribution of the Waters of the Rio Grande (IBC, 1906) and the Treaty for the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande (IBWC, 1944). Various Minutes between the U.S. and Mexican sections of the International Boundary and Water Commission (IBWC) further define water allocation and quality of those shared waters. Within the U.S., the Rio Grande Compact (1938) outlines the distribution of water among Colorado, New Mexico, and Texas along the RGB main stem, and the Pecos River Compact (1948) defines water allocation between New Mexico and Texas. Today’s RGB is an extensively regulated and diverted river whose ecosystem reflects the long history of human manipulation (Horgan, 1984). In 1580, the Spanish observed Pueblo Indian irrigation ditches, and Spanish diversion ditches were subsequently constructed in central and northern New Mexico (Scurlock, 1998). The first diversions in the El Paso/Juarez Valley were constructed in 1659, and irrigation was underway near La Junta de los Rios by 1750 (Stotz, 2000).

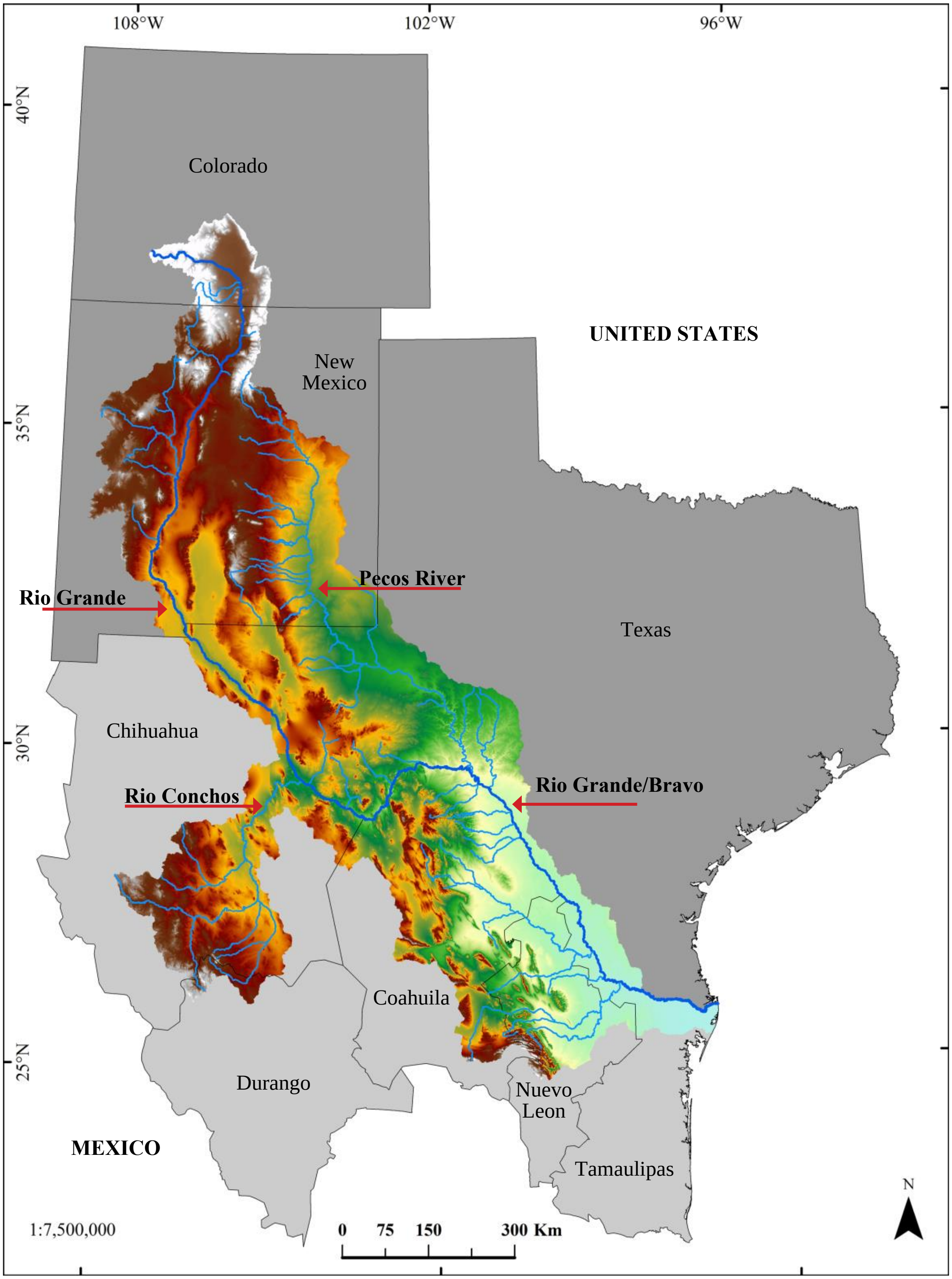


**Figure 1 Rio Grande/Bravo Basin.**

The RGB ecosystem was historically home to numerous native fish species including the silvery minnow (*Hybognathus amarus*) and endemic mussels. Now, however, the silvery minnow is endangered in the northern branch of the RGB and exists downstream from La Junta de los Rios only through restocking. Restoration efforts are complicated by numerous species of non-native fishes. The silvery minnow was likely extirpated from parts of the RGB due to the combined effects of habitat degradation caused by geomorphic changes, water quality impairments, and interactions with non-natives species; however, the relative importance of each of these limiting factors and the significance of their interactions are poorly understood.

# ACTIVITIES PERFORMED

## ***Past and present water management objectives, policies, allocation practices and water uses***

The RGB basin has an extensive history of water disputes and agreements. Its length exposes it to numerous settlement groups with diverse backgrounds and its waters connect cultures, ecosystems, and natural landscapes. Societies living in these catchments share water resources management and allocation approaches, which are aggravated from climate variability. The basin also share policies that affect water availability, which involve regulations on land use, water allocation, water quality, flood management, and the environment. Water management strategies under its transboundary context becomes particularly challenging because it requires the coordination of institutions, stakeholders, societies, governments, and regulations with diverse and sometimes conflicting objectives. The river has a fascinating water story.

### Pre-Hispanic Era (Pre-1500)

Because of the water scarce nature of the RGB and the though climate and terrain conditions, the people living in the basin were mostly nomadic. In certain part of the basin, agriculture lands were irrigated with RGB water. For instance, in El Paso del Norte Valley (El Paso - Ciudad Juarez Valley), settlers used to build a diversion dam that every year the river demolished for diverting water into their irrigated lands. Also, in Valle Española and Chamita, (Figure 2) similar temporary infrastructure and diversion procedures were used. In general, there was no allocation policy or institutional framework to allocate water. The main use of water was to supply local need for drinking and small agricultural areas. Even though the RGB river traverses through a desert, there was enough water for the uses of that time.

**Figure 2 Early RGB settlements**

## Colonial Era (1500 - 1800)

At the discovery of the Americas by Christopher Columbus in 1492 and the arrival of Hernán Cortés who overthrew the Aztec empire and conquer Mexico for the crown of Spain (1521), the entire RGB basin felt into the jurisdiction of one country: Spain. In this period, there are records of human settlements in Presidio Del Norte (El Paso – Ciudad Juarez), Presidio del Rio Grande (Presidio - Ojinaga), Laredo (Laredo - Nuevo Laredo) and Refugio (Brownsville - Matamoros). Any entity (usually a municipality) or private person (usually a farmer) who wanted to use or divert water had to ask for a *concession* to the Viceroy of Spain in Mexico. The legal figure of *water concession* was intended to keep the ownership of water by the King of Spain, and through the Viceroy, allow people the use of water, but not the ownership. A modification of the water concession legal figure still applies nowadays in Mexico. In addition, water was considered a *public property of common use*, meaning that water users had the obligation to not harm other water users, similar to riparian water rights. In practice, upper riparian users must be aware of water users downstream and avoid any harm. There was no prior appropriation rule, the Viceroy could grant high priority to certain uses, such as domestic, but besides this exception, new water users must be aware and manage their water to not negatively affect other water users. In addition, there was an absolute prohibition to obstruct and impede the navigational channels by any means. This was a natural prohibition given the success of Spanish to navigate and continue their expansion with vessels and ships.

## Mexico and Texas Independence, Texas Annexation and Mexico’s War (1810 - 1848)

After the independence of Mexico (1810-1821), all the viceroyalty laws were ratified, including those related to water. Those, in fact, there was no change in the water law or regulations related to water use in the RGB. Because of the sparse population and human settlements in the north part of Mexico and the lack of economic strength, two states joint forces to become a single: The State of Coahuila and Texas. To mitigate the lack of population in this region, Mexico’s government implemented a policy to allow foreigners to settle in this region, mostly from the United States of America. American settlers brought with them slaves, which was a practice prohibited since the colonial period, and thus ratified by Mexico. Mexico’s federal government implemented several measures to castigate anyone holding slaves, including giving the freedom to any slave in 1827. As a response, settlers from the United States forced slaves to sign contracts of un-paid for 99 years. In 1830, the federal government limited the acceptance of migrants from the United States into Texas. In 1833, the State of Texas requested its independence from Mexico, but it was not until 1835, when people from Texas started a rebellion against the Mexican government to gain sovereignty. In April 21st, 1836, in the battle of San Jacinto, the President of Mexico Antonio Lopez de Santa Anna was ambushed and forced to sign the Declaration of Independence of Texas. This is the date when the RGB became a transboundary basin.

The Republic of Texas requested its annexation to the United States of America three times, but it was not until December 29, 1845 that the State of Texas became the 28th State of the Union. There is no information related to the laws or water allocation systems in this period (1836 - 1845). The Declaration of Independence document of the Republic of Texas did not specify the borders of its territory. This created a problem when Texas got annexed to the U.S. While the Mexican government claimed that the border was the stream of the Nueces River, Texans (now part of the U.S.) claimed the border was “The Rio Grande down south.” In fact, this misunderstanding was the main case of the Mexican War (U.S invasion and occupation into Mexican territory). The Mexican war lasted two years and ended up with Mexico ceding more than half of its territory (Currently the states of California, Arizona, Utah, Nevada, Colorado and New Mexico). The treaty of Guadalupe Hidalgo (February 2, 1948) defined the terms and borders for both nations. The navigability clause for waterways was kept in this treaty. For the newly states of the union, the prior appropriation system was adopted, with the two main rules of this system applying to water users in the basin: (1) first in time – first in right, and (2) reasonable, continual and beneficial use of water (use it or lose it). For the Mexican States remaining in the RGB basin, the same legal framework of water concession is applied now by the federal government.

### Convention of 1906 (1849 - 1906)

From 1849 to 1876, there were still few people settling the States of Texas, New Mexico, and Colorado. The Donation Land Claim Act (1850) helped the colonization of the states of Washington, Oregon, Idaho and Wyoming. The Southern Homestead Act (1866) helped the colonization of Delaware, Maryland, Virginia, West Virginia, Kentucky, Tennessee, North

Carolina, South Carolina, Georgia, Alabama, Mississippi, Florida, Louisiana Arkansas Oklahoma and Texas. However, it was not until the Desert Land Act (1877) when the federal government created enough incentives for people to move into Colorado and New Mexico. The Desert Land Act sold land, up to 320 acres, at a very small price ($0.25 per acre) with the condition that individuals may apply for a desert-land entry to reclaim, irrigate, and cultivate arid and semiarid public lands. This act promoted a disproportioned expansion of agriculture land and water consumption in Colorado and New Mexico, in comparison with Texas and Mexico.

In 1875, irrigated agriculture began in the San Luis Valley and expanded rapidly. By 1890, there was 50% more irrigated land in the San Luis Valley alone than in all New Mexico. By the late 1800s, significant hydrologic and geomorphic changes had occurred along the northern branch of the RGB (Scurlock, 1998). Irrigation in San Luis Valley impacted water users in New Mexico, Texas, and Mexico by reducing summer base flows in some stretches of the river, while floodplain soils were waterlogged in other areas (Enriquez-Coyro, 1976). In 1880, there was no water flowing at El Paso Texas. Mexico formally lodged complaints about inadequate water supplies to support irrigation near Ciudad Juarez in the late 1800s. From 1880 to 1905, there were many official complaints and proposed solutions to solve the problem of lack of water in the El Paso – Ciudad Juarez region. For instance, in 1900, Mexico’s Secretary of Foreign Affairs, Federico Gamboa, performed a thorough analysis of this problematic and came up with the conclusion that: (a) due to the navigation clause in the Treaty of 1848, the U.S. cannot legally reduce the stream flow at any portion of the border, including El Paso Texas; (b) Mexico has the right to request the destruction of the facilities that harms his right to water and has the right to demand a compensation; (c) the construction of a potential dam (that lately would become Elephant Butte) to mitigate the damages by upstream riparian users only could be constructed by agreement of both countries. Furthermore, the President of the Supreme Court of Justice of Mexico, Ignacio Vallarta, added to Gamboa’s comment the following statements: (a) the rives at the border are common resources and belong 50% of its use and supply for each of the riparian states; (b) the sovereignty of one state over a portion of the international river do not authorize the right to use the water of the other state; (c) it is illegal to divert the flow of a river if this harms the navigation established in the Guadalupe Hidalgo treaty. As a result, the water of the RGB must be divided in halves between both countries; (b) the U.S. breaks the Guadalupe

Hidalgo treaty because of the excessive use of the international waters; (c) Mexico has the legal right not only to stop water diversion in the U.S., but also to stop an existing diversion in the upstream riparian states, and (d) Mexico has the right to claim for a compensation. As a response to these claims, in 1985 the U.S. general attorney, Judson Harmon, responded with the following statement known as the Harmon doctrine: “The fundamental principle of international law is the absolute sovereignty of every nation as against all others, within its own territory... all exceptions, therefore, to the full and complete power of a nation within its own territories must be traced up to the consent of the nation itself. They can flow from no other source”. In summary, the Harmon doctrine holds that a country is absolutely sovereign over the portion of an international watercourse within its borders. Thus, that country would be free to divert all the water from an international watercourse, leaving none for downstream states. Since then, this doctrine has been rejected and highly criticized (McCaffrey, 1996). In 1902, the Reclamation Act with the objective to fund irrigation projects for the arid lands of 20 states in the U.S. This act set aside money from sales of semi-arid public lands for the construction and maintenance of irrigation projects. The newly irrigated land would be sold and money would be put into a revolving fund that supported more such projects. The Reclamation Act allowed the U.S. Bureau of Reclamation to take over the project from a private investor in 1904, Rio Grande Dam and Irrigation Company, for irrigating the portion of the basin between Engle (Elephant Butte dam location) to El Paso Texas. That same year (1904), Mexican President Diaz and U.S. Ambassador Clayton arrange the terms of the convention: (a) a reservoir will be constructed in Engle (Elephant Butte reservoir); (b) the planning and management of the Rio Grande project will be done by the U.S. Bureau of Reclamation; and (c) Mexico will receive 60,000 acre-foot/year (74 million $m^3$/year), which means water for about 25,000 acres (10,100 ha). In 1905, U.S. President Theodore Roosevelt published an agreement to respond the Mexican claims, the navigability of the river, and if the diversion of water in the US violates the international laws. This study was done in a single day. A note form the State Department was sent to Mexico noting: “[…] there is no legal responsibility from the U.S. to Mexico in the water of the Rio Grande/Bravo. Although, the U.S. government is willing to engaged a water treaty […] as a courtesy, […]”, and “[…] the construction of a dam in Engle will violent all satisfactory solution of this conflict […]”. From 1905 to 1906, closed-door meeting and negotiations happened between representatives of both countries instructed by both presidents, Theodore Roosevelt from the U.S. and Porfirio Diaz from Mexico. During those year. Mexico's President, Porfirio Diaz, was planning his last re-election, and thus signing an agreement with the U.S. government could help him to get the buy-in from the U.S. government. The Convention of 1906 (IBC, 1906) provides information for water distribution of the RGB between the U.S. and Mexico, within the international segment of the river located between the El Paso-Ciudad Juárez Valley and Fort Quitman, Texas. In summary, the U.S. shall deliver to Mexico a total of 60,000 acre-feet/year (74 million $m^3$/year) at the diversion point called Acequia Madre, located close to Ciudad Juárez, Mexico. The water allocation of Mexico was considered for irrigating the Valle de Juarez region in Mexico. For this portion of the River, from Elephant Butte to Fort Quitman, water was divided and allocated as follows: 55% of the available water to New Mexico (233,000 acre-feet/year), 30% of the available water to Texas (127,000 acre-feet/year) and 15% of the available water to Mexico (60,000 acre-feet/year).

