

How Sustainable are Engineered Rivers in Arid Lands?

Jurgen Schmandt¹, Gerald R. North², George H. Ward³

¹Houston Advanced Research Center, The Woodlands, and
University of Texas, Austin, United States
e-mail: jas@harc.edu

²Department of Atmospheric Sciences
Texas A&M University, College Station, United States

³Center for Research in Water Resources
University of Texas, Austin, United States

Cite as: Schmandt, J., North, G.R., Ward, G.H., How Sustainable are Engineered Rivers in Arid Lands?, *J. sustain. dev. energy water environ. syst.*, 1(2), pp 78-93, 2013, DOI: TBA

ABSTRACT

Engineered rivers in arid lands play an important role in feeding the world's growing population. Each continent has rivers that carry water from distant mountain sources to fertile soil downstream where rainfall is scarce. Over the course of the last century most rivers in arid lands have been equipped with large engineering structures that generate electric power and store water for agriculture and cities. This has changed the hydrology of the rivers. In this paper we discuss how climate variation, climate change, reservoir siltation, changes in land use and population growth will challenge the sustainability of engineered river systems over the course of the next few decades. We use the Rio Grande in North America, where we have worked with Mexican and American colleagues, to describe our methodology and results. Similar work is needed to study future water supply and demand in engineered rivers around the world.

KEYWORDS

Hydraulic Engineering, Climate Variation, Climate Change, Reservoir Sedimentation, Irrigated Agriculture, Food Security, River Sustainability, Rio Grande

INTRODUCTION

Important rivers throughout the world share these characteristics: The headwaters are fed by snowpack or rainfall in the mountains. Hundreds of kilometres downstream, where the climate is arid or semi-arid, river water irrigates the fertile soil flushed down by annual floods and thus enables agriculture and human settlements. This is how civilizations in Mesopotamia, Egypt, China and the Americas emerged and flourished over thousands of years. Over the course of the last century most of these rivers have been changed by large-scale engineering. Rivers were dammed to capture water in reservoirs that generate electricity, irrigate crops and allow for the growth of riverine cities. As a result, sediment is now captured by the reservoirs and no longer reaches the fields. Today engineered rivers face additional challenges. Climate variation, climate change and reservoir sedimentation will reduce water supply. Population growth will force increased water allocation to urban use. This raises important questions: How will reduced water supply and increased water demand impact river basins? Can irrigated agriculture do more with less? How can water managers cope with expected shortfalls? How sustainable are engineered rivers in arid lands? — The example of the Rio Grande, a heavily engineered river in arid lands, provides initial answers to these questions.

THE RIO GRANDE

Modern water engineering began a hundred years ago when the U.S. Bureau of Reclamation built the world's first large dam and reservoir on the Rio Grande in New Mexico. After years of planning and construction Elephant Butte Reservoir was closed in 1916 [1]. Since then multiple reservoirs, diversion channels and irrigation canals have been added to the river (Figure 1). In our study we estimate future surface water supply from the largest reservoirs in the basin — Elephant Butte, Amistad and Falcón — and water demand in the major socio-economic sub-basins — Paso del Norte and Lower Rio Grande Valley. We then calculate future demand and consider ways to cope with expected shortages.

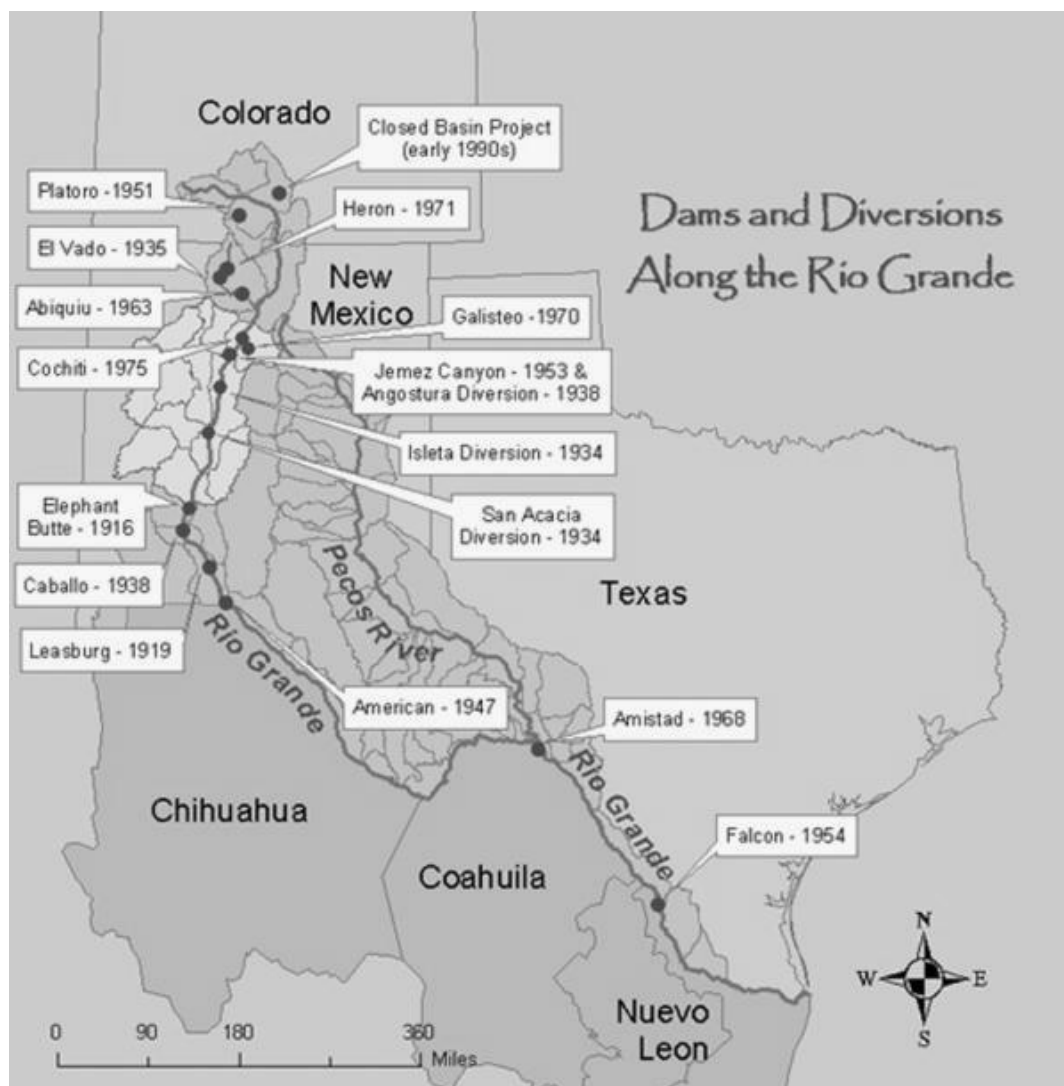


Figure 1. Dams and diversions along the Rio Grande

Basin Characteristics

In the American Southwest the dividing line between rain-fed and irrigated agriculture follows the 100th meridian. The 100th meridian runs close to the mouth of the Rio Grande at the Gulf of Mexico. Irrigated agriculture in this vast region depends on the Rio Grande east of the Rocky Mountains and the Colorado to the west of the mountain range. Water from both rivers is shared with Mexico. While the Colorado marks the

international border for just a short distance, the Rio Grande, called the Río Bravo in Mexico, does so for more than 1,000 kilometres (Figure 2). This makes management of the Rio Grande particularly complex.

