

## Impacts of groundwater pumping and climate variability on groundwater availability in the Rio Grande Basin

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**Abstract.** Groundwater is a critical resource for sustainable economic growth in an arid and semi-arid region such as the Rio Grande Basin because it provides water for municipal, industrial, and domestic, and agricultural users. The water is also important for the health of riparian ecosystems in the Rio Grande basin. Historic groundwater pumping has resulted in large groundwater level drawdown, water quality deterioration, depletion of surface water and subsidence in El Paso/Ciudad Juarez area, which in turn will limit groundwater availability in the future. Therefore, securing future groundwater availability involves a multi-spectrum of efforts, including minimizing net losses from the underground reservoir, managing groundwater as an integrated part of the hydrologic cycle, developing infrastructure based on an understanding of the natural hydrologic system, using water wisely and efficiently, and allocating and monitoring water fairly for human as well as environmental and ecological needs. This paper focuses on the current status of groundwater quantity and geochemistry—groundwater hydrology, key aquifers, water quantity and chemistry, impacts of groundwater pumping and climate variability on groundwater availability within the Rio Grande Basin along river reaches between Elephant Butte Dam and Amistad Dam. This paper is part of a larger effort to summarize the state of the science relative to water sustainability in the region. This information can be used to plan research and education agendas aimed at water sustainability under climate and social changes. Current water uses and estimates of groundwater availability are summarized for the selected regional aquifers that underlie or are located adjacent to the Rio Grande. Several research topics are identified and recommended in terms of gaining better understanding of groundwater availability and impacts of future groundwater pumping and climate variability on the regional aquifer systems.

**Key words:** aquifer; climate variability; groundwater availability; Hueco Bolson; Mesilla Basin; Rio Grande Basin; Special Feature: Sustainability on the U.S./Mexico Border.

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### INTRODUCTION

The climate has changed in the past, is changing presently and will continue to change in the future. The planet-wide observation of a warming trend may correspond to a natural

warming phase, which began in the nineteenth century and is being accelerated and increased by the anthropogenic release of greenhouse gases from fossil fuels burnt during the last two centuries. The main concern raised by global warming is that climatic variations alter the

water cycle, indeed, many studies have shown that the hydrological cycle is already being impacted by climate change (EPA 1997, Dragoni 1998, Labat et al. 2004, Huntington 2006, IPCC 2007, McCabe and Wolock 2007, Seager et al. 2007, Fagre et al. 2009, Karl et al. 2009) and human activities, such as irrigated agriculture and urban development, especially in arid regions (Zektser et al. 2004, Ma et al. 2005, Barnett et al. 2008).

Climate variability has resulted in great impacts on the hydrologic cycle. Both surface water and groundwater have been and will be affected in one way or another due to changes in precipitation patterns and intensity. Though it may be more resilient, the relationship between groundwater and climatic change has been well recognized and its importance cannot be overstated. Reduced precipitation in some arid regions could trigger exponentially large drops in groundwater levels as a result of groundwater mining (Dragoni and Sukhija 2008).

The Rio Grande receives snowmelt runoff in southern Colorado and northern New Mexico. The river flows through the Chihuahua desert (southern New Mexico, Far West Texas) and eventually discharges into the Gulf of Mexico. The Rio Grande also collects discharge from the Rio Conchos in Mexico and the Pecos River (NM and Texas), local runoffs from arroyos during monsoon seasons, wastewater discharge and return flows from the drains. The Rio Grande downstream of the El Paso/Ciudad Juarez metropolis forms the international border between the United States and Mexico. Depending on hydrological conditions, the Rio Grande collects discharge from underlying or adjacent aquifers, or recharges the underlying aquifers through seepage of riverbed and canals that divert water for irrigations and deep percolation of irrigation water. This paper will focus on regional aquifers along the river reach between Elephant Butte reservoir and Amistad reservoir, historic use of groundwater in those aquifers, and impacts of historic pumping and climate variability on groundwater availability.

The communities within the study area are located in a semiarid climate region and have experienced prolonged droughts (FWTWPG 2001). Over two million people are currently living in the region, of which 63% live in Ciudad