### State Compact Era (1907 - 1939)

The Rio Grande Compact (Rio Grande Compact, 1938) divides out the waters of the Rio Grande above Ft. Quitman, Texas, among Colorado, New Mexico and Texas. It establishes water delivery obligations and depletion entitlements for Colorado and New Mexico to Texas, and given the variable climate, it provides for debits and credits to be carried over from year to year until relinquished under the provisions of the compact. Colorado agreed to deliver water to New Mexico measured at Lobatos streamflow gage near the state line. The water, as stated in the Rio Grande Compact (1938) "shall be ten thousand acre feet less than the sum of those quantities set forth in the two following tabulations of relationship, which correspond to the quantities at the upper index stations" (Table 1, columns A and B). Intermediate quantities are proportionally estimated. New Mexico is also committed to deliver water exclusively on July, August, and September. According to the Compact, the deliveries "shall be that quantity set forth in the following tabulation of relationship, which corresponds to the quantity at the upper index station" (Table 1, column C). These deliveries should not affect any international deliveries to Mexico.

Water of the Pecos River, the largest U.S. tributary of the RGB, has been divided between New Mexico and Texas through the Pecos River Compact (Pecos River Commission, 1949). New

Mexico must deliver to Texas a quantity of water to that available to Texas under 1947 conditions. A higher flow that 1947 conditions is divided 50% to each state. Beneficial consumptive use of water saved in New Mexico is apportioned 43% to Texas and 57% to New Mexico. Any water salvaged by Texas is 100% to Texas.

**Table 1 Tabulation of relationship to estimate water deliveries according to Rio Grande Compact**

| **A** | | **B** | | **C** | |
|---|---|---|---|---|---|
| **Discharge of Conejos River** | | **Discharge of Rio Grande Exclusive of Conejos River** | | **Discharge of Rio Grande at Otowi Bridge and at San Marcial exclusive of July, August, and September** | |
| Conejos index supply (1000 af) | Conejos River at Mouths (1000 af) | Rio Grande at Lobatos less Conejos at Mouths (1000 af) | Rio Grande at Del Norte (1000 af) | Otowi index supply (1000 af) | San Marcial index supply (1000 af) |
| 100 | 0 | 200 | 60 | 100 | 0 |
| 150 | 20 | 250 | 65 | 200 | 65 |
| 200 | 45 | 300 | 75 | 300 | 141 |
| 250 | 75 | 350 | 86 | 400 | 219 |
| 300 | 109 | 400 | 98 | 500 | 300 |
| 350 | 147 | 450 | 112 | 600 | 383 |
| 400 | 188 | 500 | 127 | 700 | 469 |
| 450 | 232 | 550 | 144 | 800 | 557 |
| 500 | 278 | 600 | 162 | 900 | 648 |
| 550 | 326 | 650 | 182 | 1000 | 742 |
| 600 | 376 | 700 | 204 | 1100 | 839 |
| 650 | 426 | 750 | 229 | 1200 | 939 |
| 700 | 476 | 800 | 257 | 1300 | 1042 |
| | | 850 | 292 | 1400 | 1148 |
| | | 900 | 335 | 1500 | 1257 |
| | | 950 | 380 | 1600 | 1370 |
| | | 1000 | 430 | 1700 | 1489 |
| | | 1100 | 540 | 1800 | 1608 |
| | | 1200 | 640 | 1900 | 1730 |
| | | 1300 | 740 | 2000 | 1856 |
| | | 1400 | 840 | 2100 | 1985 |
| | | | | 2200 | 2117 |
| | | | | 2300 | 2253 |

## The Treaty of 1944 (1940 to 1944)

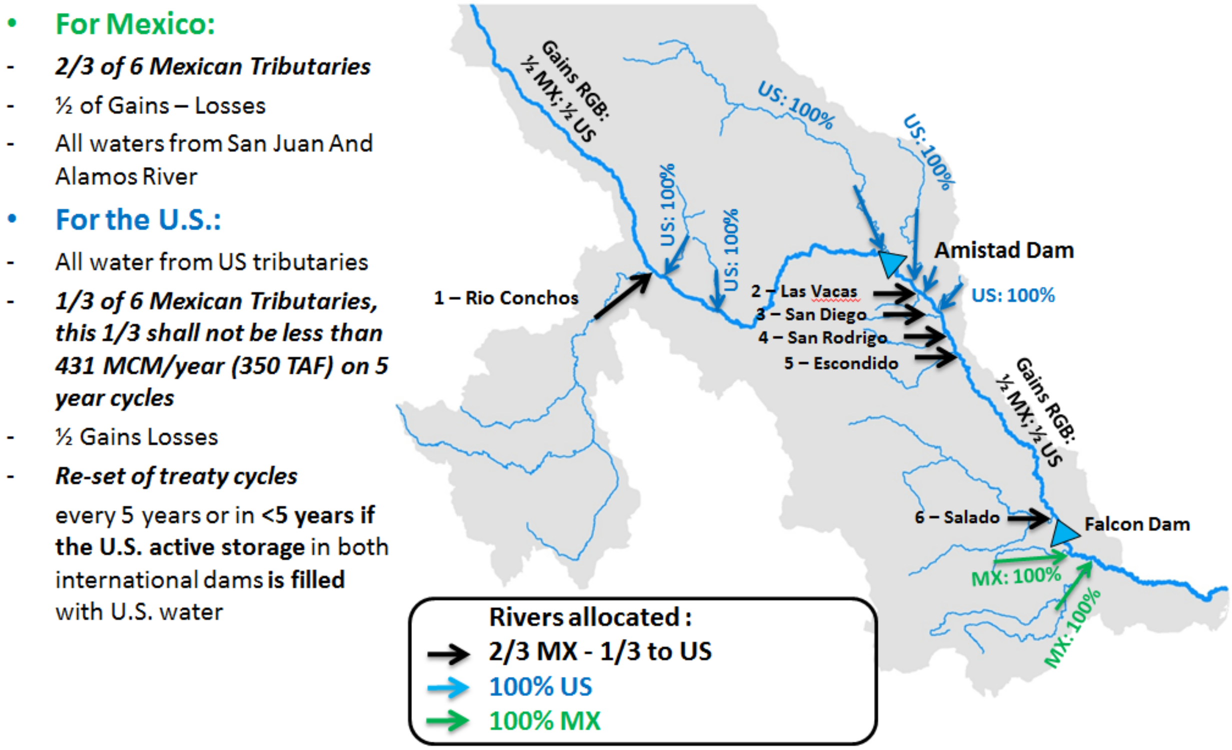
In the Rio Colorado, in the early 1900's up to 1922, water conflicts involved the distribution of water within seven states and Mexico, water distribution for the Imperial Irrigation District and frequent floods in the mouth of the river at the Gulf of California (Enriquez-Coyro, 1976). In 1922, the seven states signed the Colorado River Compact (1922) allocating the water between the upper (Wyoming, Colorado, Utah and New Mexico) and lower (California, Arizona and Nevada) basin states. While the Colorado River Compact established the overall rules of water allocation within the U.S., the water conflicts with Mexico were still unsolved.

Meanwhile in the RGB, the agriculture in the basin prospered. The lower Rio Grande valley, (McAllen-Brownsville/Reynosa-Matamoros area) grew in the agriculture land from 5,000 hectares in 1908 to 154,000 hectares in 1935. At this location, it was estimated that two thirds of the water came from Mexican sources. In addition, the variability of the water resources made impossible the full utilization of the river, sudden floods were followed by extended periods of drought. The necessity to control and regularize the river was evident if further development in the agriculture sector was expected (Enriquez-Coyro, 1976).

Non-water factors delayed the negotiation of an international agreement that would solved the water conflicts between both countries. The Mexican Revolution (1910-1921) and the First World War delayed the negotiations for a decade. In the 1920's and early 1930's, several meetings and informal negotiations took place about water distribution of the Colorado, Tijuana and the RGB waters. During this period, the conflicts moved around the negotiation of all basins at the same time and the amount of water compromised to deliver for both countries. The relationship between both countries was very distant and tense from 1936 to 1939, Mexico started commercial exchange with the axis powers and in 1937 the Mexican government nationalized the oil industry from U.S. companies. Conciliation meetings happened in 1939 to negotiate the compensation terms for U.S. companies due to the oil industry nationalization. The same year the Second World War started, the United States entered the conflict in 1941 after the Japanese bombing of Pearl Harbor, and Mexico declared the war on the axis powers in 1942.

The negotiations for 1944 Treaty started in 1940. A full hydrologic study of the Colorado and the RGB was done to examine the best agreements for both countries. While in the Colorado the negotiations moved around the amount of water delivered from the U.S. to Mexico, in the RGB the situation was the opposite, the negotiations focused on the amount of water delivered from Mexico to the U.S. This unique condition where in one basin (Colorado) one country was the upper riparian and in the other basin (Rio Grande/Rio Bravo) the same country was the lower riparian, made possible a fair discussion of the treaty terms. It was impossible to be negligent in one basin knowing that in the other basin the situation could be reverted. It is also notable the competitive but friendly spirit of the negotiations and the political willingness of Franklin D. Roosevelt and Manuel Avila Camacho administrations to show that during war times it was possible to establish agreement between nations (Enriquez-Coyro, 1976). Finally, on February 3, 1944 was signed in Washington D.C. the treaty between Mexico and the United States that defines the rules for water allocation between both countries of the Colorado and Tijuana Rivers and of the Rio Grande (IBWC, 1944). With the signature of the treaty the International Boundary and Water Commission (IBWC) was created, formed by two sections: the American and Mexican section. The IBWC replace the International Boundary Commission (IBC).

The Water Treaty of 1944 (IBWC 1944) distributes the waters located in the international segment of the Rio Grande from Fort Quitman, Texas to the Gulf of Mexico. This treaty authorized the construction and operation of two reservoirs along the mainstream of the RGB, Amistad and Falcon. In summary, there is a primary division of the water reaching the RGB mainstream from 6 tributaries originating in Mexico as one-third to the U.S. and two-thirds to Mexico. The third shall not be less than 350,000 acre-feet/year ($432X10^6$ $m^3$/year) as an average over cycles of five consecutive years. The treaty cycles can expire in less than five years if the account of U.S. storage in both dams is filled with water. The IBWC evaluates the Mexican delivery of water to the U.S. and determines if the treaty commitments have been met. If there is a deficit in the treaty delivery, it must be paid in the following cycle. The two governments entrusted the IBWC to give preferential attention to the solution of all border sanitation problems.



- **For Mexico:**
  - ***2/3 of 6 Mexican Tributaries***
  - ½ of Gains – Losses
  - All waters from San Juan And Alamos River
- **For the U.S.:**
  - All water from US tributaries
  - ***1/3 of 6 Mexican Tributaries, this 1/3 shall not be less than 431 MCM/year (350 TAF) on 5 year cycles***
  - ½ Gains Losses
  - ***Re-set of treaty cycles***
    every 5 years or in **<5 years if the U.S. active storage** in both international dams **is filled** with U.S. water

**Figure 3 Treaty of 1944**

## Infrastructure Development Era (1945 to 1968)

In this section is analyzed the period after the signature of the 1944 Treaty; however, there is no "after treaties era" since the 1944 Treaty is a dynamic international agreement that is amended each time a minute is signed. Up to now, there are 322 minutes and the last minute was signed on January 2017. Besides, there are two more international agreements signed by the United States and Mexico after 1944, the Chamizal Convention of 1963 (IBWC, 1963) and the Treaty of 1970 (IBWC, 1970). These two treaties are more focused in the border line delineation and solution of conflicts because of the changing in the RGB course.

For the RGB, the 1944 Treaty established the delivery of water from Mexico to the United States of 1/3 of the flow reaching the RGB from 6 Mexican tributaries (Conchos, Arroyo Las Vacas, San Diego, San Rodrigo, Escondido and Salado) provided that this third shall not be less, as an average amount in cycles of 5 consecutive years, than $431.721\times10^6$ $m^3$/year, although such one third may exceed this amount. Two international dams, Amistad and Falcon, were built to store water for both countries. Also, it was provided that the treaty cycles can expire earlier than five years, if the conservation capacity assigned to the U.S. in both international dams is filled with water belonging to the U.S.

The technical report presented by Orive-Alba (1945) to the Mexican Chamber of Senators shows the calculations used to define the U.S. and Mexican allotment in the Treaty, and the expected deliveries of water from Mexico to the U.S. Two different cases were considered by Orive-Alba to evaluate the treaty obligations. Case I only considers 5 year cycles, before the dam's construction, when the system is considered to not be fully developed. Historically, this case happened during the first three treaty cycles, from Oct/1953 to Sep/1958. Case II considers the system fully developed, after the international dams' construction. In this case, during wet years the treaty cycles can expire earlier if the conservation capacity assigned to the U.S. is filled. Historically, Case II happened since treaty cycle four up to the present (treaty cycle 32).

Three criteria are used to analyze the performance expected when the treaty was signed and what happened for the treaty deliveries from Mexico to the U.S.: *Reliability*, *Resilience* and *Vulnerability*. Reliability refers to the frequency in time an event is successful in relation to the total period analyzed. A successful event is defined as the event when there is no deficit in the delivery of treaty obligations. Resilience is the probability that once the system is in a deficit, the next period the system recover to a successful event. Vulnerability is the expected value of the deficits, in other words, it is the average of the deficits experienced.

**Table 2 Reliability, Resilience and Vulnerability of the Mexican delivery of water according to the 1944 Treaty**

| | Chase I: System Undeveloped | | Chase II: System Developed | |
|---|---|---|---|---|
| Performance Criteria | Expected (%) | Historical (%) | Expected (%) | Historical (%) |
| Reliability | 56% | 67% | 42% | 63% |
| Resilience | 65% | 100% | 80% | 67% |
| Vulnerability | 10% | 27% | 9% | 30% |

For Case I (see **Error! Reference source not found.**), the reliability improved from an expected value of 56% to 67%. This means that the system was fewer times in deficit than what was expected, 11% of the time less. Also, the system recovered faster, the resilience increased from an expected value of 65% to an historic value of 100%. Historically, when the system failed the following cycle the deficit was paid off. On the contrary, the vulnerability got worse, from an expected value of 10% to an historic value of 27%. When a deficit in the treaty obligation happened, it was of 27% of the treaty obligations (2,159 million $m^3$/cycle) instead of 10%, as it was planned. The people involved in the treaty negotiations knew that the system will fail very frequently, in fact 44% of the time (1-Reliability) and that system does not recover vary fast (65% of the times around two out of three times), but they relied that the failures will be small (10% of the treaty obligations) (Orive-Alba, 1945). Historic data showed that the system does not fail as much as they thought, only 33% of the time, and the recovery is faster (100% of the times for Case I, from Oct/1953 to Sep/1968) but the deficits are much bigger of what they planned (about 3 times bigger, 27% of the treaty obligations).

For Case II (see **Error! Reference source not found.**), as the system is right now, the reliability improved from an expected value of 42% to an historic value of 63%. Historically, the system was less time in a deficit of what was expected. However, the system recovered slower and the deficits were bigger of what was expected. The quickness of recovery (Resilience) decreased from an expected value of 80% to an historic value of 67%; historically it was more difficult to recover from a deficit of what was expected. The severity of the deficits (Vulnerability) increased from an expected value of 9% to an historic value of 30%. When a deficit in the treaty obligation happened, it was of 30% of the treaty obligations (30% of 2,159 million $m^3$/cycle) instead of 9%, as it was planned. The people involved in the treaty negotiations knew that the system will fail very frequently, in fact 58% of the time (Enriquez-Coyro, 1976; Orive-Alba, 1945). However, they relied that the failures will be small (9% of the treaty obligations), and the system will recover from deficit very frequently (80% of the times; around four out of five times). Historic data showed that the system does not fail as much as they thought, only 47% of the time (1-Reliability), but the recovery is slower (67% of the times, two out of thee) and the deficits are much bigger of what they planned (more than 3 times bigger, 30% of the treaty obligations). In conclusion, historical treaty deliveries have shown different performance than the 1944 Treaty signature premises: higher reliability, lower resilience and high vulnerability.

## Modern Era (Amistad Dam Completion - 2017)

### Upstream of Fort Quitman

Water upstream Fort Quitman is organized in three sub-basins: the upper basin also known as *Closed Basin*, from the headwaters to Cochiti reservoir in New Mexico, the *Middle Rio Grande Basin* from Cochiti Reservoir to Elephant Butte Dam and the *Lower Rio Grande Basin* from Elephant Butte to Fort Quitman, Texas (Nava Jimenez, 2012). This organization is characterized by the presence of different institutions and organizations responsible of the water management in this region. Water resources in this subsystem have been exhausted, all the water has been allocated to water users, thus there is almost no water flowing downstream of Fort Quitman.