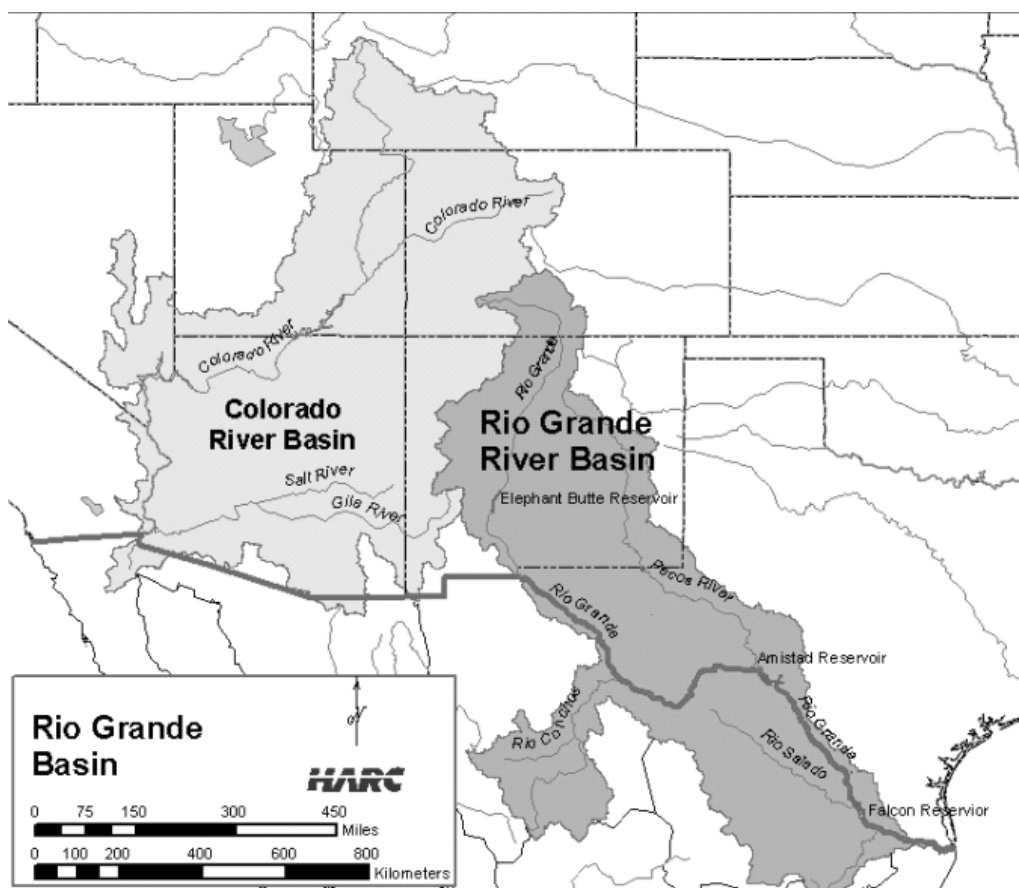


Figure 2. Colorado and Rio Grande basins

Upper Rio Grande. The Rio Grande originates from springs and snow deposits on the eastern slope of the continental divide in Colorado’s San Juan Mountains [2]. Snowmelt provides reliable flows in the spring. The river passes through Southern Colorado and New Mexico and numerous dams and agricultural diversions before reaching the Paso del Norte (PdN) sub-basin 560 kilometres downstream. Volume of precipitation and timing of snowmelt in the headwaters region determine how much and when water reaches the main storage facility in the PdN — Elephant Butte Reservoir, New Mexico. The reservoir serves as the main hydrological structure of the federal Rio Grande Project that supports irrigated agriculture in southern New Mexico and West Texas. In 1938 a second reservoir, Caballo, was built a short distance further downstream. Operation of the tandem reservoirs allows for year-round generation of electric power at Elephant Butte and seasonal release of irrigation water at Caballo. Two large socio-economic regions have seen continued growth as a result of Rio Grande engineering (Figure 3) — PdN and Lower Rio Grande Valley (LRGV).