Juarez, Chihuahua, 31% in El Paso, Texas, and 4% in Las Cruces, New Mexico. It is predicted that the population in Far West Texas will increase to 1.5 million within the next 50 years, almost doubling from its current population of 863,190 (FWTWPG 2011). The population in Ciudad Juarez will double within 20 years from its population of 1.25 million in 2000 (Paso del Norte Water Task Force 2001), and the population in Lower Rio Grande, New Mexico is anticipated to exceed 0.2 million (double of its current population of 97,375) by 2050 (NMOSE 2003). Groundwater uses will continue to soar as the regional population increases. Communities have used groundwater from the regional aquifers for over a century as the primary water supply for urban and industrial water in Ciudad Juarez, El Paso, and Las Cruces. It is also the primary water supply for military bases and supplements Rio Grande surface water source for agricultural irrigation (Hibbs et al. 1997, Sheng and Devere 2005, Hutchison 2006). Ecosystems, such as riparian vegetation and aquatic habitat, also rely on the shallow groundwater and its discharge into streams, usually called baseflow. Due to long-term groundwater pumping, some aquifers, such as the Hueco Bolson, have experienced large drops in groundwater level, deterioration of water quality due to intrusion of brackish water, and land subsidence (Sheng and Devere 2005, Hutchison 2006, Hutchison and Hibbs 2008).

Since aquifers have high storage capacities and are less sensitive to climate change than surface water bodies are, they can mitigate droughts. Major exploitations of groundwater in the region started after the 1950s drought. Even though no clear trend shows impacts on groundwater storage by climate change (NMOSE 2006, TWDB 2008), it is expected that future groundwater availability will be affected by climate change both directly, such as reduced mountain front recharge (very limited for this arid region) and increased evapotranspiration from the shallow aquifer, and indirectly, such as reduced seepage from the river and canals due to lower river flows, reduced deep percolation due to changes in land use, and increased water demands (Kumar 2012). Many studies have helped to characterize the regional aquifers and groundwater flow, understand historic groundwater

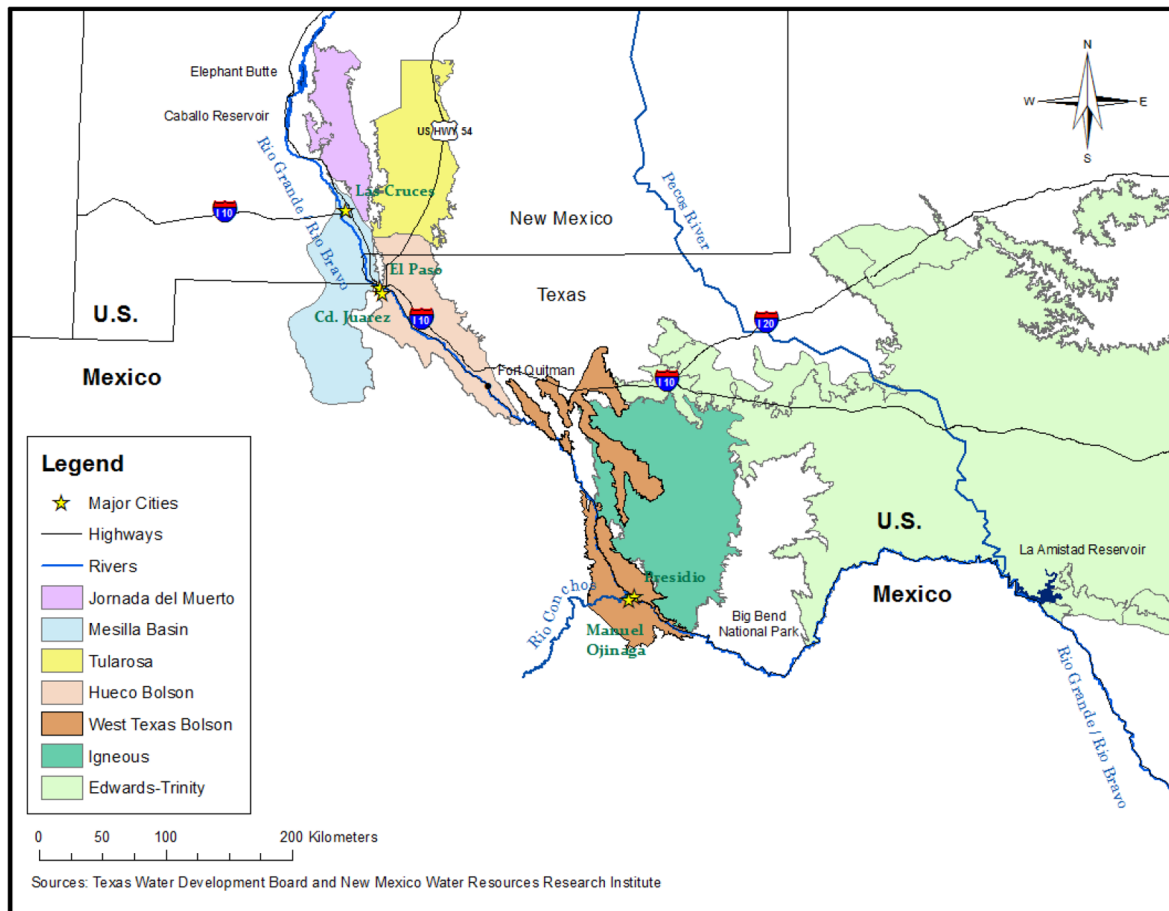


Fig. 1. Aquifers within the study area.

uses, and assess the current status of aquifers and groundwater availability (Meyer 1976, Knowles and Alvarez 1979, Wilson 1986, Groschen 1994, Hibbs et al. 1997, Heywood and Yager 2003, Sheng and Devere 2005, Hutchison 2006, Hutchison and Hibbs 2008).