Known under the name of *Closed Basin*, the highs of Colorado's catching basin extends on a 7,416 $km^2$ surface. Colorado Division of Water Resources (DWR) and specifically Colorado Water District 3 (CWD3) are the agencies responsible of managing this sub-basin. DWR has as a mission to ensure sharing of water, conforming to the laws and decrees signed by Colorado, and CWD3 is responsible of managing the quantitative sharing of waters (DWR). This project, managed by the U.S. Department of the Interior and the Colorado BOR has for objective the preservation and conservation of streamflow in the tributaries, water that would be lost otherwise due to evapotranspiration on agricultural production. The water accumulated by the all the infrastructures in this project is transferred in the Franklin Eddy Canal so that the Colorado can accumulate the amount of water that must be delivered to New Mexico and Texas in the Rio Grande Compact framework. The mainstem of the RGB basin in Colorado is protected under the name of Rio Grande Natural Area by the Committee on Energy and Natural Resources (CENR, 2005), with the goal of promoting the protection and restoration of the river zone of the RGB between Colorado and New Mexico.

The organization and management of the Closed Basin are essential for sharing and distribution of Rio Grande waters between Colorado, New Mexico, Texas and Mexico. In the *Middle Rio Grande Basin* (MRGB) from Cochiti Reservoir to Elephant Butte Dam, water is diverted for agriculture (*Middle Rio Grande Conservancy District*, MRGCD) and the development of fish and wildlife resources as well as recreational resources. In the *Lower Rio Grande Basin* (LRGB) water is mainly allocated among the Elephant Butte Irrigation District (EBID), El Paso County Water Irrigation District (EPCWID), and Mexico, which eventually distribute this water allocation to Irrigation District 009 Valle de Juarez. The water distribution and sharing upstream Fort Quitman is complex because the different state laws, sub-systems, inter-state compacts and international agreement that must be met, all at the same time while meeting with environmental and water quality requirements.

### Downstream of Fort Quitman

Below Fort Quitman, water is allocated in three steps. First, water in the RGB tributaries is allocated among water users. In Texas, for stakeholders located along the Pecos River water is allocated using the prior appropriation rule which is beneficial use plus first in time first in right (TCEQ, 2005). In the five states of Mexico (Durango, Chihuahua, Coahuila, Nuevo Leon and Tamaulipas) water is allocated using the National Water Law (LAN, 2016). Second, water reaching the RGB mainstem from any tributary and instream flows is divided between the U.S. and Mexico according to the Treaty of 1944 (IBWC, 1944). Water along the RGB is stored in two international reservoirs, Amistad and Falcon. The IBWC is responsible for this accounting and storage of water for each country. Third, based on IBWC water accounting, water is distributed among water users for each country along the RGB main stem. In Texas, water is distributed according to the Texas Administrative Code 303 (TCEQ, 2006) while in in Mexico, water is distributed according to the National Water Law (LAN, 2016).

In Texas, there are initiatives to improve the water quality of rivers. The Texas Clean Rivers Program has the goal of coordinating the water quality monitoring at local and regional scale. It also promotes the public sensitization to improving the water quality (TCEQ, 2016). In the bilateral scale, both nations should understand each other about the general problems of the shared basin. The RGB basin suffers the consequences of anthropogenic development. Dams, reservoirs, hydroelectricity generation, agricultural and municipal use of water, as well as territorial planning contribute to the water quality degradation and alteration of the streamflow regime (Small et al., 2009).

### *Water Use*

Water consumption in Mexico along the RGB mainstream and its tributaries has been driven by the high annual precipitation variability of the basin (CONAGUA, 2008; Sandoval-Solis, 2011). Water use linearly increased due to irrigation district expansion, mostly from 1965 to 1994, and after that, a dramatic decrease in their water supply during the 90's drought (1994-2007) (Figure 4, a and c). Water consumption before the 90's drought was much higher than the annual average consumption (1950 to 2004) of water users along the RGB and in Mexican tributaries, which are 1,576 and 2,392 million $m^3$, respectively.

In terms of historic water use, water consumption for U.S. has also been driven by the variability of annual precipitation in the basin (Sandoval-Solis, 2011). Water consumption for U.S. water users has been close to the mean annual value (1,442 million $m^3$) except for 1989 when more than 2,000 million $m^3$ were consumed (Figure 4, b). The mean annual water consumption for Mexican and U.S. water users along the RGB mainstream is similar, 1,576 and 1,442 million $m^3$ respectively. The main difference is that U.S. water consumption does not vary as much as in Mexico.

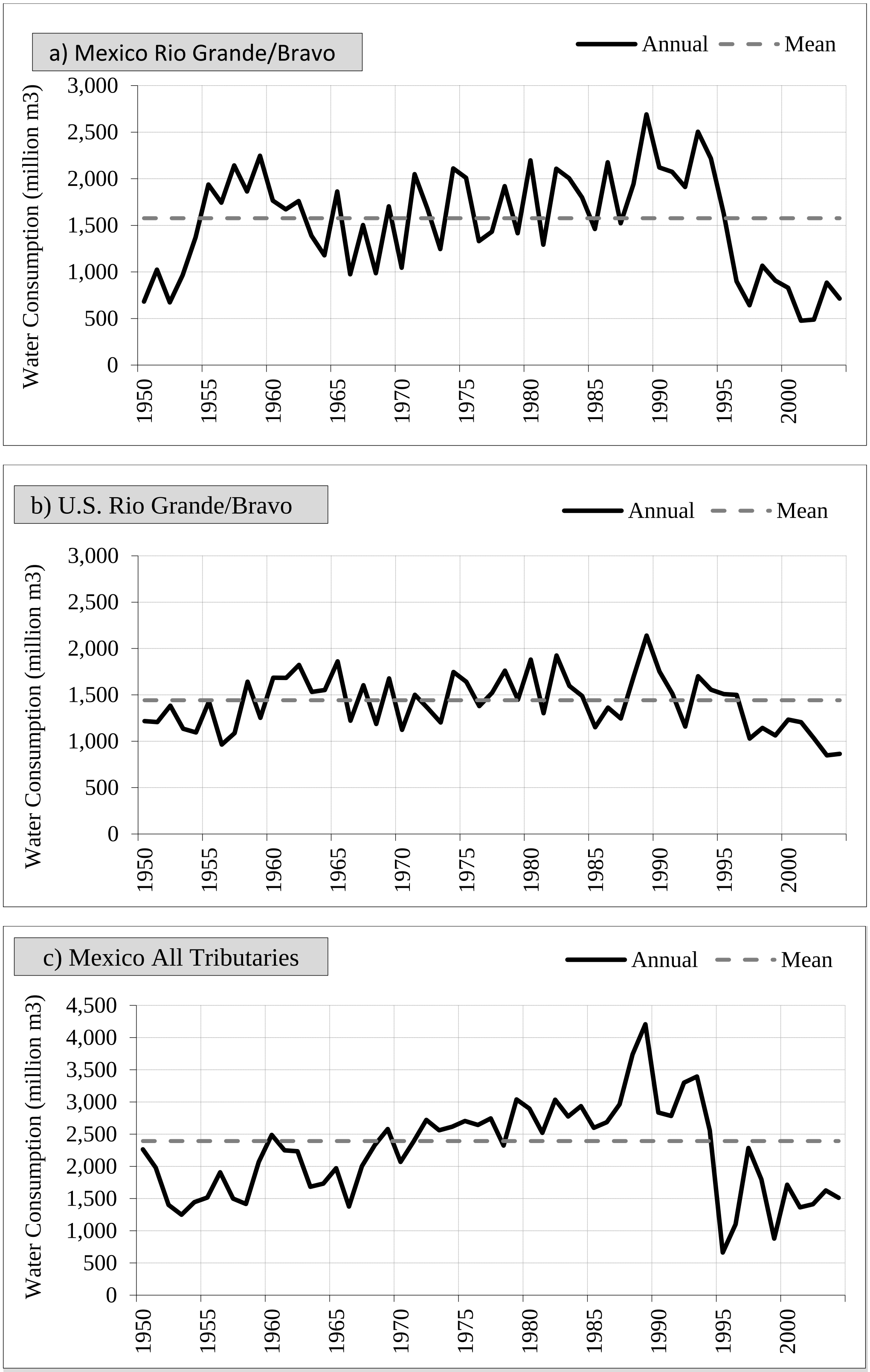


**Figure 4 Water consumption in Mexico and U.S. along the Rio Grande/Bravo and in Mexican tributaries.**

In the early 2000's, reduction in the irrigation districts water rights' was discussed by authorities from both countries (IBWC, 2003b; R. J. Brandes Company, 2004; SAGARPA, 2003); the drought of the 90's showed that the prior 1994 water consumption was unsustainable. U.S. and Mexican authorities recognized that it was physically impossible to continue providing the water consumption of the early 90's (1990-1994). In 2004, water rights in Mexico and the US were estimated to be 4,532 and 2,129 million m3/year, respectively (CONAGUA, 2004; R. J. Brandes Company, 2004). Recently, several policies have been implemented to reduce the water rights in the basin, such as buy-back of water rights, infrastructure improvements, and water rights reduction. In 2008, water rights in Mexico and the U.S. have been reduced to 4,401 and 1,953 million $m^3$/year, respectively. These values are still above the historic mean annual water consumption for Mexico and the U.S., which are 3,968 and 1,442 million $m^3$, respectively (Sandoval-Solis, 2011). Furthermore, the previous analysis does not consider water for the environment; these values shows the problem of over-allocation of water rights in the basin.

### *Reservoirs*

Reservoir construction in the basin increased water storage since the early 1900 in both U.S. (Figure 5) and Mexico (Figure 6). Such stream modification altered the natural flow of the river, degraded the aquatic and riparian ecosystems in the basin. There is evidence that in the Big Bend reach before the mid 1940's, the RGB mainstream preserved a wide, sandy and multi-threaded river. However, after the mid 1940's, a progressive channel narrowing has been the constant in this reach, temporally interrupted by occasional large floods that widen the channel and channel narrowing resumed again (Dean and Schmidt, 2011). Narrowing has occurred by the vertical accretion of fine-grained deposit on top of sand and gravel bars. Sand and gravel bars that used to be part of the dynamic channel were progressively invaded by vegetation. The invasion of non-native species, such as salt cedar (*Tamarisk* spp.) since 1910's or giant cane (*Arundo donax)* since 1938 (Everitt, 1998), has exacerbated the process of channel narrowing and vertical accretion. The geomorphic nature of the RGB has changed from a wide, laterally unstable, multi-thread river before mid 1940s; to a stable, single-thread channel with cohesive, vertical blanks, and few active in channel bars after 1940 (Dean and Schmidt, 2011). This shift in the geomorphic conditions was caused primarily by dams' construction, mostly since 1915, and it has been exacerbated by the invasion of non-native species after late 1930's.

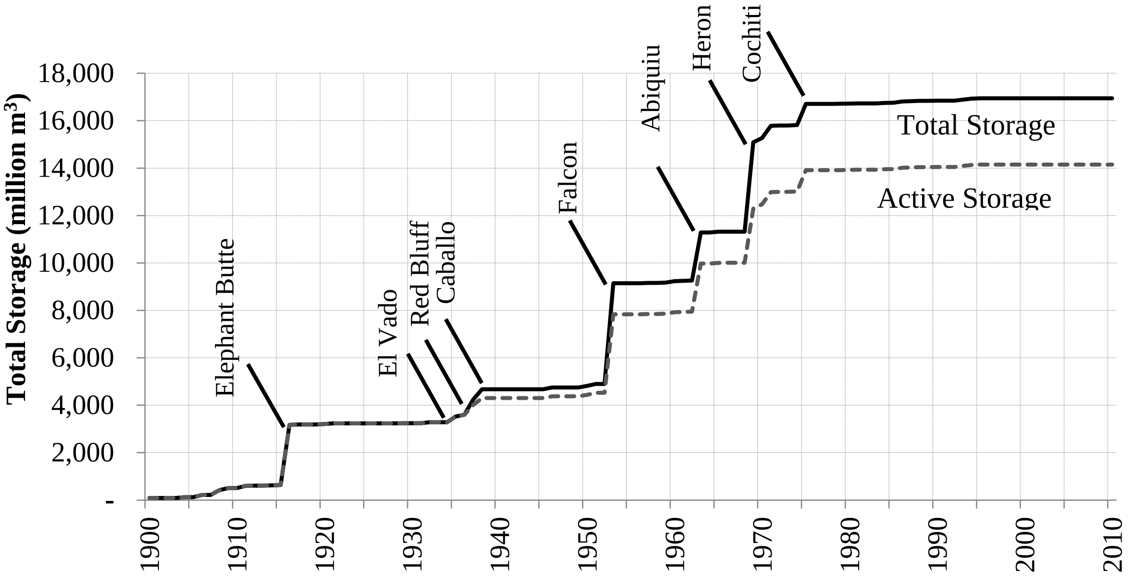


**Figure 5 Reservoir development in the United States for the Rio Grande/Bravo.**

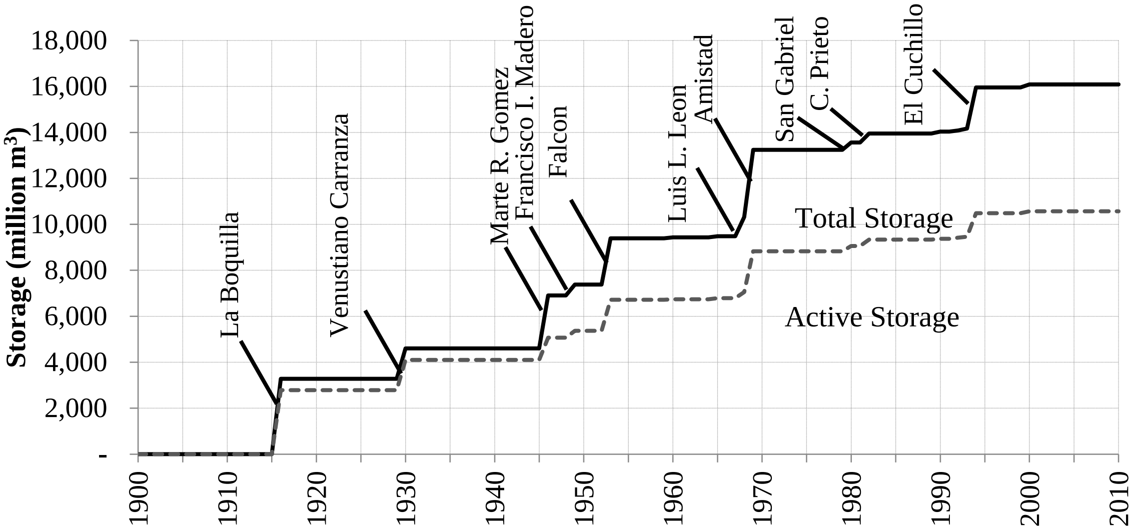


**Figure 6 Reservoir development in the Mexico for the Rio Grande/Bravo.**

Another point of environmental concern is the outlet of the river at the Gulf of Mexico. In February of 2001 the river mouth was blocked by a sand bar caused by low flow conditions due to the 90’s drought, upstream diversion and invasive aquatic vegetation (Mathis et al., 2006); it remained closed until September 2001 when the IBWC dredged it open (USACE, 2003). Subsequent tidal water changes again closed the mouth until November 2002, when higher tides and increased rainfall runoff partially opened it. The scarcity of flow in this reach is a threat to the estuary’s sustainability; side effects include degradation of the environment, lost of species and saline intrusion in aquifers, among others.

## Current Status of the Basin

Regarding the water management in the basin, after the publication of the water availability for Mexican water users by CONAGUA (2008), the Rio Bravo basin council started a process of negotiation to define the regulation to allocate water for municipalities and irrigation districts in the basin (Arreguín, 2010) these water rights account for 99% of the total Mexican water rights. To build trust among the parties, the basin council is building a water planning model to test the policies. This planning model uses the algorithms and allocation policies of the Rio Grande/Rio Bravo WEAP model built by Sandoval-Solis (2011).

Since 2001, the Texas Water Development Board create a regional water plan that evolves every five years. The purpose of the plans is to provide information to water planner regarding short and long-term water management recommendations. The last plans updates were published in 2016 (TWDB, 2016) for the three water planning region groups along the Texas border with Mexico: The Far West Texas Planning Group, The Plateau Water Planning Group, and the Lower Rio Grande Valley Development Council. These documents describe water management policies that will be implemented to deal with the increase of population and energy requirement, such as: water conservation measures in municipalities and irrigation, reuse of water either from municipal or agriculture drains, groundwater development, brackish and seawater desalination, acquisition of additional water rights. Out of the previous policies, four policies account for 75% of the water savings planned: 1) increase in efficiency of on-farm water application, 2) water conservation in conveyance for irrigation, 3) acquisition of water rights through purchase and 4) brackish desalination.