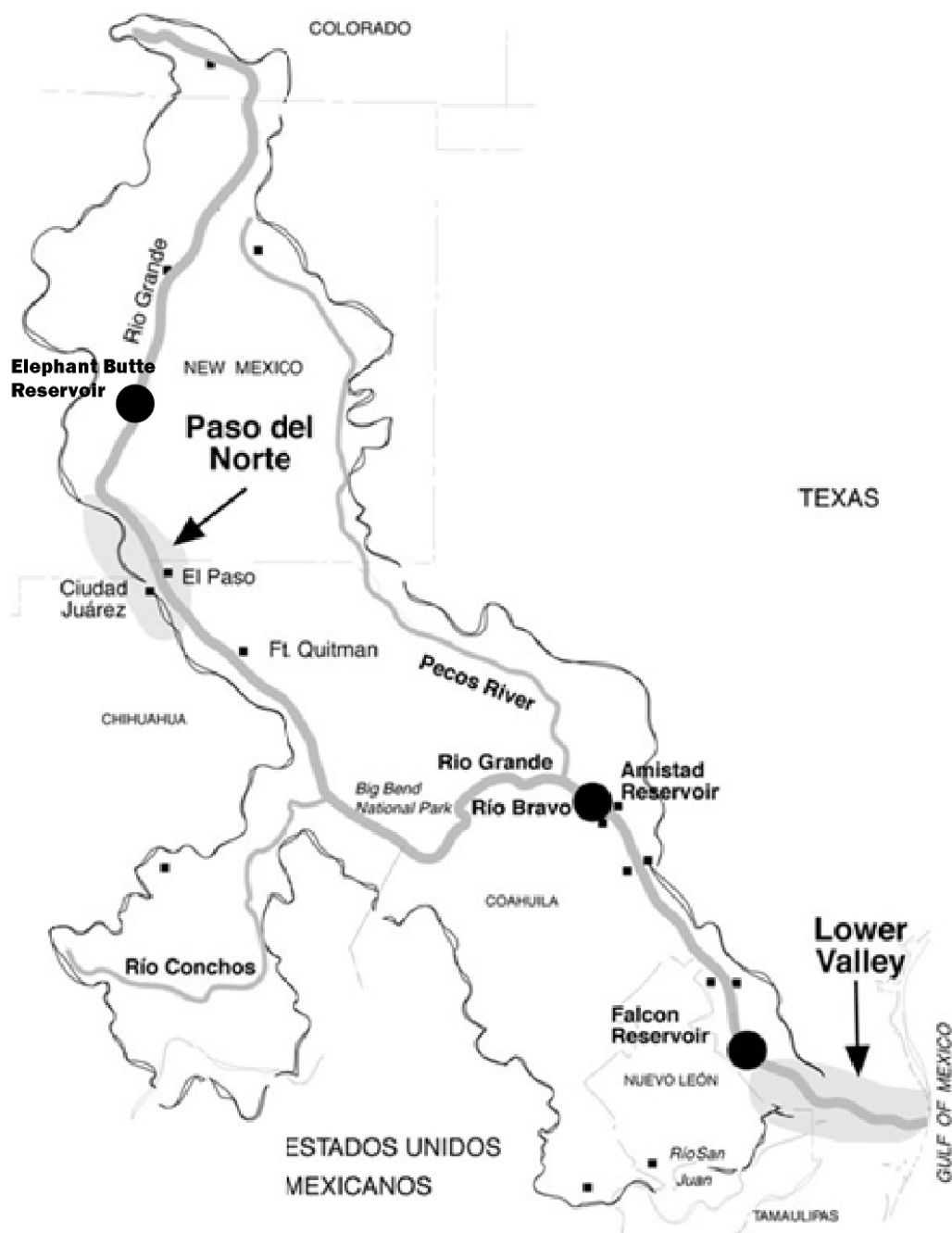


Figure 3. Paso del Norte and Lower Valley — two main economic areas and their reservoirs

The PdN is home to extensive agriculture and the cities of Las Cruces (New Mexico), El Paso (Texas) and Cd. Juárez (Mexico) with a current population of 3 million people. Population is expected to double by 2060. Groundwater provides the bulk of drinking water. El Paso operates a desalinization plant to treat brackish groundwater. From El Paso/Juárez to the Gulf of Mexico the river marks the international border with Mexico. Upper Rio Grande water is divided under interstate agreements between Colorado, New Mexico and Texas and, under a 1906 treaty, between Mexico and the United States. The United States is obligated to transfer 60,000 acre feet/year (74 million m³) to Mexico. Instream flow is low during the winter months. The Upper Rio Grande basin ends 277 kilometres downstream from El Paso at Fort Quitman, Texas. At this point most river water has been diverted, close to 90% to support thriving agriculture in New Mexico, Texas and Mexico.

Lower Rio Grande. 500 kilometres downstream from Fort Quitman the Rio Grande is rejuvenated by two tributaries — the Conchos in Mexico and the Pecos in New Mexico and Texas. Year-round stream flow in the Lower Rio Grande is ensured by these rivers. They are fed by snow melt at high elevations, by rainfall associated with the North American monsoon, and by occasional tropical storms reaching the basin from the Pacific and Gulf of Mexico [3]. The river flows over long stretches of arid plains where it is partially depleted by evaporation and withdrawals. The main storage facilities to capture Conchos and Pecos flows are Amistad and Falcón reservoirs that were built on the main stem of the Rio Grande in the 1950s and 60s. Since 1972 the two reservoirs are operated as a single system by the International Boundary and Water Commission (IBWC/CILA). The reservoirs provide 95% of available surface water to the Lower Rio Grande Valley (LRGV) region in Texas and Mexico. The LRGV is home to intensive agriculture and the rapidly growing cross border cities of Laredo-Nuevo Laredo, McAllen-Reynosa and Brownsville-Matamoros. At the end of its 3,000 km long run the Rio Grande empties into the Gulf of Mexico, except in drought years.

The LRGV has a current population of 3.5 million. Ground water is of poor quality, making the river the main source of drinking water, irrigation and the ecosystem. River water is shared between Mexico and the United States under a 1944 treaty. Mexico is obligated to transfer 350,000 acre-feet/year (432 million m³) to the United States. In exchange, Mexico receives water from the Colorado in California. Conchos deliveries have exceeded the treaty obligation in most years. This was not the case during a recent drought period, causing a serious water conflict with Mexico [4].

Water Management

The variability of the basin's arid climate entails the risks of both drought and flooding. To manage these risks and allocate water among claimants a complex array of water agencies has been created.

In the US part of the basin, Colorado, New Mexico and Texas share water under the Rio Grande Compact. The state engineers of Colorado and New Mexico, and an appointee of the Governor of Texas, serve as commissioners. Rio Grande waters at Elephant Butte are controlled by the U.S. Bureau of Reclamation (the Rio Grande Project). The U.S. share of Lower Rio Grande waters is allocated to irrigation districts and cities by the Rio Grande Water Master, an agency of the State of Texas. Río Bravo and Conchos waters are controlled by the Comisión Nacional de Agua (Río Bravo downstream from Juárez).

Bi-national management of Rio Grande waters began more than a century ago. Under treaties concluded in 1906 (Upper Rio Grande) and 1944 (Lower Rio Grande), the International Boundary and Water Commission (IBWC/CILA) is responsible for construction and maintenance of dams, diversion and irrigation channels, the clearing of flood plains, and the allocation of water between Mexico and the United States in the bi-national reach of the Río Bravo-Rio Grande from El Paso-Juárez to the Gulf of Mexico. The Commission is organized in American and Mexican sections. The division of water between the two countries reflects hydrological information that was available when the treaties were concluded. As mentioned, in the PdN the United States is obligated to transfer 60,000 acre feet (74 million m³) annually to Mexico. In the LRG sub-basin Mexico is obligated to transfer 350,000 acre feet (432 million m³) annually to the United States. Each treaty provides for reducing water transfers during drought years. However, these provisions have not prevented serious conflict between the countries during a severe drought in the Rio Grande basin that lasted for several years during the 1990s [5].

At the local level, numerous irrigation districts and city water utilities in both Mexico and the United States are responsible for water management.