Local communities have raised concerns regarding the sustainability of groundwater resources in the region and the impacts of climate change on regional water resources. In response, communities will need to adapt management strategies to address climate variability and secure water supplies for future sustainable development. In the following sections, the current status of key aquifers and future groundwater availability in context of human impacts and climate variability will be discussed. Future research needs will be identified to advance our knowledge of groundwater hydrology in re-

sponse to climate variability, to understand factors contributing to local and regional groundwater shortages; to develop strategies that promote a sustainable groundwater supply in changing climate.

#### REGIONAL AQUIFERS WITHIN THE STUDY AREA

Within the study area, there is approximately 1,313 km (815 miles) of Rio Grande reach between Elephant Butte dam and Amistad dam (IBWC 2005), and there are six groundwater aquifer systems from upstream to downstream as shown in Fig. 1, namely (1) Jornada del Muerto basin, (2) Mesilla basin, (3) Tularosa basin, (4) Hueco Bolson, (5) West Texas bolsons including (a) Presidio-Redford; (b) Ryan flat; (c) Lobo flat; (d) Wild Horse-Michigan flat; (e) Green River Valley; (f) Red Light Draw and (g) Eagle Flat; (6)

Table 1. Summary of water uses in the region.

Aquifer (Basin)	Water rights†	Populations served	Water uses (million m <sup>3</sup> )
Jornada del Muerto	NM state	Part of Las Cruces, & rural, NM	18.5
Rincon Valley, Mesilla Basin (major aquifer)‡	NM and TX states; MX federal	1/4 of population in El Paso, TX & 97,375 in Las Cruces, & rural, NM	26.7 in 2005 (El Paso, Municipal) 108 NM (Municipal and agricultural)
Hueco Bolson-Tularosa basin (major aquifer) Southeastern Hueco Bolson	NM and TX states; MX federal	3/4 of population (649,121) in El Paso & 1,328,017 in Juarez, MX	49 in 2005 (El Paso Water Utilities) 42 (others in El Paso) 185 (Juarez) 43.5 in 1995, NM
West Texas bolsons§ (minor aquifers)	TX state; MX federal	22,545	13.7
Igneous aquifer (minor aquifer)	TX state	11,500	3.7
Edwards-Trinity aquifer (major aquifer)¶	TX state	6,147	1.7

Note: Sources are Hibbs et al. (1997), FWTWPG (2001, 2006, 2011), Paso del Norte Water Task Force (2001), New Mexico Office of State Engineer (2003).

† Groundwater law, based on doctrine of prior appropriation in New Mexico, conjunctive managed with surface water; based on English common rule of absolute ownership in TX, separate from the surface water; and the Mexican Constitution provides for private ownership of land and for landowner development and use of groundwater resources subject to federal regulation.

‡ Major and minor aquifers defined by Texas Water Development Board.

§ West Texas Bolsons aquifer system includes (1) Presidio-Redford; (2) Ryan flat; (3) Lobo flat; (4) Wild Horse-Michigan flat; (5) Green River Valley; (6) Red Light Draw and (7) Eagle Flat. Presidio-Redford underlying the Rio Grande which is shared by US and Mexican communities is used as an example in this paper.

¶ Edwards-Trinity covers much large area, here only account for four counties, Brewster, Culberson, Jeff Davis and Terrell in Far West Texas Water Planning Region.

Igneous aquifer; and (7) Edwards-Trinity (Hibbs et al. 1997, FWTWPG 2001). The Rincon valley–Mesilla basin, Hueco Bolson, and Presidio-Redford Bolson and Green River Valley aquifers of the West Texas bolsons, have direct hydraulic connection with the Rio Grande, while others are not. In general these regional aquifers can be divided into three categories, alluvium (Rio Grande Alluvium within Mesilla Basin and Hueco Bolson), basin fill (aquifers 1 through 5 listed above), and fractured rock (aquifers 6 and 7) (Hibbs et al. 1997, FWTWPG 2001).