Regarding treaty obligations, cycle 32 is the current treaty cycle, it started on October 25, 2016. Cycle 31 (2010-2015) ended with a debt of 263,250 acre-feet (324.7 mcm), representing 15% of the five-year total. The debt was paid on total on January 25, 2016 (IBWC, 2016). Cycle 30 was closed on October 25th 2010, it lasted about one year and a half, and it was closed because of the filling of the U.S. storage capacity at both international reservoirs. Up to March 2017, the storage for the U.S. and Mexico at the international reservoirs, Amistad and Falcon are 65% and 30% of their conservation capacity respectively (IBWC, 2017). The biggest reservoirs in Mexico are mostly above 90% of their conservation capacity, with the exceptions of Luis L. León (58%) in the Rio Conchos and Venustiano Carranza (58%) on the Rio Salado (IBWC, 2017). In the U.S., Elephant Butte and Caballo reservoirs are at their 15% and 13% conservation capacity, respectively (IBWC, 2017).

Regarding the environment, in 2006 the environmental flows for nine control points in the Conchos basin were estimated by the World Wildlife Fund; these flows are used to evaluate the environmental requirements for the basin. More recently, in 2010 Sandoval-Solis et al. (2010) proposed an annual hydrograph for environmental restoration flows at the Big Bend Reach, this hydrograph is based on the hydrologic characteristics prior 1946, when the RGB maintained a wide, sandy, multi-thread channel (Dean and Schmidt, 2011). This investigation progressed when new environmental flow targets were set by a group of experts in the basin. Research on environmental flow for the BBR was updated to quantify the feasibility to provide such flows from LLL (on the Rio Conchos) without harming water users, the treaty obligations, or increasing the flooding risk at Presidio/Ojinaga (Sandoval-Solis and McKinney, 2014). This research was further developed by to include flow targets at three different locations along the reach (Lane et al., 2015) and optimize the water allocation (Porse et al., 2015). Later, research on the area estimated the economic effects of implementing such a change in LLL reservoir operation policy. Results suggest that net regional benefits would increase with environmental releases and even the agricultural sector would benefit from it (Ortiz-Partida et al., 2016).

In Texas, Senate Bill 3 (2007) provides the legal framework to determine and promote environmental flows for the state. In March 2009, two Science Advisory Committee were formed one for the Upper Rio Grande from Presidio to Amistad dam; and for the Lower Rio Grande from Amistad dam to the Gulf of Mexico. These committees provided an objective perspective, evaluation, and estimation of environmental flows in the RGB stream to the Environmental Flows Advisory Group, which is integrated by members of the senate, House of Representatives and people appointed by the Governor. The groups created a report with environmental flow regime recommendations to sustain the sound ecological environment consistent with Senate Bill 3 (Lower Rio Grande Bay Expert Sciences Team, 2012; Upper Rio Grande Bay Expert Science Team, 2012).

Regarding water quality, in 2010 there were two main concerns downstream Falcon to the Gulf of Mexico: 1) bacteria, listed as the main concern and 2) mercury, dissolved oxygen and nutrients. The proposed work plan of the Clean River Program for 2010-2011 includes water quality data monitoring in 46 stations, data analysis and reporting, stakeholder participation and outreach. The IBWC Texas Clean River Program has conducted several monitoring campaigns along the RGB mainstream. The analysis of these data has shown problems of bacteria, high salinity, nutrients, and excessive growth of aquatic weeds, specially in the lower part of the basin (IBWC, 2013).

Regarding politics between Mexico and the U.S., during the drought of the 90's (1994-2007), relations between both countries were tense because of the increase in water debt of Mexico. Presidents George W. Bush and Vicente Fox organized meetings to discern solutions about the problematic of water scarcity, Mexico's water debt and how it will be paid; Minutes 307, 308 and 309 are the agreements of these presidential meetings (IBWC, 2001; IBWC, 2002; IBWC, 2003b). In the Colorado River, since 1988, lining the All American Canal (AAC) started sounding as an option to save water for California; in 2002-2003 this project gained momentum and the final design for the AAC was authorized by the California legislature in September 2003 (USBR, 2006). Savings of the lining of the ACC were estimated of 67,700 acre-foot/year (83.5 million m3/year). The groundwater hydrology in this region conveyed the infiltration losses of the AAC to Mexican territory, Mexican farmers and the Colorado Delta habitat were benefited from these losses. Because of the Mexican water debt in the RGB, Mexican authorities in the Colorado delta did not raise any claim about the drawbacks that the lining of the AAC would provoke to farmers and the environment (Personal communication, Carlos A. de la Parra, El Colegio de la Fronte, 2010); they did not have a strong argument for claiming harm considering that farmers in Texas were affected by the unmet of Treaty obligations from Mexico. Once again, problems in one basin, the RGB, affected the management on the other basin, the Colorado River. When the Mexican water debt was paid in 2007 (IBWC, 2007), Mexico started claiming affectations because of the lining of the ACC but it was too late, the project already started in June 2007 (USBR, 2010) and despite the fact of the NGOs sued the State of California, in 2010 the lining of the canal was completed (USBR, 2010).

In Mexico, politics have been related to downstream – upstream water users, the state of Tamaulipas (downstream) against Chihuahua (upstream) state and federal versus regional water management. In 1994 was founded the *Rio Bravo Basin Council*, an organism whose objective is to determine efficient policies to allocate water in the Rio Bravo (CTMMA, 2001). These public organisms oversee the decision-making process for the water planning and management of the basin. The *Basin Council* is integrated by representatives of each basin's state, water users, and federal government (CONAGUA, 2016). The basin council defines rules for water allocation in the basin, in Mexican territory. In 2008, the water availability study was published as an agreement of the basin council (CONAGUA, 2008); this is the first step to define a regulation for water allocation in the basin. The politics of the basin (discussions, decisions, and agreements) are expressed on this council; this is the place where upstream (Chihuahua) and downstream (Tamaulipas) users defend their positions and negotiate about water allocation, rules and action that will benefit their interest.

## ***Rio Grande/Bravo models literature review***

An inventory of existing tools that evaluate feedbacks on human and environmental water management strategies for the RGB was created. A review of almost 60 models was performed, however this inventory prioritizes modeling tools that can address concerns of competing water uses and facilitate complex decision making in the RGB. Specifically, the inventory review includes the following information for every model:

- Model authors
- Year of publication
- Model type (groundwater, water allocation, hydrologic, hydraulic, optimization, others)
- Model source
- Model description
- Location on the basin and related river and streams
- Length/area
- Modeling platform (software)
- Period of analysis
- Time step
- Parameters and inputs
- Calibration and validation
- Publisher institution or journal
- Other Participant Agencies
- Limitations
- Applicability for developing environmental flows
- Applicability for developing alternative hydro-climatic conditions

This analysis includes a thorough review of the motivations and decision-making processes for which these tools were developed. The following is a summary of each of the models reviewed, identify by its author and in chronological order.

### **Hearne and United States. Bureau of Indian Affairs. (1985)**

It is a three dimensional groundwater simulation model of the Tesuque Aquifer System, central New Mexico, build to evaluate the aquifer response of an irrigation development plan. The rivers considered in the model include the Santa Cruz, Pojoaque, Santa Fe, and the RGB. The Pojoaque River resulted in the most affected surface water system by the development. After 50 years of withdrawals a flow reduction of 18.77 cfs ant 10.13 cfs resulted from the simulation with and without the irrigation development respectively. The model was developed using a precursor of MODFLOW and it was superseded by later models that are explained with more detail in this report. Therefore, this model is not suitable for developing or testing environmental flow objectives or assessing drought effects.

**Kernodle and Scott (1986) and Kernodle et al. (1987)**

It is a three dimensional groundwater simulation model of the Albuquerque-Belen basin in central New Mexico. The purpose of the model was to simulate steady state groundwater flow condition prior to 1960 as there were no significant groundwater level changes prior to that year. The rivers considered in the model include the Rio Puerco, Rio Salado, Jemez River, and the RGB. The model was updated to perform transient simulations of hydraulic head from 1907 to 1979 to better understand the hydrologic system of the basin and evaluate its response to groundwater withdrawals stress. Results showed that about 68% of the groundwater withdrawals came from surface water depletions, 25% directly from the aquifer storage, and 7% was induced horizontal flow from the Santo Domingo basin. Despite not being directly applicable for developing or testing environmental flow objectives or assessing drought effects, results from this model illustrates the degree in which groundwater extractions can reduce surface water flow.

**McAda and Wasiolek (1988) and McAda (1990)**

It is a three dimensional groundwater simulation model of the Tesuque aquifer, central New Mexico, used to assess the effects of groundwater extractions on the system. The rivers considered in the model include the Pojoaque River, Rio Tesuque, Santa Fe River, and the RGB. The updated version of the model focused on groundwater pumping from a single well and proposed that withdrawals would implicitly capture surface water from nearby rivers, in this case, decreasing the flow of the Rio Grande. Groundwater table was expected to decline as well as discharge to the Rio Grande from tributaries affected by groundwater extractions. The model is not suitable for developing or testing environmental flow objectives or assessing drought effects because of its scale, but it remarks the importance of considering groundwater extractions and their effect on streamflow reductions.

**Kernodle et al. (1995)**

It is a three dimensional groundwater simulation model of the Albuquerque basin, central New Mexico, to describe groundwater flow under different future scenarios. The rivers considered are the RGB and reaches of the Jemez River, Rio Salado, and Rio Puerco. The model simulated 2,400 square miles to a depth of 2,020 feet below the water table and with 11 layers. The extent of the model made it computationally demanding and therefore insufficiently tested and validated. The efforts, however, improved the understanding of the hydrologic system and serve as foundation for other models. The extent of the model would make it suitable to link with other models and test the system response; however, the model was not rigorously calibrated, validated, or tested.

### Frenzel (1995)

It is a three dimensional groundwater simulation model of the Tesuque aquifer, central New Mexico, used to assess the effects of groundwater extractions on the system near Los Alamos. It is a modification of McAda and Wasiolek (1988) model to better simulate vertical groundwater movement. Similarly, the rivers considered in the model include the Pojoaque River, Rio Tesuque, Santa Fe River, and the RGB. The model was used to estimate drawdowns at a well field from projected groundwater extractions in different areas. They suggested that developing a more accurate representation of the Geologic formations would improve the understanding of the systems groundwater flow. Like its previous version, the model is not suitable for developing or testing environmental flow objectives or assessing drought effects because of its scale, but it remarks the importance of considering groundwater extractions and their effect on streamflow reductions.

### Tiedeman et al. (1998)

It is a modification of the three dimensional groundwater simulation model of the Albuquerque basin, central New Mexico created by Kernodle et al. (1995). The modification improved the calibration using non-linear regression analysis, enhanced the representation of the hydrogeology, and revised aquifer parameters. However, they made a discretization of spatial and temporal variables to reduce computational time. The rivers considered are the RGB and reaches of the Jemez River, Rio Salado, and Rio Puerco. Due to its scale, the model could potentially be use for modeling environmental flow alternatives, such as reduction of pumping to keep more water in the river. However, is not included in the selected model because it was later updated.

**Bravo-Inclan et al. (1999)**

It is a hydrologic model for the RGB and the Pecos River. The model includes topographic, climatologic, and soil data. Despite being the only hydrologic model that includes the whole basin the documentation is incomplete and result lack of utility because they only show simulated and observed data for three points of the entire basin: Otowi Bridge, Cochiti Dam, Elephant Butte, and Red Bluff in the Pecos River). Therefore, there is not enough information to select as suitable for developing or testing environmental flow objectives or assessing drought effects.

**Schmandt et al. (2000)**

Schmandt et al. developed two different models: A reservoir operation model for Amistad-Falcon reservoir system, and a water allocation model to represent the hydrology from below Falcon reservoir to the Gulf of Mexico using a mass balance approach. The models were coupled to analyze water resources and management issues, and identify options for water management for a sustainable regional development. The rivers included are the mainstem of the RGB from Amistad Reservoir to Brownsville, the Rio Conchos, Pecos and Devils rivers, Rio Salado, and Rio San Juan. The project evaluated water availability under possible future drought and development scenarios. Results show a worst-case scenario in which the quantity of water that can be guaranteed even during a critical period, known as firm yield, decreases by 31% from current conditions of 230 mcm/month for the Amistad-Falcon reservoir system. Results suggest that there is enough water and of acceptable quality to support the increasing population, however there need to be changes in the complex array of local, state, regional, and federal water allocation and management strategies in both countries to maintain aquatic and riparian ecosystems. Due to its extent and characteristics, the model is suitable to test environmental flow objectives and assessing drought effects as it integrates water quality, and ecologic parameters as well as water scarcity future scenarios.

**Barroll (2001)**

It is a modification of the three dimensional groundwater simulation model of the Albuquerque basin, central New Mexico created by Tiedeman et al. (1998). It also uses data from hydraulic parameter from Kernodle (1998); Kernodle et al. (1995). The model was used to simulate stream depletions and groundwater drawdowns to support water rights in the Albuquerque Basin. The model considers the RGB from Cochiti Dam to San Acacia, including the Santa Fe River, Galisteo Creek, Tijeras Arroyo, Jemez River, Rio Puerco, Abo Arroyo, and Rio Salado. The model was updated with new hydrogeologic data that was being collected; therefore, this particular model is not suitable for developing or testing environmental flow objectives or assessing drought effect, but the later model is.

**Wagner Gómez and Echeverría Vaquero (2001)**

It is a water allocation model of the Rio Conchos basin developed to understand water problems and simulate alternative future scenarios considering water conveyance efficiency, irrigation demand restrictions, population growth, allocation policies, and changes in water supply sources. The rivers involved in the model are the Rio Conchos, Rio San Pedro, and Rio Florido. The model successfully represents the system and incorporates parameters to include environmental releases from reservoirs. The model seems focused on reducing the Chihuahua-Sacramento aquifer overdraft by providing water supply to the city from Luis L. Leon reservoir. There is not enough documentation to evaluate how it would impact agriculture water supply. However, it is a suitable model to evaluate Rio Conchos system responses to EF and drought periods.

**McAda and Barroll (2002)**

It is an update of Barroll (2001) three dimensional groundwater simulation model of the Santa Fe Group system to better understand the hydrogeology of the basin and provide a tool for water management planners. It considers the mainstem of the RGB from Cochiti Dam to San Acacia and some of the tributaries: Santa Fe River, Galisteo Creek, Tijeras Arroyo, Jemez River, Rio Puerco, Abo Arroyo, and Rio Salado. The model determines the firm yield of the aquifer and apply water management options to revers overdraft conditions that would restore water table levels to allow groundwater to flow into the streams instead of the water percolating into the ground. Similar conditions could be evaluated under drought scenarios. Modified versions of this model are being used by the New Mexico Office of the State (OSE) Engineer and to set boundary conditions for the Upper Rio Grande Water Operation Model (URGWOM).

**Weeden (1999)**

It is a three dimensional model groundwater simulation model of the Mesilla Bolson aquifer in New Mexico Lower Rio Grande Basin. The purpose of the model was to evaluate the response of the RGB flow to municipal and industrial groundwater pumping and to assess the effects of non-irrigation releases from Caballo reservoir on the water budget to evaluate water supply alternatives to the city of El Paso, Texas. The model considers the mainstem of the RGB below Caballo dam to El Paso del Norte. Similar than models developed upstream, the outputs show decrease in RGB flow as pumping increases. Also, non-irrigation releases from Caballo reservoir do not seem to have significant effects on the water budget. It distinguishes between two seasons; the dry season may be useful to represent drought scenarios. The model was updated by CH2MHILL (2002).

**CH2MHILL (2002)**

It is a modification from a three dimensional groundwater simulation model of the Mesilla Bolson aquifer, New Mexico Lower Rio Grande Basin, created by Weeden (1999). The model was developed to increase understanding of the groundwater system of the Cañutillo wellfield area and as a water operation tool to analyze different operation scenarios. The model used the newest groundwater data to create boundary conditions for a local scale model. It would be important to consider the surface water interaction to account for instream base flow when setting targets for environmental flow.

**Tate (2002)**

It is a step by step optimization model for the Lower Rio Grande (Fort Quitman to the Gulf of Mexico). Its purpose was to simulate drought in the basin and allow policy maker to evaluate alternatives. The rivers involved are the RGB, Pecos and Devils rivers, Rio Conchos, San Diego, Rio Escondido, Rio Alamo, and Rio San Rodrigo. Optimization model often needs to incorporate more simplifications than simulation models; this model assumes no change to irrigation areas, and it does not consider environmental issues such as water quality, endangered species, invasive species, in streamflow requirements, or delta outflows. Environmental concerns should be included to be useful for evaluating environmental flow targets.

**IBWC (2003a)**

It is a hydraulic model to re-design a flood control project in the lower RGB, upstream Peñitas (river mile 186) to downstream of Brownville (river mile 28). It was part of the Lower Rio

Grande Flood Control Project (LRGFCP). The model was used to determine design flood flows under existing vegetation conditions. It could be used now to determine water stage for evaluating environmental flow targets in relation to aquatic species ecosystem functions; however, the data is old and might have changed dramatically.