Successful water management in this multijurisdictional international basin requires accurate water accounting and fair water diplomacy. Over time, there have been conflicts between irrigation districts and cities, the three US states, as well as between the two countries, but by and large this complex system of water management works well.

RESEARCH DESIGN

Our research proceeds in several steps. First, we study precipitation and runoff in the headwater regions of Rio Grande, Conchos and Pecos. Second, we assess current conditions in the main economic regions — the Paso del Norte (PdN) and the Lower Rio Grande Valley (LRGV) where people and agriculture are concentrated (Fig. 3). Results of headwater and economic region analysis are then used to estimate future water supply and demand. Key study components include: (1) assessing critical change factors; (2) developing a Rio Grande water budget; and (3) providing policy advice to basin management agencies.

Assessment of Critical Change Factors

We examine three physical factors that determine future surface water supply: climate variation, climate change and reservoir sedimentation. We then study three social and economic factors that change future water demand: population growth, changes in land use/regional economic development, and increased efficiency in using water. Finally, we estimate the volume of instream flow as a result of changing conditions.

Climate variation and climate change. Methodology for assessing reservoir operations under climate change conditions was first developed as part of a study of California's Central and State Valley systems [6]. Based on this work the U.S. Geological Survey issued policy guidance on how to integrate climate change into water management [7]. The report suggests surveying an ensemble of climate projections, selecting the most likely one for detailed analysis, and quantifying impacts under a variety of future scenarios. A study by the U.S. Department of Agriculture predicts increased drought, severe rainstorms, and erosion from wind and water, which will help spark desertification across the West's arid lands. "Extreme climate events such as drought may act as triggers to push arid ecosystems experiencing chronic disturbances, such as grazing, past desertification 'tipping points'" [8].

Climate change will affect the stream flows of the Rio Grande and its main tributaries — Conchos and Pecos — in two ways: 1. Since the rivers are fed primarily by snow and its resulting melt, volume and seasonality of the deposition and melting will affect the traditional flow rate. Even small changes in the average timing due to climate change will have an effect on stream flow. 2. Flow along the rivers' paths will be affected by precipitation and evaporation and their seasonality [9-12]. A report by the U.S. Bureau of Reclamation finds that the Upper Rio Grande is likely to experience "reductions in storage capture and ... reductions in water supply for warm season delivery" [13].

Simulations of future climate in subtropical regions have been conducted for the Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC). The general conclusion is that the descending branch of the Hadley Circulation will expand northwards and that the resulting climate throughout West Texas and Northern Mexico will be drier as the century proceeds [14-16]. New simulations for the next IPCC report are nearing completion and these will make it possible to estimate the snow

accumulations with special attention to changes in the phase of the annual cycle of deposit and its associated melt and evaporation.

Predicting future rainfall patterns for a region as small as Texas, Southern New Mexico and the Mexican states bordering the Río Bravo — home of the PdN and the LRGV — is still difficult. North offers this conclusion: “There can be legitimate differences of opinion: this author opts for more rain in the eastern part of the state [Texas] and less in the west, but confesses that strictly speaking the jury is still out” [17]. An even more assertive statement about the negative impact of climate change on water resources in the American Southwest is offered by the January 2013 draft report of the National Climate Assessment and Development Advisory Committee: “There is high confidence in the continued trend of declining snowpack and stream flow given the evidence base and remaining uncertainties. For the impacts on water supply, there is high confidence that reduced water supply will affect the region” [18]. It all adds up to the stern warning by Milly et al against relying on water strategies based on information about past conditions: “In view of the magnitude and ubiquity of the hydro-climatic change apparently now under way ... we assert that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning” [19].

Observations to date document that, compared to years before 1950, the Rocky Mountains snowpack is melting earlier in the year, rain is replacing some snow storms, and the April snow pack is containing less water. Observed changes reflect the impacts of climate variability (El Niño Southern Oscillation and Pacific Decadal Oscillation) and, increasingly, climate change [20-23]. Both sub-basins have suffered extensive droughts in recent years during which agricultural diversions were curtailed. In the LRGV this led to massive economic losses and a conflict with Mexico. The PdN sub basin was able to tap ground water and avoid major losses. This strategy is not available in the LRGV due to the poor quality of groundwater.

Reservoir sedimentation. The U.S. Bureau of Reclamation has studied Elephant Butte sedimentation since 1915, a year before the dam was completed. By now a data set covering almost a century is available. The 1999 survey reported a 23.3% loss of storage capacity since closure [24]. The report projected additional 5% losses for future 14 year intervals. The 2007 survey corrected these findings as follows: "Since the last reservoir survey in 1999, the reservoir volume has increased 1,228 acre-feet (1.5 million m³) due to the dewatering and resulting compaction of the previous measured sediments that have been exposed during the extended drought conditions. The average annual rate of sediment accumulation since 1915 is 6,575.6 acre-feet (8.1 million m³) compared to the 1999 study computation of 7,253.2 acre-feet (8.9 million m³)." Thus, between 1915 and 2007, 23.16% of storage capacity was lost [25].

In the Lower Rio Grande the greatest siltation occurs in the upstream reservoir — Amistad. From the closure of Amistad in 1968 through 1992, when the lake was extensively surveyed by the IBWC, 760,800 acre-feet (938 million m³) had been lost to storage in the combined Falcon-Amistad system, about 12.5% of conservation capacity, of which 95% is in Amistad. Projected to the present, the loss of conservation capacity due to siltation is about 22% [26]. This is consistent with the 2010 Region M Texas Water Plan, which estimates “annual reductions in ... conservation storage capacities equal to about 0.6% for Amistad and about 0.03% for Falcon” [27].

Available data document an annual storage volume loss of 0.25% in Elephant Butte. The Amistad loss is in the range of 0.5% (IBWC and Ward data) to 0.6% (2010 Region M Texas Water Plan). The measured plus projected loss for Elephant Butte (1915-2060)

amounts to 36.5%. For Amistad (1968-2060) the loss will amount to 55.2%. It is possible that Amistad will lose somewhat less in future years because some siltation from the main tributary, the Río Conchos, is likely to be caught by recently built reservoirs in Mexico. Even so, reservoir losses in the 40% range are highly significant for both economic impact regions — the PdN and the LRGV.