The total annual groundwater withdrawal in the region is approximately 423 million m<sup>3</sup> (Table 1) in comparison with a normal year release of 974 million m<sup>3</sup> of surface water from the Elephant Butte reservoir, which has been used primarily for agricultural irrigation. It should be noted that the Rio Conchos also delivers approximately 432 million m<sup>3</sup> of surface water per year on average into the Rio Grande, however it is mainly used in the Lower Rio Grande below Amistad reservoir.

## GROUNDWATER AVAILABILITY AND SUSTAINABILITY

Theoretically, the quantity of water in a hydrologic system, such as a groundwater basin,

can be measured, computed, or estimated. Assuming the groundwater budget in an aquifer system is in long-term equilibrium, under predevelopment conditions inflow (recharge) into the aquifer system is approximately equal to outflow (discharge). The quantity of water stored in the aquifer system is constant or varies about some average condition in response to annual or longer-term climatic variations (Alley et al. 1999). The groundwater budget can be described by the following equations in terms of rates (or volumes over a specified period of time) as (Alley et al. 1999)

$$\sum Q_i^{\text{in}} - \sum Q_i^{\text{out}} = \Delta S \quad (1a)$$

$$\sum Q_i^{\text{in}} - \sum Q_i^{\text{out}} = 0 \quad (1b)$$

where  $Q_i^{\text{in}}$  and  $Q_i^{\text{out}}$  are each component for inflow and outflow rates and  $\Delta S$  is change in storage, reflecting annual or longer-term climatic variations. Under natural conditions, inflow (recharge) includes (1) areal recharge from precipitations through unsaturated zone to the groundwater surface; (2) recharge from losing streams, lakes and wetlands; and (3) subsurface (groundwater) inflow or interbasin exchange; while outflow (discharge) includes (1) discharge to streams, lake, wetlands, springs and saltwater

bodies (not applicable in the study area); (2) evapotranspiration; and (3) subsurface outflow (ASCE 1987, Alley et al. 1999). If we assume no change in storage occurs, equation 1b shows that the inflow is equal to outflow, which means the system reaches equilibrium.

Such equilibrium in the aquifer can be broken by pumping groundwater for use, modifying deep percolation by irrigation and urban development, changing the type of vegetation, and other anthropogenic activities. Focusing attention on the effects of withdrawing groundwater, one can conclude that the source of water from pumpage must be supplied by (1) more inflow into the aquifer system (increased recharge, for example, induced seepage from the losing surface water bodies: artificial recharge or other watershed management measures); (2) less water leaving the system (decreased natural discharge, for example, reducing evapotranspiration by lowering groundwater levels in the surficial/shallow aquifer and reducing discharge into the surface water bodies); and (3) removal of water that was stored in the aquifer system, or some combination of these three (ASCE 1987, Alley et al. 1999).

The groundwater budget can now be written as

$$\sum Q_i^{\text{in}} - \sum (Q_i^{\text{out}} + Q_i^p) = \Delta S \quad (2a)$$

$$\sum Q_i^p = \sum Q_i^{\text{in}} - \sum Q_i^{\text{out}} - \Delta S. \quad (2b)$$

As a dynamic system, pumpage  $Q_i^p$  will be achieved by increasing  $Q_i^{\text{in}}$ , decreasing  $Q_i^{\text{out}}$ , decreasing storage  $S$  or a combination of all. Once pumping starts, the aquifer system will adjust itself and try to reach a new equilibrium after some time, called aquifer system response time or time to full capture (Bredehoeft and Durbin 2009), which is defined as the time that it takes for water level and storage changes throughout the aquifer system to become negligible after an increase or decrease in withdrawal (Walton 2011). Aquifer system response time can range from days to centuries or more (Bredehoeft et al. 1982, Sophocleous 2000, Alley et al. 2002, Bredehoeft and Kendy 2008), depending on many factors, such as aquifer system dimensions, aquifer transmissivity and storativity, confining layer storage, confining layer leakance, aquifer system boundary conditions, and well location

and penetration.

Even though the groundwater budget can be calculated or estimated with acceptable accuracy, water availability or sustainability has proved to be an elusive and multifaceted concept to define in a precise manner and with universal applicability. *Water availability* is not a simple function of the quantity and quality of water in a river basin or aquifer system, but is constrained by the physical structures, laws, regulations, and socio-economic factors that control its demand and use (Alley and Leake 2004). Therefore, determining *groundwater availability* means more than calculating the volume of groundwater underlying a particular area or within an aquifer. One must also consider that some of the water may not be economically recoverable or of poor quality as well as the fact that groundwater is connected to the rest of the hydrologic system. Groundwater withdrawals can and usually do affect the amount (and quality) of surface water. For example, depletion of a small part of the total volume of groundwater in storage (sometimes only a few percent) can have substantial and undesirable effects on the availability of surface water, which becomes the limiting factor to development of the groundwater resource (Alley 2007). The Texas Water Development Board defines groundwater availability as the effective recharge plus the amount of water that can be recovered annually from storage over a specified planning period without causing irreversible harm such as land-surface subsidence or water-quality deterioration (Muller and Price 1979, Mace et al. 2001).