**Heywood and Yager (2003)**

It is a three dimensional groundwater simulation model of the middle RGB to evaluate water management strategies for Hueco Bolson Aquifer. It considers the RGB mainstem across the aquifer in Texas. A monthly temporal discretization allowed improving seepage computation from the river. As the other groundwater models, it could potentially be applied to infer the baseflow and quantify the effects of groundwater pumping in the RGB flow.

**Tidwell et al. (2004)**

It is a systems dynamics Model for community-based water planning applied to the middle RGB. The purposes were to quantify and compare water management alternatives, provide education on the complexity of regional water systems, and engage the public in the decision process. The model includes the mainstem of the RGB and considers the city of Albuquerque along with several smaller communities, Rio Rancho, Belen, Los Lunas, and Bernalillo are the most representative. The models allow stakeholders to observe groundwater changes, water saved, and cots of certain actions. It was used as an educational and public engagement tool that informed the public about the complex interactions between systems and the water cycle. It does not consider the environment as an independent element in the system. It seems to be included only on the water that is left on the river. It was not expected to be used as a predictive or realistic scenarios management tool, therefore it is only suitable for testing or developing environmental flow targets and drought scenarios on a qualitatively basis.

**Sanford et al. (2004a)**

It is a modified version of the three dimensional groundwater simulation model of the Albuquerque basin, central New Mexico, developed by McAda and Barroll (2002). The rivers considered are the RGB, Santa Fe River, Galisteo Creek, Tijeras Arroyo, Arroyo Tonque, Jemez River, Rio Puerco, Abo Arroyo, Rio Salado. Compared to previous models, this model incorporated better interpretations of the subsurface and the surfacewater-groundwater interaction in the inner valley. The model was developed to improve estimates of model parameters, including recharge values by using $^{14}C$ (carbon isotope) activities. This model could be applicable to stablish the predevelopment conditions of the aquifer and recharge rates.

**Tetra Tech Inc (2004)**

It is a two dimensional hydraulic water routing model to compute overbank flood inundation to support the Upper Rio Grande Water Operations Model (URGWOM), analyses of restoration projects, and the design of flood mitigation projects. The model extends along the RGB from Cochiti reservoir to the headwaters of Elephant Butte reservoir. It could give the depth duration in hours and could be used to identify and conserve areas of protection for the silvery minnow or other aquatic and riparian species; however, the crossection measurements may be unreliable now. Due to its detail and extent, an updated version of this model would be very relevant for developing and testing environmental flow targets.

**R. J. Brandes Company (2004) Water Availability Model (WAM)**

It is a simulation model governed by the continuity equation for Texas. The model determines water availability in the basin considering different policy and planning scenarios in accordance with the Prior Water Appropriation Doctrine and TCEQ Rio Grande operating rules. The model includes all the main reaches of the basin from below New Mexico state line. The main objectives of the model were to determine the amount of water that would be available during an extended drought for all permit holders; and evaluate potential impacts of reusing municipal and industrial effluent on existing water uses. The model is suitable for determining water available that could be allocated for EF or could be appropriated by environmental groups for these purposes. The model includes the available water also during extended drought scenarios.

**Hathaway and Shafike (2006)**

Three groundwater simulation models were developed: Upper Albuquerque (UAB) (Angostura Dam south to below Interstate 40 (I-40), Lower Albuquerque (LAB) (I-40 south to below the Bernalillo-Valencia county line. Belen (BEL) (The Bernalillo-Valencia county line to the Valencia-Socorro county line. These models can simulate surface and groundwater interactions within the floodplain of the RGB; their objective was to support the analysis of water management and restoration plans. These models had a much finer resolution (but smaller extent) than previous groundwater models developed for the area to be able to quantify water level changes in the floodplain of the RGB under different vegetation, river channel conditions, and water supplies. These models are suitable to developing and testing environmental flow objectives, and analyze system responses to drought scenarios. Results of the models show a minimal different on the water level by changing non-native to native riparian vegetation; however, the difference was considerable in areas with high salt cedar density. These models were developed as part of the Endangered Species Act Collaborative Program for the Middle Rio Grande. They have good applicability in a high scale but relatively low are coverage. Water flow targets for the silvery minnow and the southwest willow flycatcher could be developed from these models.

**Keating et al. (2005)**

It is a three dimensional groundwater simulation model for the Pajarito plateau in the Moddle Rio Grande Basin (also known as Albuquerque Basin). The model is useful for quantifying the magnitude of different hydrologic elements in the aquifer water budget. This model can be used to interpret contaminant transport velocities in the vadose zone. The model can be used for interpreting contaminant migration velocities in the overlying vadose zone. It considers the RGB through the Albuquerque basin, and the Santa Cruz River, Rio Chama, Santa Clara Creek, Rio Frijoles, Santa Fe, Pojoaque Creek. Results from this model suggest that about 70% of the annual recharge in the Pajarito plateau is extracted from the aquifer storage, affecting also discharge to the RGB. The model provides important insights on the effects of groundwater pumping to the aquifer storage and impacts on the RGB flow; however, the extent of the model is not sufficient to consider it for testing EF.

**Booker et al. (2005)**

It is a non-linear programming optimization model for the New Mexico Upper Rio Grande. The model is developed to maximize total economic benefits from water resources allocation to test if institutional adjustments can reduce damages caused by drought. It considers the mainstem of the RGB and main tributaries. By incorporating more environmental constraints to the model could be applicable to test EF and evaluate their economic effects; so far it only incorporates minimum flow constraint for the Silvery Minnow. The model is also suitable to evaluate drought scenarios as it is its main focus; however, it considers drought scenarios in a simplified way by reducing the inflow in a certain percentage.

### Teasley and McKinney (2005)

It is a mass balance simulation model of the Forgotten Reach of the RGB, from Fort Quitman to Ojinaga, above the Rio Conchos. The model was developed to determine effects on streamflow from restoration work along the river, and to recommends restoration hydrographs for the reach. Despite having uncertainty and limitation because of data availability, it might be possible to couple the recommended hydrograph from this document with other proposes hydrograph for environmental restoration, for example, the models developed by Lane et al. (2014); Sandoval-Solis and McKinney (2014). This model is useful for providing insights on the feasibility of EF in the area; however, the monthly time step is insufficient to develop EF targets as it would not be possible to evaluate the inundation plain and flow relationships, duration of floodplain inundation, water temperature, and flow recession.

### MacClune et al. (2006)

Five groundwater simulation models were developed for Middle Rio Grande in New Mexico from the Angostura Diversion Dam to the northern edge of Bosque del Apache National Wildlife Refuge. The models goal was to simulate shallow riparian environments to develop restoration projects and river management strategies along the Rio Grande in New Mexico. The models seems to follow the same characteristics as the ones developed by Hathaway and Shafike (2006). Similarly, these models could have important consideration for assessing the impacts of environmental flow in riparian areas along the Rio Grande in Middle New Mexico. These models were developed as part of the Endangered Species Act Collaborative Program for the Middle Rio Grande.

### Novak (2006)

It is a two dimensional hydraulic water routing for the Middle Rio Grande, from Cochiti Dam to Galisteo Creek. It was developed to measure spatial and temporal changes in channel geometry, discharge, and sediment in Cochiti Dam reach. The purpose was to estimates future potential conditions of the reach to help developing restoration projects for endangered species. This hydraulic model could help to evaluate the inundation plain and flow relationships, duration of floodplain inundation, and flow recession, as specific parameters to support silvery minnow habitat in the area, which is included in the current extent of the endangered fish. The reduced extent of the model, however, makes it difficult to consider for a basin wide tool.

**Amato et al. (2006)**

It is a hydrologic model for the Río Conchos basin that uses the rainfall runoff soil moisture method. It includes the Río Conchos, Río Sacramento, Río San Pedro, Río Balleza, Arroyo el Parral, and Río Florido. The model was constructed to explore the hydrologic capabilities of the Water Evaluation and Planning Platform (WEAP) (Yates et al., 2005). Results show a good approximation to both annual and monthly flows. Hydrologic models allow inputs from climate change models, as they consider precipitation, temperature and other climate variables as part of the inputs. The model could be useful to evaluate systems response under climate change scenarios. An updated version of this model developed by Ingol-Blanco and McKinney (2009) is considered for testing EFs.

**Ho et al. (2006)**

It is a physical and 2D hydraulic model for the Rio Grande Diversion Structure at Albuquerque. It’s downscaled representation of 305m upstream and 152m downstream of the diversion structure. The purpose was to construct physical model to test gates operation over different flow rates, flow transitions and sediment. This model considers a fish bypass for fish protection but fish was not part of the tests. The model may not be available anymore.

**Chowdhury and Mace (2007)**

It is a three dimensional groundwater simulation model for the Gulf Coast Aquifer in the Lower Rio Grande Valley. The system is composed of the Jasper, Evangeline and Chicot aquifers, which are an important groundwater resource for municipal and agricultural uses. The purpose was to evaluate the feasibility of groundwater desalination as an option for water supply in the future. It also improved the understanding of groundwater flow in the region and evaluated potential water level declines due to pumping. If pumping continues at current levels, a considerable decline in the water table is expected. The monthly time-step of the model could help evaluating system response under environmental flow scenarios; however, drought scenarios were considered in future predictions, which makes it suitable to evaluate responses under a changing climate.

**Passell et al. (2007)**

It is systems dynamic model for water quality, specifically for dissolved un-ionized ammonia, $NH_3$. The model is for the New Mexico Upper Rio Grande, near Albuquerque. The purpose was to address impacts of ammonium in fish population. The study concludes that NH3 toxicity must be seriously considered as a potential ecological impact in the River, especially for the silvery minnow. This model could be useful for identifying the maximum level of ammonia instream before it represents high risk for the silvery minnow and other species. Ammonia concentrations during drought conditions are not part of the model and should be considered for future evaluations and policy development as the study concludes that it has impacted on silvery minnow population decline.

**Ward and Pulido-Velázquez (2008)**

It is a deterministic, dynamic, non-linear optimization model. It optimizes the net present value of the basin totals economic benefits subject to constraints on equity, sustainability, hydrology, and institutions. It analyzed a two tire drinking water pricing of urban water supply; results suggest that the proposed water pricing could improve efficiency, equity and sustainability in the system. It included the Middle Rio Grande Conservancy District, Elephant Butte Irrigation District, and El Paso County Water Improvement District, in addition to the most populated cities in the basin, Albuquerque, NM and El Paso, TX. The model is not considered suitable for developing or testing EF or analyzing drought scenarios because it has a yearly time-step and it assumes that hydrologic conditions produce constant inflow level to the basin for twenty consecutive future years (2006-2020). In addition, the study has limitations for implanting the value of aquatic ecosystem and services.

**Stone (2008)**

It is a two dimensional hydraulic model of habitat evaluation for the Middle Rio Grande, from Alameda Boulevard bridge to the Paseo Del Norte bridge in Albuquerque, NM. The model was developed to evaluate silvery minnow habitat suitability under unsteady flow conditions; it provides valuable information for targeting restoration sites. Despite not considering drought or climate change scenarios, it provides interesting data for habitat restoration. Nevertheless, the applicability on testing EF is limited due to its scale. Model outputs showed that habitat for the silvery minnow highly depends on the flow.

**Danner et al. (2006 Revised 2008)**

It is a mass balance simulation model for the Middle and Lower Rio Grande, from above Elephant Butte (San Marcial gage) to the Gulf of Mexico. It includes the mainstem and main tributaries in U.S. (Pecos, Devils, Alamito, Terlingua, San Felipe, Pinto Creek) and Mexico (Conchos, San Diego, San Rodrigo, Escondido, Salado, San Juan, Alamo, Arroyo las Vacas). It addresses all the inputs for demands and supplies for the Rio Grande/ Bravo Basin to import water allocation in the basin. The model was developed as part of the Physical Assessment Project, which objective as "examine the hydro-physical opportunities for expanding the beneficial uses of the fixed water supply in the Rio Grande/Bravo to better satisfy an array of possible water management objectives, including meeting currently unmet needs in all sectors (agricultural, urban, and environmental), all segments, and both nations". Because of its monthly time-step it is only a useful as a tool for planning for developing and testing EF. Climate change projections cannot be directly applied to model because it does not incorporate climatic data; however hypothetical drought scenarios could be developed for drought and climate change scenarios.

**Molotch (2009)**

It is a Distributed Snow Water Equivalent (SWE) simulation model for the Rio Grande Headwaters. The purpose of the model is to resolve the spatial and temporal variability of SWE in the Rio Grande headwaters at high resolution by incorporating remote sensing analysis. It considers the RGB from its headwaters to the Del Norte gage station. It only considers a drought year (2002) and a normal year (2001) for the analysis, however, there seems to be application for real-time estimates of SWR that could help on different water management objectives, including the development of environmental flow targets based on streamflow estimates from the headwaters.

**Cañón et al. (2009)**

It is an optimization model developed for the Río Conchos basin. The purpose is to minimize water deficits and maximize net crop benefits in irrigation districts during drought periods through reservoir operations and water allocation objectives, using the Drought Frequency Index (DFI). The DFI is a stochastic index that modifies a parameter (i.e. precipitation) towards its lowest value based on a probability density function. The index allows measuring the severity and duration of a drought in each time step relatively to its probability of occurrence. It considers the Rio Conchos, Rio Florido, and Rio San Pedro. Results from the model suggest an improvement on reservoir operation when considering the DFI, which increases the net economic benefits in the basin. It does not consider the environment as an independent element in the system.

**Oad et al. (2009)**

It is an optimization model developed for the Middle Rio Grande Basin from Cochiti reservoir to the Bosque del Apache National Wildlife Refuge. The purpose of the model was to assist implementation of scheduled water delivery in the Middle Rio Grande Conservation District (MRGCD) service area. It is of relevancy for environmental flow because the objective is to divert the minimum amount of water from the mainstem, so more water can be maintained in the river, which ultimately benefits the aquatic and riparian ecosystems. The model has a considerable extent and a sufficient time-step to help on testing EF. Regarding to its application for drought or climate change, it does not implicitly consider such scenarios, but drought scenarios could potentially be evaluated as it uses climate data.

**Gastélum et al. (2009)**

It is a semi-distribution model based on systems dynamics for the Rio Conchos Basin. It includes the Rio Conchos, Río Florido, Río San Pedro, and Río Chuviscar. The purpose was to improve water resources management in the Basin and to evaluate temporary water transfers in the Río Conchos Basin. The model does not consider any water for environmental purposes.

### Teasley (2009)

This was a modification of Danner et al. (2006 Revised 2008) simulation model for the Middle and Lower Rio Grande, from above Elephant Butte (San Marcial gage) to the Gulf of Mexico. Its application was on calculating characteristic functions for a cooperative game analysis to determine if cooperation can exist across individuals along the river. It concluded that there might be not enough water (due to system losses) to downstream "players" to induce cooperation. The updated version of the model can be applicable for the same purposes as Danner et al. (2006 Revised 2008) model.

### Sandoval-Solis et al. (2010)

It is a statistical analyses of river flow that identified a considerable hydrograph change pre-1946 and post-1946 at Johnson Ranch. It then proposes a new hydrograph to try to mimic the pre-1946 conditions to revert the channel width loss and the environmental impacts from human infrastructure. It includes the Rio Conchos from LLL, downstream to its confluences with the RGB mainstem and continues until Amistad Dam. Despite not being a simulation or optimization model, it is highly applicable for EF, because it is one of the focus of the research. It shows a hydrograph that can be considered as pre-alteration of the Rio Grande Bravo.

### Bestgen et al. (2010)

It was a fishway physical model to assess Rio Grande silvery minnow swimming performance under different flows, temperatures, and fishway substrates. The experiment site was the Aquatic Research Laboratory at Colorado State University. Results showed that the endurance of the silvery minnow dramatically declines when the flow is higher than 60cms; the endurance of the fish positively correlates with temperature; and a rock channel seems to be the best substrate to increase silvery minnow passage success. Outcomes from this experiment helped decision regarding fishways characteristics and information developed from this research need to be considered when developing environmental flow targets.

### Yalcinkaya and McKinney (2011)

It is a hydrologic model for the Pecos River that uses the soil moisture method. The purpose of the model is to developed water availability simulations in the Pecos River Basin considering climate change effects. It considers the Pecos River from Red Bluff Reservoir to Rio Grande/Bravo near Langtry. Despite having a monthly time-step, the model is highly relevant for developing EF in the Pecos River, because there are no other comprehensive models in the area. In addition, the model directly considers climate change effects, which makes it suitable to address future drought scenarios.

### Sandoval-Solis (2011)

It is a mass balance simulation model for the Middle and Lower Rio Grande, from above Elephant Butte to the Gulf of Mexico. It includes the mainstem of the RGB, the Río Conchos, Pecos River, Devils River, Arroyo las Vacas, Rio San Diego, San Rodrigo, Río Escondido, Rio Alamo, Río Salado, and Rio San Juan. The goal of the research was to develop a methodology to evaluate different water management policies in a large scale transboundary river basin. The evaluation was made in terms of performance criteria such as reliability, vulnerability, and resilience. Results were later summarized in the Sustainability Index, which is summary index that measures the sustainability of water resources systems. The model is very applicable as a planning tool for developing environmental flow scenarios and address the question of how new operation policies could affect water allocation for individual users in the basin.