Population growth. Population in the economic impact regions has doubled every twenty years since the 1950s. In 2010, El Paso County had 833,640 inhabitants. Across the border, Cd. Juárez counted 1.5 million people. Growth has been driven by high birth rates and in-migration. Other factors include military installations, the maquiladoras legislation, NAFTA free trade agreements, the availability of agricultural and industrial jobs, as well as affordable housing. The Mexican side of the border has been a magnet for people from interior Mexico due to its relatively higher standard of living. Behind population growth stands the availability of cheap agricultural water. Population growth is projected to continue into the future. By 2060, population in the U.S. part of the PdN will have risen to over 1.6 million, while the U.S. LRGV population will have risen from 1.6 million in 2010 to 3.9 million in 2060. Adding a rough estimate of Mexican population growth in the economic impact regions, the total population downstream from Elephant Butte will reach 13 million by 2060.

Changes in land use. The Texas Water Development Board projects that irrigated land will shrink in the Texas portion of the basin. Market forces and urbanization are cited as the principal causes of this change. The projected decline in agricultural water demand is fairly small — for the Texas parts of the PdN (El Paso and Hudspeth counties) from 429,738 acre (1,739 km²) in 2010 to 389,304 acre (1,575 km²) in 2060; for the Texas part of the LRGV from 1,163,634 acre (4,709 km²) in 2010 to 981,748 acre (3,973 km²) [28-30]. This change may be driven by Texas law that allows irrigation water rights to be sold or leased to cities. New Mexican and Mexican laws do not treat water rights as private property. Their irrigation district managers state that they do not foresee a reduction in agricultural land use.

More efficient water use. Irrigation is the largest consumptive use of water in the river basin, ranging from 80 to 90%. Changes in irrigation use will have significant impacts on surface and groundwater hydrology, economic activities, and population growth. In our research in the LRGV we found that changed crop patterns and improved irrigation techniques can conserve 40% of surface water without economic loss [31]. Lining of canals, use of modern sprinkler systems, changes to less water intensive crops, floodwater capture, water reuse and conservation make it possible to save water and do more with less. At the municipal level water conservation, grey-water distribution systems and repair of leaky distribution systems have the same potential.

Changes in environmental flow. Construction of Elephant Butte reservoir significantly reduced the floods and high flow pulses reaching El Paso. Increased water demand in the Rio Conchos basin dramatically reduced the late summer/early fall high flow pulses entering the Lower Rio Grande. Reduction in the size and frequency of flood events has also decreased the rate and size of modifications in the geomorphology of the river channel. This has caused significant ecological damage in both upper and lower Rio Grande [32].

Estimating the Impact of Key Change Factors on Future Surface Water Supply and Demand

The largest deficit in current water planning is the lack of reliable information of the likely impact of climate change at the river basin level. An early model for integrating climate change into the analysis of a region's hydrological and economic future was developed at Resources for the Future [33]. Improvements to integrated assessments of natural resource systems were developed subsequently [34-36]. We refined the methodology in the above mentioned NSF/EPA sponsored study on "Water and Sustainable Development in the Binational Lower Rio Grande/Rio Bravo Basin" [31]. To integrate climate change along with other change factors into a model of future surface water supply and demand we followed these steps.

Baseline study. We describe current conditions in the study region and identify critical subsystems and the linkages among them — water resources under non drought and pre-climate change conditions, reservoir sedimentation, instream flow, population and land use, and ecological conditions.

Future scenarios. We develop five future scenarios: (1) "2060 Business as Usual" — current hydrology, current development trends and 2060 population (including a High and Low Population variant); (2) "2060 Climate variation" and (3) "2060 Climate change" — hydrology during drought/Southern Oscillation years or under permanent climate change combined with 2060 sedimentation, population and various assumptions about future land use; (4) "2060 worst case" — drought plus climate change, sedimentation, no change in land use, high population projection; (5) "2060 sustainable development" — climate change hydrology, sedimentation, low population growth, more efficient agricultural and municipal use, better water management strategies and agencies, as well as improved in stream flow.

For each scenario we integrate the hydrological, social, economic and environmental components of the project. Figure 4 illustrates the linkages between physical and social factors that we analyse and, where possible, quantify. Hydrology is at the centre of the assessment.

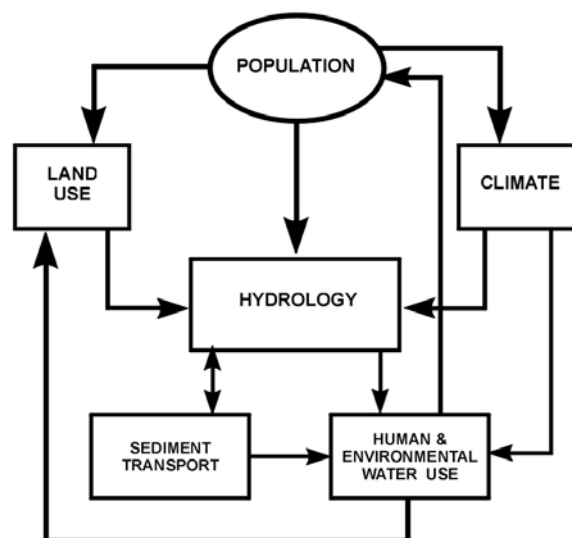


Figure 4. Linkages between hydrology and other change factors in the BRACERO water model

The BRACERO water budget. The impact of climate change on water resources and reservoir storage has been studied for more than three decades [37-47]. Based on this literature and our previous work we quantify the linkages between water, climate, sedimentation, land use and population by use of the BRACERO water budget model. BRACERO models water supply of riverine systems controlled by reservoir operation. We developed and tested the model as part of our EPA/NSF study of the Bi-national Lower Rio Grande [31]. BRACERO can easily be used on other hydrological systems characterized by main-stem reservoirs and feeding river reaches. The model is driven by river flows into the reservoir system (from historical data or future climate driven surface water projections), and past, current or future water demand for municipalities, industry, irrigated agriculture and the environment.

The value of the modelling, such as BRACERO, is to provide a quantitative framework for the exploration of alternative future scenarios coupled with adaptive water-management strategies. For example, the model enables the user to calculate monthly water demands needed under the various scenarios of socio-economic development, and then determine the surface water stresses that result from attempting to meet water demands. Monthly rather than annual resolution is important because stream flow and water demand in the Rio Grande/Bravo change dramatically during the course of the year. The model can also be used to estimate water shortfalls for specific sub regions of the basin and to determine firm yield as an index to water availability.