A number of other terms have been used to describe groundwater availability. One of them is *groundwater sustainability* that was defined by Alley et al. (1999) as “development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.” The term *safe yield* has been used and amended to quantify sustainable groundwater development (Lee 1915, Meinzer 1920, 1923, Williams and Lohman 1949, Bear and Levin 1967, Bear 1979, Domenico and Schwartz 1990, Fetter 1994, Sophocleous 1997, 2000). Zhou (2009) presented a critical review of the groundwater budget myth, safe yield, and sustainability, and concluded that both the natural recharge and the

induced recharge by dynamic development of pumping determine the safe yield or sustainable yield of a groundwater basin. The term *groundwater mining* or *groundwater overdraft* usually refers to a prolonged and progressive decrease in the amount of water stored in a groundwater system (Reilly et al. 2008), for example, in heavily pumped aquifers in arid and semiarid regions as the study area.

Groundwater is not a non-renewable resource, nor, is it completely renewable in the same manner and timeframe as solar energy (Alley et al. 1999). Groundwater availability can range from nothing to all of the drainable water from an aquifer. Therefore any method for determination of groundwater availability should recognize such characteristics. Quantifying groundwater availability requires intersection of policy and science: policy defining socio-economic and environmental goals, and science estimating the actual amount of water that can be produced based on socio-economic goals (Mace et al. 2001).

#### CURRENT STATUS: GROUNDWATER USES AND AVAILABILITY FOR SELECTED AQUIFERS

Among the six aquifer systems associated with the study area, the Hueco Bolson and Mesilla Basin aquifer systems have been used extensively for both urban water supplies and agricultural production. The other four aquifer systems have not been fully utilized. For this reason the Hueco Bolson and Mesilla Basin aquifer systems are selected for further discussion in terms of groundwater availability and impacts of groundwater pumping. Due to extensive development of groundwater, the Hueco Bolson and Mesilla Basin aquifers have experienced undesired consequences such as large water level drops, water quality deterioration and depletion of surface water. Land subsidence has been observed in Hueco Bolson aquifer system.

##### *Hueco Bolson aquifer system*

*Aquifer characterization.*—The Hueco Bolson aquifer system is located in southern New Mexico, Far West Texas, and Northern Chihuahua, Mexico with a surface coverage of approximately 6,475 km<sup>2</sup> (Hibbs et al. 1997, Hutchison and Hibbs 2008) as shown in Fig. 1 and Table 2. The Hueco Bolson consists of asymmetric gra-

bens, bounded by mountains that are mostly tilted fault blocks. The Hueco Bolson is bounded by the Tularosa Basin on the north, and these systems are hydraulically connected with each other in the subsurface (Richardson 1909, Wilkins 1986, Sheng and Devere 2005, Hutchison and Hibbs 2008, Hawley et al. 2009). The Hueco Bolson is bounded by the Franklin Mountains to the west, the Sierra Juarez, Sierra El Presidio, and Sierra Guadalupe to the south, and the Hueco Mountains to the east.

The major water-bearing formation in the Hueco aquifer system is composed of basin fill sediments that are weakly consolidated, heterogeneous material that overlie Precambrian through Tertiary-age rocks (Wilkins 1986). The basin fill includes fluvial, alluvial-fan, lacustrine-playa, and recent alluvial deposits of gravel, sand, silt, and clay (Collins and Raney 1991, Heywood and Yager 2003). The basin fill thickness decreases from a maximum thickness of 2,743 m at the central area (El Paso) to an infinitesimal thickness where the bolson thins out near Indian Hot Springs in Hudspeth County, Texas (Collins and Raney 1991, Hibbs et al. 1997, Hawley et al. 2009). The Quaternary alluvium and terrace deposits adjacent to the Rio Grande were formed by sediment deposition by the river, consisting of irregularly distributed gravels, sands, clay, and silt lenses and beds with a maximum thickness of 61 m (Alvarez and Buckner 1980, Hutchison and Hibbs 2008). Over most of the aquifer system, groundwater occurs under unconfined conditions. In the El Paso lower valley, however, groundwater is unconfined in the Rio Grande alluvium and is partially confined where sands occur in the underling bolson deposits (Davis and Leggat 1965, Gates et al. 1980). The Hueco Bolson aquifer occurs within the Upper and Middle Santa Fe strata, with water at depths of 91 m or more throughout most of the basin. Fresh water is present on the west side of the Hueco Bolson, in an upper lens, up to 350 m thick. Elsewhere water is saline (Hibbs et al. 1997).