### Ingol-Blanco and McKinney (2012)

It is an update for the Amato et al. (2006) hydrologic model using the rainfall runoff soil moisture method for the Rio Conchos Basin. It includes the Río Conchos, Río Sacramento, Río San Pedro, Río Baleza, Arroyo el Parral, Río Florido. The purpose of the model was to evaluate the effects of climate change on hydrology and water resources with emphasis on the water treaty of 1944. The Calibration and Validation was extended to a 10-year period in comparison with its previous version, instead of 1 with the appropriate adjustments to model parameters. This model is highly applicable for testing environmental flow target and can be useful for evaluating climate change in the Rio Conchos basin, which ultimately affects the RGB.

**USDOI et al. (2013) The Upper Rio Grande Simulation Model (URGSiM)**

It is a suite of tools to "better understand, predict, plan, and account for surface water movement through the Rio Grande system in New Mexico". URGSiM was developed closely following the Upper Rio Grande Water Operations Model (URGWOM). It includes the RGB from its headwaters to below Caballo reservoir, and 20 rivers reaches, including the Rio Chama, Jemez River, Rio Puerco, Rio San Jose, Rio Salado. The model also incorporates temperatures and precipitation data, which makes is suitable for evaluating climate change scenarios. This model is very relevant as it one of the models that are currently in use by governmental agencies in the basin. It is suitable for analyzing effects of EF in the water allocation of the Upper Rio Grande Basin.

**Nuñez-Lopez et al. (2013)**

It is a spatial precipitation model for the RGB in the side of Mexico. The purpose of the model was to represent the spatial variability of monthly average precipitation in Rio Grande/Bravo basin. Results from this model are not suitable for developing environmental flow targets or evaluating drought scenarios because it shows static monthly average precipitation from 1970-2004. It is a statistical model, not a simulation or optimization model.

**USACE (2014) Upper Rio Grande Water Operation Model (URGWOM)**

It is a simulation model that accounts for year to date water allocation for individual water users, streamflow, and reservoir operations in the Upper Rio Grande, in New Mexico. It includes the mainstem of the RGB between Lobatos, CO and El Paso, TX; Willow Creek, Rio Chama, and the lower reach of the Jemez River. Like URGSiM, this model is currently in use by governmental agencies in the basin. It would be useful to address effects of environmental flow policies on water users in the basin.

**Sandoval-Solis and McKinney (2014)**

It is a water allocation simulation model for the Big Bend Reach (BBR) of the RGB. It Includes the Rio Conchos from LLL reservoir and the mainstem of the RGB from above the Rio Conchos to Amistad Dam. The purpose was to estimate the maximum volume of water available for EF without affecting human and international water requirements, and without increasing the flood risk in Presidio and Ojinaga. The model objective was to meet the flow targets proposed by Sandoval-Solis et al. (2010) in Foster Ranch. This model was updated by Lane (2014) and is highly applicable for evaluating environmental flow policies at a planning time scale.

**Lane et al. (2014)**

It is a modification from Sandoval-Solis and McKinney (2014) model. Similar to Sandoval-Solis and McKinney (2014) model, the purpose of this model was to estimate the maximum volume of water available for EF without affecting human and international water requirements, and without increasing the flood risk in Presidio and Ojinaga. The update of this model was on estimating the reliability, vulnerability, and resilience on achieving environmental flow targets at three different locations along the RGB. It also incorporated the environmental flow targets developed by Upper Rio Grande Bay Expert Science Team (2012). The model proposed a reoperation policy for LLL reservoir, which increased water supply reliability and resilience with respect to the baseline water management while reducing the systems vulnerability in both countries. These results are highly significant because suggest the hydrologic feasibility of meeting environmental flow demands without affecting human water uses in the BBR. Efforts are undergoing to downscale the time step to better represent streamflow need of the aquatic and riparian ecosystems.

**Sayto-Corona (2015)**

It is hydrologic and hydraulic model currently under development for the Lower Rio Conchos, from LLL reservoir to Presidio-Ojinaga Valley. It is a model that determines river channel capacity and flood prone areas with the purpose of modifying a reservoir operation policy to reduce flood risk from tropical storms. Models like this are very important for testing and developing environmental flow targets, however the extent is small when compared to the basin. The model does not directly considerer environmental objectives, however, it could be used for evaluating drought scenarios as it includes climate date as inputs.

**Porse et al. (2015)**

It is a linear programming optimization and water planning model for the BBR of the RGB. It Includes the Rio Conchos from LLL reservoir and the mainstem of the RGB from above the Rio Conchos to Amistad Dam. The purpose of the model was to perform an analysis of reservoir operation strategies to integrate EF into existing management objectives considering five EF regimes. Results suggest that there is enough water to increase EF allocation without affecting water deliveries or international treaty allocations. Such finding add up to the previously stablish hydrologic feasibility by Lane et al. (2015) of providing EF in the BBR.

**Gómez-Martinez (2015)**

It is a water allocation simulation model for the San Juan Basin that includes the Río San Juan, Río Salinas, Río Pesquería, and Río Pablillo Camacho. The purpose of the model was to develop water supply and demand evaluation for Monterrey Metropolitan Area (Mexico) under different future alternatives. It focused attention into a water supply alternative named Monterrey VI, which is a controversial water project to construct a channel to divert water from a different watershed in Mexico. The model does not consider EF or drought scenarios, but could be potentially added.

**RGBRT & Dinatale Water Consultants (2015)**

It is a surface water simulation model for the Upper Rio Grande Basin, which includes the RGB and the Conejos River system in Colorado. The model was developed to identify projects and methods to meet basin specific municipal, industrial, agricultural, recreational, and environmental water needs. The model allows assessment of current and future conditions considering climate change, wildfires, dust on snow, infrastructure, water rights, and administrative policies. This model is relevant for testing outcomes of environmental flow policies in Colorado as the model includes some parameter for environmental purposes. Also, it includes possible future scenarios under climate change.

## ***Summary of models suitable for testing EF or drought scenarios***

Numerous models have been developed for a variety of purposes on the basin. Some of them are modifications of previous models or are simply reused for investigating different hypotheses. The models were grouped into six general categories: (1) Groundwater simulation, (2) Water allocation simulation, (3) Hydrologic simulation, (4) Hydraulic simulation, (5) Optimization, and (6) others.

Groundwater models are located mostly in the New Mexico Middle RGB in the area known as the Española Basin. Groundwater models tend to be focused on a single basin and have a modeling time-step of one year, as decreasing the temporal scale or increasing the area requires greater computational time. Due to complexity of underground systems, some groundwater models have been updated as new data becomes available. An example is the Kernodle et al. (1995) model that was modified multiple times for almost 10 years until it became Sanford et al. (2004b) model.

Water allocation models lead towards a monthly time-step often developed for planning purposes of feasibility studies. In the RGB, the extensions of these models together cover the mainstem and main tributaries except for the upper segment of the Pecos River. Similarly, water allocation models are often updated or used for different purposes. Examples are Danner et al. (2006 Revised 2008) updated by Sandoval-Solis (2011) and applied by Teasley and McKinney (2011) for calculating characteristic functions for a cooperative game analysis. Together, groundwater and water allocation models facilitate water accounting to identify available water for EF at a planning stage. However, EF requires also geomorphic, hydrologic, and hydrochemistry considerations to include floodplain and flow relationships and water quality parameters, which are relevant characteristics for individual aquatic species response. Some of those considerations are accounted in hydraulic, hydrologic, and water quality models.

Hydraulic models in the RGB have been developed for two main functions, design of flood management projects and identification of restoration areas to support aquatic species. The general limitation of these models is their extent because it is difficult to measure channel geometry at different sites along the river, and such geometry may be highly variable from one year to another. Hydraulic models in the RGB would allow to quantify floodplain and flow relationships, but currently their extent is insufficient even if the geometry of the channel hasn't change since the model where developed. A productive application of these models for EF would include accurate river discharge inputs provided by hydrologic models.

Hydrologic models have been developed for the main tributaries to the RGB, the Pecos River and the Rio Conchos basins. Hydrologic models include climatic measurements of precipitation, temperature, and humidity at small time-steps (seconds, minutes, or hours) that, when combined with soil and land cover characteristics, permit the predictions runoff and ultimately river discharge. The same set of parameters, facilitate the application of hydrologic model on climate change future alternatives. A substantial difference with the water allocation models is the extent of the model as a grid matrix instead of streams connected with nodes. In general a matrix representation allow the estimation of river flow in areas without streamflow gages, which would be relevant to test environmental flow targets along the river. However, hydrologic models have numerous data limitations that lead to simplifications of physical process and model assumptions.

Lastly, optimization models, in this context, would be useful to include the different outputs from the diverse models and approximate to optimal allocation of water among agriculture, population centers, recreational activities, and the environment, without increasing the risk of flood events. Yet, combination of different models is challenging because of differences in spatial and temporal resolutions, extent and location in the basin, type, period of analysis, and their limitations.

The following selection was made considering the suitability of model for testing either EF or drought scenarios. Models that could be suitable but were later updated are out of the selection, as well as physical models. Regarding limitations of the models, common errors and uncertainties such as the stability and accuracy of measurements are not included.

**Table 3 Summary of groundwater simulation models in the RGB**

| Zone | Platform | Period of Analysis | Time Step | Natural recharge | Pumping demands | Historic groundwater levels | Seepage from surface water | Discharge from aquifer | Gaged river flows | Vegetation cover | Wastewater return flows | Hydraulic conductivity | Lateral water movement | Limitations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **McAda and Barroll (2002)** | | | | | | | | | | | | | | |
| Middle RGB, Albuquerque Basin | MODFLOW-2000 | Average annual conditions (Prior 1990)<br>Seasonal conditions (1990-2000) | Yearly | X | X | X | X | X | X | X | X | | | Areas towards the limits of the model have low values of hydraulic conductivities that are highly uncertain. The model should not be used to estimate stream depletion effect of wells on these areas. Steady state conditions assume to exist prior 1900. The further from the Rio Grande, the less the match between measured and simulated groundwater level. Lack of detailed geohydrologic data in some areas. There are uncertainties in the distribution of pumping with depth for each well. |
| **CH2MHILL (2002)** | | | | | | | | | | | | | | |
| Middle RGB, Cañutillo Wellfield | MODFLOW-96 | 1991-1995 | Yearly | X | X | X | X | X | X | | X | | | Regional conductivity appears to be adequate, but the individual hydraulic conductivity is not well represented in the model. River canal and drain network was simplified in the model, estimates of hydraulic parameter in the Rincon Valley were limited. Agriculture groundwater pumping is implicitly accounted from consumptive water use in agriculture. |

| **Zone** | **Platform** | **Period of Analysis** | **Time Step** | **Natural recharge** | **Pumping demands** | **Historic groundwater levels** | **Seepage from surface water** | **Discharge from aquifer** | **Gaged river flows** | **Vegetation cover** | **Wastewater return flows** | **Hydraulic conductivity** | **Lateral water movement** | **Limitations** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sanford et al. (2004b)** | | | | | | | | | | | | | | |
| Middle RGB, Albuquerque Basin | MODFLOW & MODPATH | N/A | N/A | X | X | X | X | X | X | X | X | | | Steady state conditions assumed to exist prior 1900. The further from the Rio Grande, the less the match between measured and simulated groundwater level. Lack of detailed geohydrologic data in some areas. There are uncertainties in the distribution of pumping with depth for each well. |
| **Hathaway and Shafike (2006)** | | | | | | | | | | | | | | |
| Middle RGB | MODFLOW-2000 | 2000-2004 | Daily | X | X | X | X | | X | X | | | | Some inputs are based on a regional groundwater model that has its own limitations. |
| **MacClune et al. (2006)** | | | | | | | | | | | | | | |
| Middle RGB, Albuquerque Basin | MODFLOW & FLO-2D | 2003-2004 | Weekly | X | | | X | | | X | | | | Not was rigorously calibrated. |
| **Chowdhury and Mace (2007)** | | | | | | | | | | | | | | |
| Lower RGB | MODFLOW-96 | 1980-2000 | Monthly | X | X | X | | | | | | | | It is a steady state model. Uncertainty in pumping information projections. Areas with few data points. Rainfall estimates because there were just a little number of rain gages |

**Table 4 Summary of water allocation & reservoir operation simulation models in the RGB**

| Zone | Platform | Period of Analysis | Time Step | Historical streamflow | Historic water demands | Infrastructure characteristics | Evapotranspiration | Water rights priorities | Environmental water demand | Historic reservoir storage | Treaty/compacts obligations | Limitations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Schmandt et al. (2000)** | | | | | | | | | | | | |
| Lower RGB | Spreadsheet | 1980-2030 for the model. Other data in the document (Historic up to 1995 with projections from 1900 to 2030) | Monthly | X | X | X | X | | X | X | X | Besides the limits of accuracy of the modeling and analytical techniques, there is data limitation in streamflow and water demands. They considered the possibility of additional environmental releases but solely base on a high flood pulse. |
| **Tate (2002)** | | | | | | | | | | | | |
| Lower RGB | Oasis with OCL | 1992-1998 | Monthly | | | | | | | | | Assumes no change to irrigation areas. It does not consider environmental issues such as water quality, endangered and invasive species, instream flow requirements or delta flows |
| **Wagner Gómez and Echeverría Vaquero (2001)** | | | | | | | | | | | | |
| Lower RGB | Stella Research | 1940-1999 | Monthly | X | X | X | X | | | X | | It seems to be a very simple model. The document does not explain well all the components and considerations. |
| **R. J. Brandes Company (2004)** | | | | | | | | | | | | |
| Basin from below New Mexico State line | WRAP (Water Rights Analysis | 1940-2000 | Monthly | X | | | | X | | | | A lot of data estimations and "zero" values for unavailable data. "It has been assumed that Mexico will continue to impound all upstream inflows to its reservoirs on tributaries of the Rio Grande and that none of this water will be |

| Zone | Platform | Period of Analysis | Time Step | Historical streamflow | Historic water demands | Infrastructure characteristics | Evapotranspiration | Water rights priorities | Environmental water demand | Historic reservoir storage | Treaty/compacts obligations | Limitations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Package) | | | | | | | | | | | deliberately released for complying with the provision of the 1944 Treaty that requires an average of 350,000 acre-feet per year be delivered to the United States from six named Mexican tributaries." |
| **Teasley and McKinney (2005)** | | | | | | | | | | | | |
| Lower Rio Grande | HEC-ResSim & Indicators of Hydrologic Alteration (IHA) | 1925-1945<br>&<br>1984-2004 | Monthly | X | X | X | | | | X | | Only one site of analysis (Fort Quitman). The model seems to overestimate the historical streamflow in the low flow periods and underestimated during high flow periods. |
| **Danner et al. (2006 Revised 2008) and Teasley and McKinney (2011)** | | | | | | | | | | | | |
| Middle and lower RGB Basin | WEAP | 1976-2000 | Monthly | X | X | X | | X | | X | X | Assumes stationarity, does not have groundwater and climatic components, and does not consider the environment as water demand. |
| **Sandoval-Solis (2011)** | | | | | | | | | | | | |
| Middle and lower RGB Basin | WEAP | 1940-2000 | Monthly | X | X | X | | X | X | X | X | Assumes stationarity, does not have groundwater and climatic components, and does not consider the environment as water demand. |
| **USDOI et al. (2013) Upper Rio Grande Simulation Model** | | | | | | | | | | | | |
| Upper RGB | RiverWare | 1975-1999 | Monthly | X | X | X | X | | | X | X | Considers empirical equations and approximations to calculate water demands, evapotranspiration, among others and there are uncertainties associated with them. Uses data from other models that has their own limitations. In general, |

| Zone | Platform | Period of Analysis | Time Step | Historical streamflow | Historic water demands | Infrastructure characteristics | Evapotranspiration | Water rights priorities | Environmental water demand | Historic reservoir storage | Treaty/compacts obligations | Limitations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | model performance decreases proportionally to distance downstream. Considerable discrepancies between modeled and observed reservoir residual validations. Environmental considerations just as minimum flow requirements |
| **USACE (2014) Upper Rio Grande Water Operations Model** | | | | | | | | | | | | |
| Upper RGB | RiverWare | 1984-2014 | Daily | X | X | X | | X | | X | X | Considers empirical equations and approximations to calculate water demands, evapotranspiration, among others and there are uncertainties associated with them. |
| **Sandoval-Solis and McKinney (2014) and Lane et al. (2014)** | | | | | | | | | | | | |
| Rio Conchos and RGB | WEAP | 1955-2009 | Monthly | X | X | X | | X | X | X | X | Assumes stationarity, does not have groundwater and climatic components, and does not consider the environment as water demand. |
| **RGBRT & Dinatale Water Consultants (2015)** | | | | | | | | | | | | |
| Upper RGB | RiverWare | 1980-2008 Baseline Prediction periods 2009-2037, 2038-2066, 2067-2095 | Monthly | X | X | X | | X | X | X | X | They used to alter historic hydrology to account for climate change scenarios. It's application is only for the State of Colorado |