RESULTS AND DISCUSSION

Reliable projections to 2060 can be made for reservoir sedimentation and population growth. To date the three main reservoirs on the Rio Grande have lost about a quarter of their storage capacity. By 2060 total losses will have reached or surpassed 40%. Population in the economically important parts of the basin has increased rapidly since the 1950s. The current population of 6 ½ million people in the bi-national economic sub-basins (PdN and LRGV) will reach 13 million by mid-century. Climate variation causes periodic multi-year droughts. Climate change will have a significant impact on water supply by mid-century. Precise forecasts of likely supply losses are not yet available. However, climate models predict a decrease in winter snowpack in the headwaters regions, reduced runoff and higher evapotranspiration from reservoirs and the river itself. This information is sufficient to plan for a significant reduction of stream flow by mid-century. Combined with reservoir sedimentation prudent water managers must prepare for a 50% reduction in surface water supplies by 2060. Depending on decisions yet to be taken, part of the shortfall may be reduced by building new reservoirs. For example, Texas has long planned to construct two new major reservoirs in the LRGV. However, both projects are controversial.

More importantly, expected losses in surface water supply can be coped with, to a significant degree, by improvements in irrigation technology and rural as well as urban water management focusing on conservation, reuse and system improvements.

First, the current use of over 80% of river water by agriculture can be reduced by improvements in water distribution and use, water metering, and changes in crop patterns. More realistic water pricing would help. But this faces fierce opposition from farmers and irrigation districts. Improved storage of flood waters provides another strategy for increasing resources. We estimate that current crop yields in non-drought years can be maintained while reducing agricultural water use by 40%.

Second, urban and industrial activities use 12% of river water. To meet the demands of the projected population by 2060, the share of municipal and industrial water use must rise to 25%. Part of the shortfall can be met by development of new groundwater resources

which is more feasible in the PdN than in the LRGV. This strategy is being pursued by the Mexican water authorities to meet the needs of Cd. Juárez. All cities need to reduce often substantial leakage in their distribution systems and continue to practice water conservation.

Third, a substantial amount of agricultural water will need to be transferred to cities. Urbanization and market changes will facilitate this process. To transfer water by law will be controversial because it would affect the existing rights of water users. A better solution will be to develop a regional water market modeled on California's successful water market, which has helped the state to cope with drought. Texas law allows for the selling of water rights and a water market has developed in the LRGV. Laws in New Mexico allow for a limited water market. The Republic of Mexico does not allow for the sale or lease of water rights.

Fourth, the basin has already suffered significant damage to aquatic and terrestrial resources. Reduced water supply and increasing demand will further reduce environmental flow.

Fifth, desalinization of brackish groundwater or seawater is becoming cost effective for cities but not for small communities where concentrate disposal can be a huge cost. Good experience is being gained by the desalinization plant operated by the El Paso water utility.

Sixth, a multiyear drought under climate change conditions will be more severe than traditional droughts, and will require exceptionally large transfers of water from irrigation to municipal use. Agricultural production will be severely constrained.

Seventh, given the high probability of substantial losses in future surface water supply the IBWC and the national governments of Mexico and the United States need to address these questions:

- 1) Are the treaty obligations concerning water transfers, agreed to in 1906 and 1944, based on obsolete climatological and hydrological assumptions?
- 2) Will the existing provisions for curtailing water transfers between the countries under extraordinary circumstances be sufficient to deal with projected shortfalls?
- 3) What needs to be done to reduce the risk of a protracted water conflict between Mexico and the United States?

We conclude that the sustainable 2060 scenario — climate change hydrology, reservoir sedimentation, low population growth, more efficient agricultural and municipal use, and improved environmental flow — is not achievable. However, the basin will be able to supply drinking water to its projected 13 million people. In normal years, irrigated agriculture can continue to be the backbone of the basin economy and ensure food security, provided that farmers and managers begin now to learn how to do more with less. During drought years this will not be possible. The PdN may cope better than the LRGV, due to the availability of good or fair quality ground water.

To date water planning in the Rio Grande basin — in Mexico as well as in the United States — considers changes resulting from reservoir sedimentation, population growth and changes in land use. Climate change, on the other hand, is barely considered.

In 2008 the Texas Water Development Board, in response to a legislative mandate, organized a conference to explore ways to incorporate climate change in water planning for the PdN [48]. However, the conference recommendations were not acted upon in the 2011 water plan for the region [49]. The 2012 draft water plan for Texas merely acknowledges that “climate change and climatic variability both pose challenges to water planning because they add uncertainty” [50]. To meet the challenge the “agency monitors climate science for applicability to the planning process.”

Our research suggests that a more aggressive approach is needed. While perfect quantitative information is not available, enough is known to warrant consideration of

climate change and variability in a number of ways: monitoring changes in upstream snowpack; quantifying evaporation losses that will result from a 1.40°C warming (the minimum warming expected by 2050); developing supply predictions that do not assume unchanged validity of historical stream flow data; preparing for more frequent and prolonged droughts; and aggressively implementing strategies for doing more with less. Water managers should also work with city leaders to explore the costs and benefits of desalinating brackish groundwater or sea water.

CONCLUSION

The assessment methodology developed for the study of future water supply and demand in the Rio Grande is applicable elsewhere. It provides managers and policy makers with a tool to evaluate the future of engineered rivers in arid lands. Such assessments are needed worldwide to deal with rapidly changing physical, social and economic conditions. As in the case of the Rio Grande, special attention should be given to climate variation, climate change, reservoir sedimentation, population growth, and changes in land use, technology and water management. Assessments of this kind will lay the foundation for new water management strategies that acknowledge the inevitable loss of surface water and define ways for doing more with less. Each continent has engineered rivers in arid lands that will benefit from this approach. We mention Colorado, Rhône, Euphrates-Tigris, Nile, Yellow, Murray-Darling and São Francisco. Table 1 shows the importance of irrigated acreage in selected river basins. It is urgent to develop management strategies for these and other rivers in arid lands that are based on best available information about projected changes in natural and socio-economic systems. The world's food security and the economic well-being of large riverine populations are at stake.