*Groundwater budget.*—The Hueco Bolson aquifer system is recharged by limited mountain-front recharge, seepage from the Rio Grande and irrigation canals; deep percolation of agricultural irrigation in El Paso and Hudspeth County in Texas and District 009 in Chihuahua, Mexico,

Table 2. Summary of aquifers in the region.

Aquifer (Basin)	Surface drainage area (km <sup>2</sup> )	Groundwater storage (billion m <sup>3</sup> ) <sup>†</sup>	Annual recharge (million m <sup>3</sup> )	Climate	Aquifer type	Aquifer material
Jornada del Muerto	8,660	123 (A)	4.7	Semi-arid	Unconfined & confined	Basin fill (gravel, sand, silt and clay)
Rincon Valley, Mesilla Basin (major aquifer) <sup>‡</sup>	3,720 (Rincon) & 28,500 (Mesilla)	123 (A) (Wilson et al. 1981) in US portion of Mesilla Basin	5.6 (Rincon) 16 & 25–120 (river seepage)	Semi-arid	Unconfined & confined	Rio Grande alluvium deposits & basin fill
Hueco Bolson-Tularosa basin (major aquifer)	10,800 (67% in NM; 22% in TX and 11% in MX)	10 (C) (Tularosa), 11.6 (B) (El Paso, TX) 10.5 (B) (MX)	7 (Hueco) & 40.7 (Rio Grande alluvium) 52–107 (Tularosa)	Semi-arid	Unconfined with localized confinement	Basin fill sediments (sands, silt and clay) Rio Grande alluvium (140 ft in MX to 170 in US)
Southeastern Hueco Bolson	Southeastern Hueco 2,150 (61% in TX and 39% in MX)					
West Texas bolsons <sup>§</sup> (minor aquifers)	4,920 (Presidio–Redford)	8.5 (A) (US)	4.5–8.6	Sub-tropical arid	Unconfined	Basin fill & Rio Grande alluvium
Igneous aquifer (minor aquifer)	21,200	58 (A)	211	Sub-tropical	Unconfined	Igneous
Edwards-Trinity aquifer (major aquifer) <sup>¶</sup>	12,150	13.3 (A)	40	Sub-tropical arid/sub-tropical steppe	Unconfined & confined	Limestone & dolomite (Edwards group) and sands (Trinity)

Note: Sources are Hibbs et al. (1997), FWTWPG (2001, 2006, 2011), Paso del Norte Water Task Force (2001), New Mexico Office of State Engineer (2003).

<sup>†</sup> Groundwater storage was estimated by different methods. Some storage values (A) included both fresh water (Total dissolved solids (TDS) < 1,000 mg/L) and brackish/slightly saline (1,000–3,000 mg/L TDS) and moderately saline water (3,000–10,000 mg/L TDS), (B) only account for fresh water; and (C) only account for recoverable freshwater volume.

<sup>‡</sup> Major and minor aquifers defined by Texas Water Development Board.

<sup>§</sup> West Texas Bolsons aquifer system includes (1) Presidio-Redford; (2) Ryan flat; (3) Lobo flat; (4) Wild Horse-Michigan flat; (5) Green River Valley; (6) Red Light Draw and (7) Eagle Flat. Presidio-Redford underlying the Rio Grande which is shared by US and Mexican communities is used as an example in this paper.

<sup>¶</sup> Edwards-Trinity covers much large area, here only account for four counties, Brewster, Culberson, Jeff Davis and Terrell in Far West Texas Water Planning Region.

and artificial recharge of reclaimed water through deep injection wells and infiltration basins in El Paso (Knorr and Cliett 1985, Land and Armstrong 1985, White et al. 1997, Hibbs et al. 1997, Sheng 2005, Sheng and Devere 2005, Hutchison and Hibbs 2008). Mountain-front recharge is very limited due to low precipitations in an arid climate.

Before development of the aquifer and consequent heavy pumping, water in the aquifer discharged naturally to the Rio Grande. After pumping caused water levels to decline, the Rio Grande began to lose water into the Rio Grande Alluvium aquifer, which eventually recharged the Hueco Bolson aquifer. Unlined irrigation canals and laterals also leak water into the aquifer; however, the water quality varies within

the area of interest. Model analysis indicated that the recharge from the Rio Grande alluvium to the Hueco Bolson was 41 million m<sup>3</sup>/year between 1968 and 1973 (White 1987). Annual recharge from applied irrigation water was estimated about 14 million m<sup>3</sup> on average (Hutchison 2006). Lining of the Rio Grande channel in 1973 along the Chamizal zone with a low permeability grout as well as using concrete lined American Canal extension to deliver water on the US side reduced recharge by the Rio Grande significantly. A recent study by Hutchison and Hibbs (2008) concluded that induced infiltration from the Rio Grande Alluvium to the Hueco Bolson by pumping amounts more than 25% of current municipal pumping in El Paso and Ciudad Juarez.