**Table 5 Summary of hydrologic simulation models in the RGB**

| Zone | Platform | Period of Analysis | Time Step | Catchment area | Precipitation | Temperature | Humidity | Wind speed and direction | Land Use | Deep water capacity | Root zone conductivity | Deep conductivity | Infrastructure characteristics | Limitations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Yalcinkaya and McKinney (2011)** | | | | | | | | | | | | | | |
| Pecos River | WEAP | 1981-2000 | Monthly | X | X | X | X | X | X | X | X | X | | Land use and soil data is very limited for the area and the groundwater component is very simplified. |
| **Ingol-Blanco and McKinney (2012)** | | | | | | | | | | | | | | |
| Rio Conchos Basin | WEAP | 1980-1999 | Daily | X | X | X | X | X | X | | | | X | Land use and soil data is very limited for the area and the groundwater component is very simplified. |

**Table 6 Summary of hydraulic simulation models in the RGB**

| Zone | Platform | Period of Analysis | Time Step | Channel topography | Discharge | Flood infrastructure capacity | Roughness coefficients | Limitations |
|---|---|---|---|---|---|---|---|---|
| **IBWC (2003a)** | | | | | | | | |
| Lower Rio Grande | HEC-RAS | 2003 | Seconds | X | X | X | X | Some of the cross sections and roughness coefficients were taken from a study made 1992. |
| **Tetra Tech Inc (2004)** | | | | | | | | |
| Middle Rio Grande Valley | FLO-2D | Present | Seconds | X | X | | X | Grid element size, floodplain spatially variable roughness and infiltration parameters, model calibration for high flows, modeling details, sediment transport, simulation time. |
| **Stone (2008)** | | | | | | | | |
| Middle Rio Grande | HEC-RAS as input and CCHE2D (Center for Computational Hydrosciences and Engineering) to evaluate | 2006 | N/A | X | X | | X | Just 3 km of reach inside Albuquerque. Only focus on Silvery Minnow. There is no validation. |

**Table 7 Summary of optimization models in the RGB**

| Zone | Platform | Period of Analysis | Time Step | Parameters /Inputs | Limitations |
|---|---|---|---|---|---|
| **Booker et al. (2005)** | | | | | |
| Upper RGB | GAMS | 2004-2009 | Yearly | Streamflow gauges. Infrastructure. Water Demands. Consumptive Uses. Return Flows. Net Seepage. Institutional constraints (compacts). Minimum instream flow. Economic benefits | Optimized for total economic benefits; uncertainties exist on estimating the value from ecosystem functions. |
| **Cañón et al. (2009)** | | | | | |
| Rio Conchos | Not specified | 1000 years Montecarlo analysis | Monthly | Maximum soil holding capacity, maximum infiltration rate, runoff coefficient, and aquifer discharge coefficient | Simplification of the reservoir operation rules. Does not consider environmental components. |
| **Oad et al. (2009)** | | | | | |
| Middle RGB | Decision Support System | 2003-present | Daily | Priority of deliver, water demand, irrigation efficiency, infrastructure capacity, conveyance loss, irrigated area, crop type, channels layout, service areas, weather, soil type | It has uncertainties in evaporation rates from diversion channels, soils moisture depletion, and return flows. |
| **Porse et al. (2015)** | | | | | |
| Rio Conchos and RGB | GAMS | 1955-2009 | Monthly | Known inflows, diversions, and demands, treaty obligations | Considers only 5 flow regimens (1200, 1100, 1000, 800, 600). |

**Table 8 Summary of other relevant models in the RGB**

| Zone | Platform | Period of Analysis | Time Step | Parameters /Inputs | Limitations |
|---|---|---|---|---|---|
| **Passell et al. (2007)** | | | | | |
| Upper RGB | Studio Expert 2001 developed by Powersim. Inc. | 1989-2002 | Daily | Ammonium (NH4+) concentrations, discharge, temperature, pH | It only considers a small segment along the city of Albuquerque |
| **Molotch (2009)** | | | | | |
| Rio Grande Headwaters | Not specified | 2001-2002 | Daily | Remotely sensed imagery | Simplified vegetation cover data that may affect the results. There is a limited number of high resolution imagery data. |
| **Sandoval-Solis et al. (2010)** | | | | | |
| Lower RGB | HEC-SSP & Indicators of Hydrologic Alteration (IHA) | 1901-1913 1930-1946<br>&<br>1980-2009 | Monthly | Stream gages data series | Hydrologic alteration measured at only one site (Johnson Ranch) |
| **Bestgen et al. (2010)** | | | | | |
| Physical model | Physically modeled using a swim chamber. | Fish captured in 2001 and 2002 | N/A | Water temperature. Water velocity. Fishway characteristics. Fishway substrate. | It includes only the Silvery Minnow. It does not describe how the planning for the silvery minnow may affect other species. |

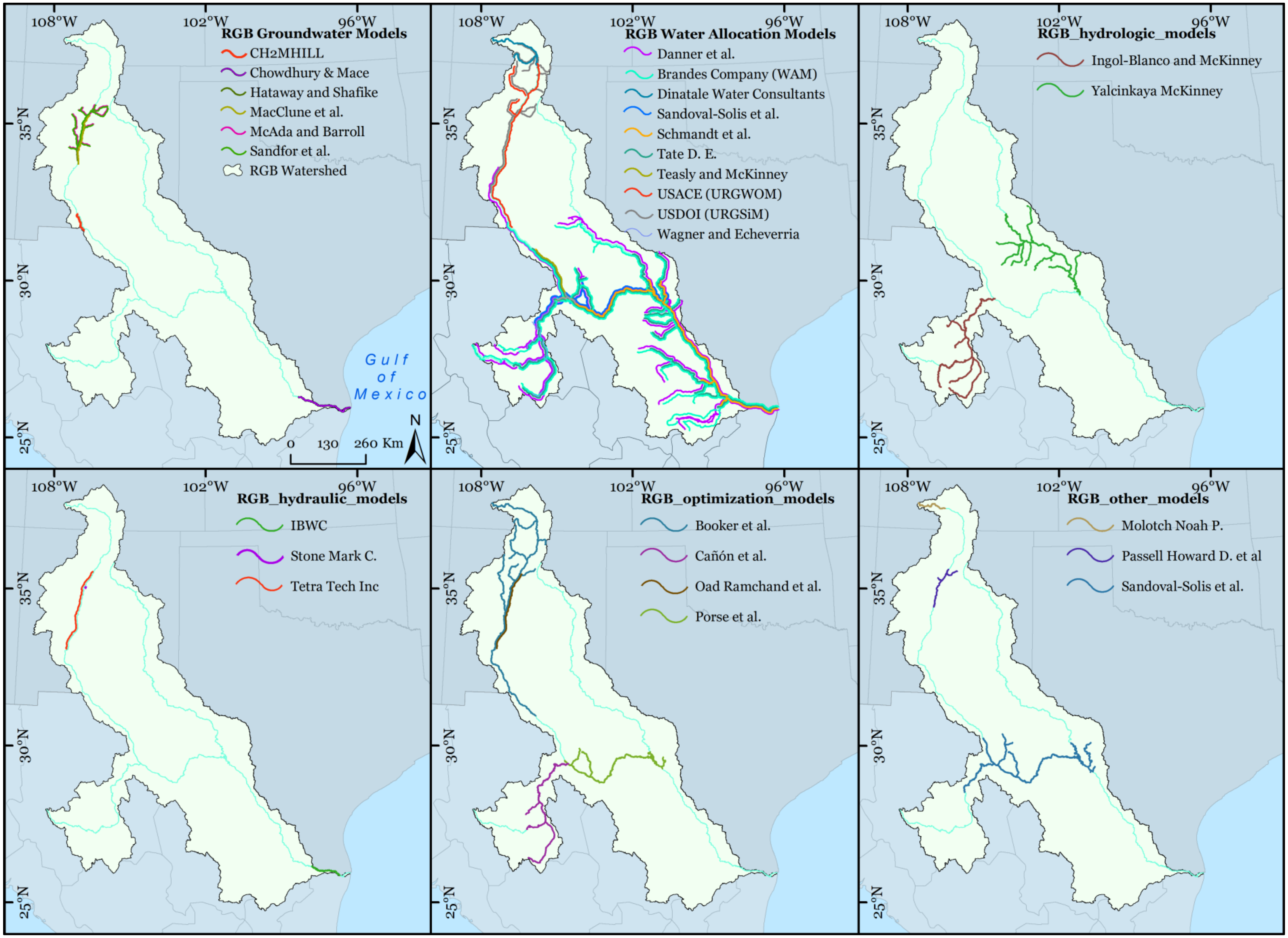


**Figure 7 Stream segments of RGB mainstem and tributaries that relates with the models.**

There is a variety of models that can assist planning activities to implement environmental flows across the RGB. However, no models with the appropriate spatial extent and the necessary time-step exist for developing operational environmental flow targets in the basin.

After environmental targets are proposed, integrating environmental release into the water management framework of the multiple stakeholders on the basin will be complex. An adaptive management strategy should be implemented to allow for evaluation and correction of environmental releases.

Recommendation from this report consist on moving from monthly planning models into weekly or operational models that mix surface water and hydraulic characteristics to account for other factors such as sediment concentration and water quality. Also, inundation plain and flow relationships, duration of floodplain inundation, water temperature, and flow recession are some of the parameters that should be addressed under an operational scenario, as they are not represented under the monthly time step and are relevant for fish spawning cues.

## ***Geodatabase of water-related elements***

A collection of geographic datasets of water-related elements on the RGB was made to identify information gaps that merit additional research and resources, describe promising future steps to couple and improve existing systems models, and propose ideas to share and serve science syntheses in a digital and spatially-explicit database. Selected elements were categorized in the following topics:

a) Boundaries and populated places
b) Hydrology and climate
c) Environmental
d) Land use and cover
e) Water management

The boundary and populated places category includes information about the countries, states, counties, and cities that intersect the basin. Hydrology and climate incorporates data of the watershed, including rivers, water bodies, aquifers, monitoring points, and average precipitation, temperature, and evapotranspiration on the basin. The environmental category covers the natural protected areas, endanger species critical habitat, and national parks, among others. Land use and cover also considers agriculture information and soil types. Lastly, the water management category includes information on water infrastructure (i.e. dams) water districts, water agencies, and an inventory of all water related models that has been develop for different purposes on the RGB.

The collection of datasets was built by retrieving information from many different sources that includes state and federal agencies from U.S. and Mexico. Data coming from different agencies is frequently found with different characteristics or formats; an important part of this job was to homogenize such differences, when possible. Three of the most relevant differences are the Geographic Coordinate System (GCS), the Metadata, and the language.

A GCS defines the location of an element on the Earth by using a three-dimensional surface. The selected GCS was the GCS_North_American_1983, as it is the standard used around the world, while the chosen datum was NAD_1983_Contiguous_USA_Albers because of the extent of the RGB watershed across multiple states.

Metadata is used to describe the data; it includes information regarding its purpose, author, description, and usage limitations, among other characteristics. The Federal Geographic Data Committee (FGDC) metadata format was selected to consistently describe the datasets. When the FGDC metadata was already included in the dataset, it was not modified. When metadata was included in the dataset but in a different format, it was changed to FGDC format. There were cases when the metadata had to be created with available information on the specific dataset, in which case it is mentioned in the metadata. After geoprocessing two or more datasets, the metadata from both datasets was mixed into the new dataset to describe how it was made.

A geographic database is presented with this report. It contains the one the original files and the merges of information with specific information for the RGB. For example, the geographic boundaries of the States in the U.S. and Mexico are two different datasets. Such files are included as downloaded from the corresponding source into the and after, a new dataset is created with only the relevant States from both countries with consistent GCS and metadata.

The dataset, a short description, the source, and the original download link for each of the original datasets are included in the following tables.

Data sources acronyms:

| | |
|---|---|
| ASTER | Advance Spaceborn Thermal Emission and Reflection |
| CCMEO | Canada Center for Mapping and Earth Observations |
| CDSS | Colorado Decision Support System |
| CDWR | Colorado Division of Water Resources |
| Chih | Chihuahua |
| CO | Colorado |
| Coah | Coahuila |
| CONABIO | National Commission for Knowledge and Biodiversity of Mexico |
| CONAGUA | National Water Commission of Mexico |
| CONANP | National Commission of Natural Protected Areas of Mexico |
| CWCB | Colorado Water Conservation Board |
| Dgo | Durango |
| DWR | Colorado Division of Water Resources |
| EDAC | Earth Data Analysis Center |
| ESA | European Space Agency |
| FAO | Food and Agriculture Organization of the United Nations |
| GAP | Gap Analysis Program |
| ISCS | Idaho State Climate Services |
| INEGI | National Institute of Statistics, Geography, and Informatics of Mexico |

| | |
|---|---|
| IUCN | International Union for Conservation of Nature |
| MX | Mexico |
| NACSE | Northwest Alliance for Computational Sciences and Engineering |
| NHD | National Hydrography Dataset of United States |
| Nl | Nuevo León |
| NM | New Mexico |
| NPS | National Park Service of the United States |
| NRCS | Natural Resources Conservation Service |
| OSE | New Mexico Office of the State Engineer |
| OSE | New Mexico Office of the State Engineer |
| PADUS | Protected Areas Database of the United States |
| Tamps | Tamaulipas |
| TCEQ | Texas Commission on Environmental Quality |
| TWDB | Texas Water Development Board |
| TX | Texas |
| US | United States |
| USCB | United States Census Bureau |
| USDA | United States Department of Agriculture |
| USDC | United States Department of Commerce |
| USDOI | United States Department of the Interior |
| USFWS | United States Fish and Wildlife Service |
| USGS | United States Geological Survey |

## Boundaries and populated areas datasets

**Table 9 Boundaries and populated places original datasets**

| Dataset | Short description | Source |
|---|---|---|
| US_states | US states boundaries | USDC, and USCB Geography Division |
| MX_states | MX states boundaries | CONABIO and INEGI |
| CO_counties | Colorado county boundaries | USDC, and USCB Geography Division |
| NM_counties | New Mexico county boundaries | USDC, and USCB Geography Division |
| TX_counties | Texas county boundaries | USDC, and USCB Geography Division |
| Chih_municipalities | Chihuahua municipalities boundaries | INEGI |
| Coah_municipalities | Coahuila municipalities boundaries | INEGI |
| Dgo_municipalities | Durango municipalities boundaries | INEGI |
| Nl_municipalities | Nuevo Leon municipalities boundaries | INEGI |
| Tamps_municipalities | Tamaulipas municipalities boundaries | INEGI |
| CO_cities_polygones | Geographic boundaries of census designated places in Colorado | USDC, and USCB Geography Division |
| NM_cities_polygones | Geographic boundaries of census | USDC, and USCB Geography |

| | | |
|---|---|---|
| | designated places in New Mexico | Division |
| TX_cities_polygones | Geographic boundaries of census designated places in Texas | USDC, and USCB Geography Division |
| MX_cities_polygones | Geographic boundaries of cities in Mexico | INEGI |
| US_cities | Location of 38,186 populated places in United States | National Atlas of the United States form the USGS |
| NM_cities | Points for 1600 populated places, cities and towns, in New Mexico | EDAC University of New Mexico |
| MX_cities | Location of 192,245 populated places in Mexico in 2010 | CONABIO and INEGI |
| Chih_services | Location of city services in the state of Chihuahua (i.e. schools, temples, etc) | INEGI |
| Coah_services | Location of city services in the state of Coahuila (i.e. schools, temples, etc) | INEGI |
| Dgo_services | Location of city services in the state of Durango (i.e. schools, temples, etc) | INEGI |
| Nl_services | Location of city services in the state of Nuevo Leon (i.e. schools, temples, etc) | INEGI |
| Tamps_services | Location of city services in the state of Tamaulipas (i.e. schools, temples, etc) | INEGI |
| CO_cities_pop_1910_2014 | Population data 1910 - 2014 added to the cities polygons shapefiles in Colorado | USDC, and USCB Geography Division |
| NM_cities_pop_1910_2014 | Population data 1910 - 2014 added to the cities polygons shapefiles in Colorado | USDC, and USCB Geography Division |
| TX_cities_pop_1860_2014 | Population data 1860 - 2014 added to the cities polygons shapefiles in Colorado | USDC, and USCB Geography Division |
| MX_cities_pop_1910-2010 | Population data 1910 - 2010 added to the cities polygons shapefiles in Mexico | CONABIO and INEGI |