Table 1. Selected engineered rivers in arid lands

	Length (km)	Drainage area (1,000 km ²)	Irrigated land (10 ⁶ ha)	Discharge at mouth (m ³ /s)	Main engineering structures
Colorado	2,330	640	1.5	59	Hoover, Imperial, Glen Canyon
Colorado: Euphrates	2,740	640	1.5	-	Ataturk, Euphrates
Murray-Darling	2,560	1,072	2	391	Dartmouth, Hume
Nile	6,800	2,881	5	1,584	Roseires, Sennar, Aswan
Rhône	812	98	~0.5	1,900	Multiple dams and diversions
Rio Grande	3,059	570	1.4	82	Elephant Butte, Amistad, Falcón
São Francisco	2,914	610	~0.7	3,300	5 hydroelectric dams
Yellow	5,464	745	5.7	1,365	7 hydroelectric dams

ACRONYMS

CILA	Comisión Internacional de Limites y Aguas
IBWC	International Border and Water Commission
IPCC	International Panel on Climate Change
LRGV	Lower Rio Grande Valley
PdN	Paso del Norte

REFERENCES

1. Kelly, S.; Augusten, I.; Mann, J; Katz, L. History of the Rio Grande reservoirs in New Mexico. *Nat. Resources J* 2007, 47, 525-611.
2. Tidwell, V.C; Michelsen, A.M; Aparicio, J; Passell, H. The Rio Grande/Río Bravo—a river of change. *Water Resources Impact* 2004, 6, 14-17.
3. Higgins, R.; Yao, R; Wang, X. Influence of the North American monsoon system on the U.S. summer precipitation regime. *J. Climate* 1997, 10, 2600-2622. ([http://dx.doi.org/10.1175/1520-0442\(1997\)010<2600:IOTNAM>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(1997)010<2600:IOTNAM>2.0.CO;2))
4. Patiño-Gomez, C.; McKinney, D.C.; Maidment, D.R. Sharing water resources data in the bi-national Rio Grande/Bravo basin. *J. Water Resources Planning and Management* 2007, 133 (5), 416-426. ([http://dx.doi.org/10.1061/\(ASCE\)0733-9496\(2007\)133:5\(416\)](http://dx.doi.org/10.1061/(ASCE)0733-9496(2007)133:5(416)))
5. Rosson, C. P.; Hobbs, A; Adcock, F. The U.S./Mexico water dispute: Impacts of increased irrigation in Chihuahua, Mexico. Center for North American Studies, CNAS 2003-4, Department of Agricultural Economics, Texas A&M University, College Station, Texas, 2003.
6. Brekke, L.D.; Maurer, E.P; Anderson, J.D; Dettinger, M.D; Townsley, E.S.; Harrison, A; Pruitt, T. Assessing reservoir operations risk under climate change. *Water Resour. Res.* 2009, 45, W04411. (<http://dx.doi.org/10.1029/2008WR006941>)
7. Brecke, L.D.; King, J.E.; Olsen, J.R. Climate change and water resources management—A federal perspective, U.S. Geological Survey Circular 1331. Washington, D.C, 2009.
8. Backlund, P.; Janetos, A.; Schimel, D. The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Department of Agriculture, Washington, D.C., 2008, p. 362.
9. Seager, R.; Vecchi, G; Huang, Huei-Ping; Harnik, N; Leetmaa, A; Lau, Ngar-Cheung; Li, C; Velez, J; Naik, N. Model projections of an imminent transition to a more arid climate in Southwestern North America, *Science* 2007, 316, 1181-1184. (<http://dx.doi.org/10.1126/science.1139601> PMID: 17412920)
10. U.S. Global Change Research Program, Climate change impacts on the United States: The potential consequences of climate variability and change. Overview report. A Report of the National Assessment Synthesis Team. Cambridge University Press: Cambridge and New York, 2000.
11. Karl, T. R.; Melillo, J.M.; Peterson, T.C.; Hassol, S.J., Eds. Global climate change impacts in the United States. Cambridge University Press: Cambridge and New York, 2009.
12. U.S. Global Change Research Program. Water: The potential consequences of climate variability and change for the water resources of the United States. A Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change. 2000. <http://www.gcrio.org/NationalAssessment/water/water.pdf> (accessed November 15, 2011).
13. U.S. Department of the Interior, Reclamation, SECURE Water Act Section 9503(c) – Reclamation, climate change and water, Report to Congress. Washington, D.C., 2011, p. 121. <http://www.usbr.gov/climate/SECURE/docs/SECUREWaterReport.pdf> (accessed November 17, 2011).

14. Archer, C. L.; Caldeira, K. Historical trends in the jet streams. *Geophys. Res. Lett.* 2008, 35 (<http://dx.doi.org/10.1029/2008GL033614>)
15. Bengtsson, L.; Hodges, K.; Roeckner, E., Storm Tracks and Climate Change. *J. Clim* 2006, 19, 3519-3543. (<http://dx.doi.org/10.1175/JCLI3815.1>)
16. Yin, J. H., A consistent poleward shift of the storm tracks in simulations of 21st century climate. *Geophys. Res. Lett.* 2005, 32 (<http://dx.doi.org/10.1029/2005GL023684>)
17. North, G. Climate science and climate change. In *The Impact of Global Warming on Texas*; Schmandt, J.; North, G.; Clarkson, J., Eds. 2nd edition, University of Texas Press, Austin, TX 2011.
18. National Climate Assessment and Development Advisory Committee, Draft Climate Assessment Report, 2013 (<http://ncadac.globalchange.gov/download/NCAJan11-2013-publicreviewdraft-chap20-southwest.pdf>. Accessed January 2013).
19. Milly, P.C.D.; Betancourt, J.; Falkenmark, M.; Hirsch, R.M.; Kundzewicz, Z.W.; Lettenmaier, D.P.; Stouffer, R.J., Stationary is dead: Whither water management? *Science* 2008, 319, 573-574. (<http://dx.doi.org/10.1126/science.1151915> PMID: 18239110)
20. Guido, Z., Mountain Snowpack in the West and Southwest, Southwest Climate Change Network 2008. <http://www.southwestclimatechange.org/impacts/water/snowpack> (accessed December 10, 2011).
21. Hidalgo, H.G.; Das, T.; Dettinger, M. D.; Cayan, D.R.; Pierce, D.W.; Barnett, T.P.; Bala, G.; Mirin, A.; Wood, A.W.; Bonfils, C.; Santer, B.D.; Nozawa, T. Detection and attribution of streamflow timing changes to climate change in the Western United States. *J. Climate* 2009, 22, 3838–3855. (<http://dx.doi.org/10.1175/2009JCLI2470.1>)
22. Nemec, J.; Schaake, J. Sensitivity of water resource systems to climate variation. *Hydrol. Sci.* 1982, 27(3), 327-343. (<http://dx.doi.org/10.1080/02626668209491113>)
23. Nitze, W. A.; Schmandt, J; Lim, E. S. The role of climate change and climate variability in water management in the U.S.-Mexico order region, 2004. Unpublished report prepared for the U.S. Environmental Protection Agency, available from the authors.
24. U.S. Department of Interior, Bureau of Reclamation, Elephant Butte Reservoir: 1999 reservoir survey, Washington, D.C., 2000. <http://www.usbr.gov/pmts/sediment/projects/ReservoirSurveys/Reports/Elephant%20Butte%20Reservoir%201999%20Reservoir%20Survey.pdf> (accessed November 15, 2011).
25. U.S. Department of Interior, Bureau of Reclamation, Elephant Butte Reservoir: 2007 reservoir sedimentation survey, Washington, D.C., 2008. <http://www.usbr.gov/pmts/sediment/projects/ReservoirSurveys/Reports/Elephant%20Butte%20Reservoir%202007%20Sedimentation%20Survey.pdf> (accessed November 15, 2011).
26. Unpublished calculations by George Ward, University of Texas, Austin.
27. Texas Water Development Board, Region M regional water plan, Austin, Texas, 2007, p. ES-7, p. 3-51. http://www.twdb.state.tx.us/publications/reports/State_Water_Plan/2007/2007StateWaterPlan/CHAPTER%202_REGIONAL%20M_FINAL%20112706.pdf (accessed November 16, 2011).
28. Texas Water Development Board, Water for Texas, 2007. Doc. No. GP-8-1, TWDB, Austin, Texas, 2007. <http://www.twdb.state.tx.us/wrpi/swp/swp.htm> (accessed November 16, 2011).