El Paso Water Utilities has also used reclaimed wastewater to recharge the Hueco aquifer at its NE well fields since 1985. Even though facing challenges, this system has successfully recharged approximately a total of 75 million m<sup>3</sup> (on average 4.7 million m<sup>3</sup>/year) of reclaimed wastewater into the Hueco Bolson aquifer through 10 recharge wells as well as infiltration basins (after 2001) (Hahn et al. 2003, Sheng 2005; S. Reinert, *personal communication*). The Hueco Bolson also receives interbasin flow from the Tularosa Basin on the north. It was estimated 7.4 million m<sup>3</sup>/year under predevelopment condition, which has been increased to about 20 million m<sup>3</sup>/yr due to pumping in El Paso and Ciudad Juarez (Hutchison 2006).

Discharge from the Hueco Bolson aquifer under natural conditions is by direct evaporation from bare soil where the capillary fringe is near land surface, by leakage to springs and streams, by consumptive use by phreatophytes, and by interbasin and cross-formational flow (Hibbs et al. 1997). Once developed, well pumping becomes one of the discharge components of the aquifer. In fact, well pumping now accounts for the largest component of discharge from the aquifer system. Quantities of groundwater discharge due to leakage to springs and evaporation at playas are not known. Most discharge in the Hueco Bolson is due to withdrawals for municipal, industrial, and military water supply. Most of groundwater discharge from the southeastern Hueco Bolson aquifer occurs by cross-formational leakage to the Rio Grande Alluvium aquifer, which eventually discharges into the Rio Grande (Hibbs et al. 1997, Hutchison and Hibbs 2008). Along the heavily urbanized Chamizal zone, the alluvium aquifer is depleted by heavy pumping in the Hueco Bolson aquifer. Downstream from the Chamizal zone to the El Paso/Hudspeth county line, discharge occurs as irrigation pumping during droughts, and by leakage to many drains which help to maintain nearly constant water levels in the alluvial aquifer. From county line to Fort Quitman, discharge includes seepage into the river and leakage to a few drains. Consumptive use by phreatophytes is another component of discharge (Hibbs et al. 1997). Saltcedar forms dense thickets along the Rio Grande reach below Fort Quitman and consumes significant amount of groundwa-

ter from the Rio Grande Alluvium aquifer, though no accurate estimate has been reported.

*Groundwater quality.*—North of the Texas-New Mexico border, water tends to have total dissolved solids (TDS) greater than the secondary safe drinking water standard of 1,000 mg/L (Hibbs et al. 1997). Water quality in the Texas part of the Hueco Bolson tends to be asymmetrical with better quality water concentrated to the west rather than to the east, although there are pockets of good-quality water in the eastern part of the bolson (Gates et al. 1980). The upper part of the aquifer tends to be fresher with TDS ranging between 500 and 1,500 mg/L, with an average of about 640 mg/L (Ashworth and Hopkins 1995). Water quality beneath Ciudad Juarez is generally less than 1,000 mg/L TDS (Hibbs et al. 1997). Water quality in the shallow part of the alluvium aquifer along the Rio Grande has degraded because of leakage of poor-quality irrigation-return flow into the aquifer (Sheng and Devere 2005, Szykiewicz et al. 2011) and possible leakage of saline groundwater originating from an ancient playa setting buried beneath the contemporary Rio Grande floodplain (Hibbs and Merino 2006). TDS values in El Paso County vary substantially, but fall mostly within the range of 1,000 to 3,000 mg/L. TDS values are higher in alluvial deposits in Hudspeth County, falling mostly within the 3,000 to 6,000 mg/L range. TDS values are lower in the Mexican part of the floodplain aquifer due to mixing of dilute runoff waters with older, more enriched alluvial waters (Hibbs et al. 1997).