## Hydrology and climate datasets

**Table 10 Hydrology and climate original datasets**

| Dataset | Short description | Source |
|---|---|---|
| CO_NHD_M08 | Contains flow network consisting predominantly of stream/river and artificial path vector features and extent of flowlines and waterbodies in Colorado | USGS and NHD |
| NM_NHD_M35 | Contains flow network consisting predominantly of stream/river and artificial path vector features and extent of flowlines and waterbodies in New | USGS and NHD |

| | | |
|---|---|---|
| | Mexico | |
| TX_NHD_M48 | Contains flow network consisting predominantly of stream/river and artificial path vector features and extent of flowlines and waterbodies in Texas | USGS and NHD |
| TX_precip_1981-2010_NRCS | Average monthly and annual precipitation for the climatological period 1981-2010. | TWDB with data from NRCS |
| MX_hydrometric_stations | Location 1126 hydrometric stations within Mexico | CONABIO |
| RGB_monitoring_points | The monitoring points is a compilation of hydro-climatic stations, streamflow gages, and others. The shapefile contains its name, source, purpose and location | Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model. |
| IBWC_streamflow_gages | Geographic location of IBWC streamflow gages from in the Rio Grande/Bravo | Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model. |
| USGS_streamflow_gages | Geographic location of USGS streamflow gages from in the Rio Grande/Bravo | Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model. |
| MX_streamflow_gages | Geographic location of CONAGUA streamflow gages in the Rio Grande/Bravo | Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model. |
| RGB_waterbodies | Geographic boundaries of the Rio Grande/Bravo waterbodies (lakes, reservoirs) | Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model. |
| RGB_main_rivers | Extent of main rivers in the Rio Grande/Bravo | Compiled from different sources by Patiño-Gomez, C., & McKinney, D. C. (2005). GIS for Large-Scale Watershed Observational Data Model. |
| RGB_FAO_prcXX_mmm | 12 Global map of monthly precipitation 1960 - 1990 | FAO GeoNetwork |
| RGB_US_mean_yr_prc | Raster files of annual mean precipitation values in the United States side of the Rio Grande/Bravo (1981-2010) | NACSE, PRISM Climate Group |
| RGB_MX_mean_yr_prc | Isohyets of mean annual precipitation in the Mexican side of the RGB | INEGI |
| RGB_MX_nunez_prc_mmm | Raster files of monthly mean precipitation values in the Mexican side | Nuñez-Lopez, D., Treviño-Garza, E. J., Reyes-Garza, V. |

| | | |
|---|---|---|
| | of the Rio Grande/Bravo created by Daniel Nunez et al with data from 201 hydro-climatic stations. | M., Muñoz-Robles, C. A., Aguirre-Calderón, O. A., & Jiménez-Pérez, J. (2013). Interpolación Espacial de la Precipitación Media Mensual en la Cuenca del Rio Bravo/Grande. Tecnología y Ciencias del Agua, IV(2), 185-193. |
| RGB_US_mean_yr_tmp | Raster files of annual mean temperature values in the United States side of the Rio Grande/Bravo (1981-2010) | NACSE, PRISM Climate Group |
| RGB_US_max_yr_tmp | Raster files of annual maximum temperature values in the United States side of the Rio Grande/Bravo (1981-2010) | NACSE, PRISM Climate Group |
| RGB_MX_min_yr_tmp | Raster files of annual minimum temperature values in the United States side of the Rio Grande/Bravo (1981-2010) | NACSE, PRISM Climate Group |
| RGB_FAO_evpXX_mmm | 12 global map of monthly evapotranspiration 1960 - 1990 | FAO GeoNetwork |
| RGB_MX_mean_yr_evap | Mean annual evapotranspiration in the Mexican side of the Rio Grande/Bravo | INEGI |
| RGB_MX_mean_yr_tmp | Isotherms of mean annual temperature 1910-2009 in the Mexican side of the Rio Grande/Bravo | INEGI |
| MX_climate_unit | Denomination of climate units in the Mexican side of the Rio Grande/Bravo | INEGI |
| US_climate_unit | Denomination of climate units in the United States side of the Rio Grande/Bravo according to a Koppen climate classification | ISCS (Point of Contact) |
| US_Aquifers | Shallowest principal aquifers of the conterminous United States | USGS Water Resources NSDI Node |
| TX_major_aquifers | The 9 Major aquifers of Texas according to TWDB. | TWDB |
| TX_minor_aquifers | The 21 Minor aquifers of Texas according to TWDB. | TWDB |
| MX_aquifers | The 653 aquifers in Mexico | CONAGUA |
| MX_Hydrogeology | Hydrogeology of Mexico | CONABIO |
| NM_groundwater_basins | This data represents the locations of the declared ground water basins within New Mexico administered by the New Mexico Office of the State Engineer. | OSE / Interstate stream Commission |

## Environment datasets

**Table 11 Environment original datasets**

| Dataset | Short description | Source |
|---|---|---|
| US_Critical_Habitat | Critical habitat are areas considered essential for the conservation of a listed species | USFWS |
| MX_Natural_Protected_Areas | Geographic boundaries of Federal Natural Protected Areas in Mexico | CONANP |
| MX_Ramsar_sites | Information and geographic boundaries of 142 Ramsar sites in Mexico | CONANP |
| CO_protected_areas | Geographic boundaries of protected Areas in Colorado | PADUS, version 1.3, USGS, GAP |
| NM_protected_areas | Geographic boundaries of protected Areas in New Mexico | PADUS, version 1.3, USGS, GAP |
| TX_protected_areas | Geographic boundaries of protected Areas in Texas | PADUS, version 1.3, USGS, GAP |
| Silvery_minnow_range | Hybognathus amarus (Silvery minnow) distribution information on the RGB | The IUCN Red List of Threatened Species(tm) |
| US_National_parks | National Park boundaries in United States | NPS |

## Land use and Cover datasets

**Table 12 Land use and cover original datasets**

| Dataset | Short description | Source |
|---|---|---|
| CO_div3_districts | Colorado Division of Water Resources (DWR) Water District Boundaries. District boundaries are administrative boundaries set by the State Engineer, which are based primarily on stream drainage systems. | Colorado Decision Support Systems (CDSS)<br>DWR and CWCB |
| CO_Div3_Irrig_XXXX | A collection on 9 dataset that contain spatial and informational database of irrigated parcels in Division 3 of the Rio Grande Basin for the years 1936, 1998, 2002, 2005, 2009-2015 growing season in support of the Rio Grande Decision Support Tool (RGDSS). | Colorado Decision Support Systems (CDSS)<br>DWR and CWCB |
| CO_Div3_Ditches_XXXX | A collection on 9 dataset that contain spatial and informational database of ditch headgates associated with irrigated lands in Division 3 of the Rio Grande Basin for the years 1936, 1998, 2002, 2005, 2009-2015 growing season in | Colorado Decision Support Systems (CDSS)<br>DWR and CWCB |

| | | |
|---|---|---|
| | support of the Rio Grande Decision Support Tool (RGDSS). | |
| CO_Div3_Wells_XXXX | A collection on 9 datasets that contain spatial and informational database of wells associated with irrigated lands in Division 3 of the Rio Grande Basin for the years 1936, 1998, 2002, 2005, 2009-2015 growing season in support of the Rio Grande Decision Support Tool (RGDSS). | Colorado Decision Support Systems (CDSS)<br>DWR and CWCB |
| RGB_major_soils | Major Soil Groups of the World (FGGD) | FAO GeoNetwork |
| CO_ssurgo | Information about soil as collected by the National Cooperative Soil Survey over the course of a century in United States. This dataset is for Colorado. SSURGO (Soil Survey Geographic Database) | USDA and NRCS |
| NM_ssurgo | Information about soil as collected by the National Cooperative Soil Survey over the course of a century in United States. This dataset is for New Mexico. (Soil Survey Geographic Database) | USDA and NRCS |
| TX_ssurgo | Information about soil as collected by the National Cooperative Soil Survey over the course of a century in United States. This dataset is for Texas. (Soil Survey Geographic Database) | USDA and NRCS |
| MX_soils | Soil type in the Mexican side of the Rio Grande/Bravo basin. | CONABIO |
| RGB_ESA_land_cover_2000 | Land Cover Map 2000 for the Rio Grande/Bravo basin. The original data is from soil global maps developed by the European Space Agency (ESA) | Land Cover (LC) project of the Climate Change Initiative (CCI) European Space Agency (ESA) |
| RGB_ESA_land_cover_2005 | Land Cover Map 2005 for the Rio Grande/Bravo basin. The original data is from soil global maps developed by the European Space Agency (ESA) | Land Cover (LC) project of the Climate Change Initiative (CCI) European Space Agency (ESA) |
| RGB_ESA_land_cover_2010 | Land Cover Map 2010 for the Rio Grande/Bravo basin. The original data is from soil global maps developed by the European Space Agency (ESA) | Land Cover (LC) project of the Climate Change Initiative (CCI) European Space Agency (ESA) |
| RGB_MX_land_cover_2011 | Land cover in 2011 for the Mexican side of the Rio Grande/Bravo basin | CCMEO, CONABIO, INEGI, USGS |
| RGB_US_land_cover_2011 | National Land Cover Database 2011 for the United States side of the Rio Grande/Bravo basin (NLCD 2011) | USDI and USGS |
| RGB_US_agriculture_XXXX | Collection of 8 (2008-2016) rasters for the United States side of the Rio | USDA,<br>National Agricultural Statistics |

| | | |
|---|---|---|
| | Grande/Bravo that represent combine the CropScape and Cropland Data Layers for Colorado, New Mexico, and Texas. The information provide acreage estimates to the Agricultural Statistics Board for the state's major commodities and (2) produce digital, crop-specific, categorized geo-referenced output products. | Service |
| RGB_dem | 30m spatial resolution of digital elevation model for the Rio Grande/Bravo basin | ASTER global digital elevation model |
| RGB_slope | Percentage slope | ASTER global digital elevation model |

## Water Management datasets

**Table 13 Water management original datasets**

| Dataset | Short description | Source |
|---|---|---|
| TX_water_districts | Geographic location of water districts within the state of Texas | TCEQ |
| NM_water_districts | Geographic location of water districts within the state of New Mexico | OSE, Interstate stream Commission |
| CO_water_districts | Geographic location of water districts within the state of Colorado | DWR and CWCB |
| MX_Dams | Location of dams in Mexico | CONAGUA |
| US_Dams | Location of dams in United States | National Atlas of the United States form the USGS |

When possible, multiple datasets were merged into a single datafile that represent the RGB basin instead of a single state or region (Figure 8). The merge of information included the attribute tables and metadata. All the metadata from the Mexican data sources was changed to English. An example is the four different cities shapefiles (CO_cities_polygones, NM_cities_polygones, TX_cities_polygones, and MX_cities_polygones) that displayed the city’s boundaries of the entire states or of the entire country in the case of Mexico. Also, the attribute table had different field titles for storing the name of the cities, NAMESAD in Colorado, NAME10 in New Mexico, NAME in Texas, and NOM_LOC in Mexico. Other fields in the attribute table related to the area, an identification numbers, or different classification codes had a similar problem. These differences in the dataset were compiled and fixed when doing so would not represent a substantial modification of the original information of the dataset. Additionally, fields to identify the country and the states within each country were added.

Table - MX_cities_polygones

MX_cities_polygones

| CVEGEO | NOM_ENT | NOM_MUN | NOM_LOC |
|---|---|---|---|
| 010010001 | Aguascalientes | Aguascalientes | Aguascalientes |
| 010010239 | Aguascalientes | Aguascalientes | General José María Morelos y Pavón (Cañada Honda) |
| 010010293 | Aguascalientes | Aguascalientes | Norias de Ojocaliente |

(0 out of 4525 Selected)

CO_cities_polygones

| FID | Shape * | PLACENS | GEOID | NAMELSAD | CLASSFP | FUNCSTAT | ALAND | AWATER | INT |
|---|---|---|---|---|---|---|---|---|---|
| 0 | Polygon | 02412339 | 0800760 | Aguilar town | C1 | A | 1016074 | 0 | +37.4 |
| 1 | Polygon | 02412340 | 0800925 | Akron town | C1 | A | 6797239 | 0 | +40.1 |
| 2 | Polygon | 02409673 | 0801090 | Alamosa city | C1 | A | 19273771 | 322229 | +37.4 |

(0 out of 271 Selected)

NM_cities_polygones

| GEOID10 | NAME10 | NAMELSAD10 | LSAD10 | CLASSFP10 | PCICBS |
|---|---|---|---|---|---|
| 3573260 | Silver City | Silver City town | 43 | C1 | Y |
| 3570270 | Santa Clara | Santa Clara village | 47 | C1 | N |
| 3533850 | Hurley | Hurley town | 43 | C1 | N |

(0 out of 443 Selected)

TX_cities_polygones

| NAME | NAMELSAD | LSAD | CLASSFP | PCICBSA | PCINECTA | MTFCC | FUNCSTAT |
|---|---|---|---|---|---|---|---|
| Chester | Chester town | 43 | C1 | N | N | G4110 | A |
| Barstow | Barstow city | 25 | C1 | N | N | G4110 | A |
| Pyote | Pyote town | 43 | C1 | N | N | G4110 | A |

(0 out of 1748 Selected)

Table

RGB_cities_polygones

| Name | ALAND | Pop_1910 | Pop_1920 | Pop_1930 | Pop_1940 | Pop_1950 | Pop_1960 | Pop_1970 | Pop_1980 | Pop_1990 | Pop_2000 | Pop_2010 | Notes | Country | State | City_ID |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pharr city | 61070810.317 | 0 | 1565 | 3225 | 4784 | 8690 | 14106 | 0 | 0 | 32921 | 47387 | 70789 | | United States | Texas | 4857200 |
| Rio Rancho city | 268512248.23 | 6172 | 7033 | 11173 | 13482 | 25738 | 39593 | 0 | 0 | 44480 | 52706 | 88023 | | United States | New Mexico | 3563460 |
| Santa Fe city | 119253111.942 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 345 | 63286 | 68147 | | United States | New Mexico | 3570500 |
| Las Cruces city | 198470272.486 | 3836 | 3969 | 5811 | 8385 | 12325 | 29367 | 0 | 0 | 62648 | 73605 | 98206 | | United States | New Mexico | 3539380 |
| Delicias | 34044723.4252 | 866 | 0 | 426 | 6020 | 18290 | 39919 | 0 | 0 | 87412 | 98615 | 118071 | | Mexico | Chihuahua | 080210001 |
| Hidalgo del Parral | 31777206.7877 | 0 | 15181 | 18581 | 21231 | 32063 | 41474 | 0 | 0 | 88197 | 98876 | 104836 | | Mexico | Chihuahua | 080320001 |
| McAllen city | 128493992.838 | 0 | 5331 | 9074 | 11877 | 20067 | 32728 | 0 | 0 | 84021 | 107030 | 13089 | | United States | Texas | 4845384 |
| Brownsville city | 378865431.195 | 10517 | 11791 | 22021 | 22083 | 36066 | 48040 | 0 | 0 | 107027 | 143368 | 175662 | | United States | Texas | 4810768 |
| Laredo city | 242754885.531 | 14855 | 22710 | 32618 | 39274 | 51910 | 60678 | 0 | 0 | 122899 | 179492 | 237032 | | United States | Texas | 4841464 |
| Albuquerque city | 490916889.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 450557 | 547085 | | United States | New Mexico | 3502000 |
| El Paso city | 666521713.98 | 39279 | 77560 | 102421 | 96810 | 130485 | 276687 | 0 | 0 | 515342 | 564792 | 651676 | | United States | Texas | 4824000 |
| Chihuahua | 270527410.977 | 39706 | 37078 | 32 | 56805 | 87000 | 150430 | 0 | 0 | 516153 | 657876 | 809232 | | Mexico | Chihuahua | 080190001 |
| Juárez | 343279540.241 | 67 | 0 | 685 | 48881 | 11242 | 252119 | 0 | 0 | 789522 | 1187275 | 1321004 | 1950("C | Mexico | Chihuahua | 080370001 |

(0 out of 1226 Selected)

**Figure 8 Example of dataset merge.**

The process was performed for other datasets, including the states, the counties and municipalities, water bodies, rivers, aquifers, land cover, and some climatic variables. When the data was not available for both countries the merge was performed for only one side of the border. Substantial geographic information is now available for the RGB basin and has the potential to be used on multiple projects related to demographics, restoration actions, and modeling tools among others.

# DISCLAIMER

This material is based upon work supported by the U.S. Geological Survey under Grant Agreement No G15AP00174 from the Southwest Climate Science Center. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Geological Survey. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Geological Survey. This manuscript is submitted for publication with the understanding that he United States Government is authorized to reproduce and distribute reprints for Governmental purposes.

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