29. Texas Water Development Board, Region E regional water plan, Austin, Texas, 2007, p. ES-6.
http://www.twdb.state.tx.us/publications/reports/State_Water_Plan/2007/2007StateWaterPlan/CHAPTER%20REGIONAL%20E%20final_112706.pdf (accessed November 16, 2011).
30. Texas Water Development Board, Region M regional water plan, Austin, Texas, 2007, p. ES-5.
http://www.twdb.state.tx.us/publications/reports/State_Water_Plan/2007/2007StateWaterPlan/CHAPTER%20REGIONAL%20M_FINAL%20112706.pdf (accessed November 16, 2011).
31. Houston Advanced Research Center, Water and Sustainable Development in the Binational Lower Rio Grande/Río Bravo Basin. Final Report to the Environmental Protection Agency. The Woodlands, Texas, 2000.
<http://www.harce.edu/ProgramAreasProjects/PastProgramsProjects/tabid/1862/Default.aspx> (accessed November 16, 2011).
32. Stotz, N.G., Historic reconstruction of the ecology of the Rio Grande/Río Bravo channel and floodplain in the Chihuahuan desert. Chihuahuan Desert Program, World Wildlife Fund, Las Cruces, New Mexico, 2001.
33. Rosenberg, N.J.; Crossen, P.R., Processes for identifying regional influences of and responses to increasing atmospheric CO₂ and climate change—The MINK project. Resources for the Future, Washington, D.C., 1991. (<http://dx.doi.org/10.2172/538038>)
34. Morgan, M.G.; H. Doiwlatabadi. Learning from integrated assessment of climate change. *Climatic Change* 1996, 34, 337-368.
35. Frederick, K.; N. Rosenberg. Assessing the impacts of climate change on natural resource systems. Kluwer Academic Publishers: 1994.
36. Rosenberg, N.J., Climate change impacts for the conterminous USA: From MINK to the Lower 48. *Climatic Change* 2005, 69(1) 2005.
(<http://dx.doi.org/10.1007/s10584-005-3608-5>)
37. Wallis, J. Climate, Climatic change and water supply. Studies in Geophysics, National Academy of Sciences: Washington, D.C., 1977.
38. Gleick, P.H. Global climatic changes and regional hydrology: Impacts and responses. In: *The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources*, IAHS Pub. No. 68, 1987.
39. Gleick, P.H. The development and testing of a water balance model for climate impact assessment: modeling the Sacramento Basin. *Wat. Res. Res.* 1987, 23(6), 1049-1061.
(<http://dx.doi.org/10.1029/WR023i006p01049>)
40. Wurbs, R.; Bergman, C. Evaluation of factors affecting reservoir yield estimates. *J. Hydrology* 1990, 112, 219-235. ([http://dx.doi.org/10.1016/0022-1694\(90\)90016-Q](http://dx.doi.org/10.1016/0022-1694(90)90016-Q))
41. Ward, G. H. A water budget for the State of Texas with climatological forcing. *Texas Journal of Science* 1993, 45(3), 249-264.
42. Schmandt, J.; Ward, G. Climate change and water resources in Texas. In *Proceedings of the First National Conference on Climate Change and Water Resources Management*, Ballyntine, T.M.; Stakhiv, E.Z; Smith, J.B., Eds. Institute for Water Resources. U.S. Army Corps of Engineers, Alexandria, Virginia, 1993.
43. Ward, G.; Proesmans, P. Hydrological predictions for climate-change modeling. Global Climate Change Response Program, U.S. Bureau of Reclamation, Denver, Colorado, 1996.
44. Ward, G.H. Hydrological analysis of international reservoir operation on the Lower Rio Grande/Río Bravo. Working Paper, EPA/NSF Task Force, Houston Advanced Research Center, The Woodlands, Texas, 1998.

45. Wurbs, R.; Muttiah, R.; Felden, F. Incorporation of climate change in water availability modeling. *J. Hydrol. Engr* 2005, 10(5), 375-385.
([http://dx.doi.org/10.1061/\(ASCE\)1084-0699\(2005\)10:5\(375\)](http://dx.doi.org/10.1061/(ASCE)1084-0699(2005)10:5(375)))
46. International Water Management Institute, Flexible water storage options and adaptation to climate change. *Water Policy Brief*, 31, Colombo, Sri Lanka, 2009.
47. Ward, G., *Water Resources*. Chapter 3 in *The Impact of Global Warming on Texas*; Schmandt, J.; North, G; Clarkson, J., Eds.; 2nd edition, University of Texas Press, Austin, TX 2011.
48. Texas Water Development Board, Far West Texas climate change conference: Study findings and conference proceedings, Austin, Texas, 2008.
<http://www.twdb.state.tx.us/publications/reports/climatechange.pdf> (accessed December 8, 2011).
49. Far West Texas Water Planning Group, Far West Texas water plan, 2011.
http://www.twdb.state.tx.us/wrpi/rwp/3rdRound/2011_RWP/RegionE/PDF's/Complete_Final_Report.pdf (accessed December 9, 2011).
50. Texas Water Development Board, *Water for Texas, 2012 Draft State Water Plan*, Austin, Texas, 2011, p. 231.
http://www.twdb.state.tx.us/publications/reports/state_water_plan/2012/draft_2012_swpartC.pdf
(accessed December 9, 2011).

Paper submitted: 04.02.2013
Paper revised: 29.03.2013
Paper accepted: 19.04.2013