Druhan et al. (2008) identified two regional recharge sources in northern Hueco Bolson on the basis of stable isotopes deuterium ( $\delta D$ ) and <sup>18</sup>O ( $\delta^{18}O$ ) data, one originating from western mountain-fronts and another from through-flow of the adjacent Tularosa aquifer. Strong correlation between chloride concentrations and lithologic formations and both Cl/Br and <sup>36</sup>Cl ratios suggested that the elevated chloride concentration in the Hueco Bolson are attributed to dissolution of Fort Hancock halite deposits. In contrast, sulfur isotopes support that that primary source of sulfate is Tularosa basin Permian gypsum (Druhan et al. 2008). The results suggested that upconing of waters from the Fort Hancock formation is the cause for chloride salinization of wells. Eastoe et al. (2008) identi-



fied four recharge sources based on four distinct sets of stable isotopes  $\delta D$  and  $\delta^{18}O$  data: (1) Mixtures of the Rio Grande water before and after construction of Elephant Butte Dam in New Mexico, occurring beneath the Rio Grande flood plain. (2) Pre-dam Rio Grande water, occurring beneath Ciudad Juarez and the adjacent Rio Grande flood plain, showing the river's recharge to the regional aquifer in those areas before aquifer development. (3) Both ancient and modern precipitation on the Franklin and Organ Mountains, occurring on the west side of the Hueco Bolson north of the Rio Grande. (4) Precipitation on the Diablo Plateau, occurring in the southeastern part of the Hueco Bolson, north of the Rio Grande. From those study results, one can conclude that the Hueco Bolson have had different recharge sources, which resulted in complex distribution patterns of groundwater quality within the bolson.

*Groundwater availability and historic groundwater uses.*—Several groundwater availability studies have been conducted to estimate the amount of recoverable fresh, and brackish (1,000 to 3,000 mg/L TDS) groundwater in the Hueco Bolson aquifer system (Knowles and Kennedy 1956, Meyer 1976, Muller and Price 1979, White 1987, Huff 2004, Hutchison 2006). Most recent estimates by Hutchison (2006) show that the fresh groundwater (chloride <250 mg/L) storage in El Paso area is 11.6 billion  $m^3$ , while its storage in Ciudad Juarez is approximately 10.5 billion  $m^3$  (Table 2). Estimates of the quantity of fresh and slightly saline water for the southeastern Hueco aquifer cannot be derived because lithologic, geophysical, and water quality data are not sufficient to permit analysis.

Groundwater from the Hueco Bolson aquifer has been used for municipal and industrial (M&I) and domestic water supplies, and agricultural irrigation. Groundwater use for municipal water supplies in El Paso started as early as 1903 and in Ciudad Juarez in the 1910s. El Paso reached its peak annual pumpage of 86 million  $m^3$  in 1990 and thereafter continuously reduced its pumpage from the Hueco Bolson to preserve fresh groundwater (Sheng and Devere 2005). In 2010 the volume of fresh groundwater pumped from the Hueco Bolson was estimated 42 million  $m^3$  by military and other municipal utilities districts in El Paso (FWTWPG 2006), about 40

million  $m^3$  by the El Paso Water Utilities (EPWU) (S. Reinert, *personal communication*), and 185 million  $m^3$  by Ciudad Juarez (Paso del Norte Water Task Force, 2001), a total of approximate 267 million  $m^3$ . In 2010 EPWU also pumped 4.5 million  $m^3$  of brackish water for treatment and blending at its desalination plant and recharged 1.9 million  $m^3$  of reclaimed water into the aquifer (S. Reinert, *personal communication*).

*Impacts of historic groundwater development.*—As shown in Fig. 2, natural, artificial recharge, and recharge captured from the surface water (deep percolation of irrigations, seepage from the river and canals), historic pumpage, and other inflows and outflows should be balanced with an increase or decrease in groundwater storage. Using Eq. 2b, estimated inflows and outflows defined in the previous section, one can conclude that the Hueco Bolson aquifer system has been overdraft/mined because the groundwater storage has been continuously depleted. If we look at the Hueco Bolson aquifer in the El Paso and Ciudad Juarez areas, groundwater has been mined since 1950s even with increased lateral interbasin flow from the Tularosa Basin, increased cross-formational flow from the Rio Grande alluvium aquifer, and reduced discharge into the river and lateral flow downgradient southeastern Hueco Bolson. The depletion of storage continuously increased up to 140 million  $m^3$ /yr until 1990s when El Paso reduced its pumpage from the Hueco Bolson (Hutchison and Hibbs 2008).

In 2010 the total pumpage from the Hueco Bolson amounted approximately 267 million  $m^3$ . The amount was offset by the inflow terms discussed above: the increased interbasin flow from Tularosa (20 million  $m^3$ ), cross-formational flow from the alluvium aquifer (25% of El Paso and Ciudad Juarez municipal pumping, or approximately 56 million  $m^3$ ), as well as limited mountain front and artificial recharge (approximately 8.6 million  $m^3$ ), and the reduced discharge, which consisted of induced reversed flow from the east of El Paso (12 million  $m^3$ ) based on Heywood and Yager's (2003) groundwater model simulation (Hutchison 2006). The remaining pumpage is simply supplied by the fresh groundwater storage of approximately 170 million  $m^3$ . It is very similar to estimates from other studies (Hutchison and Hibbs 2008). It should be

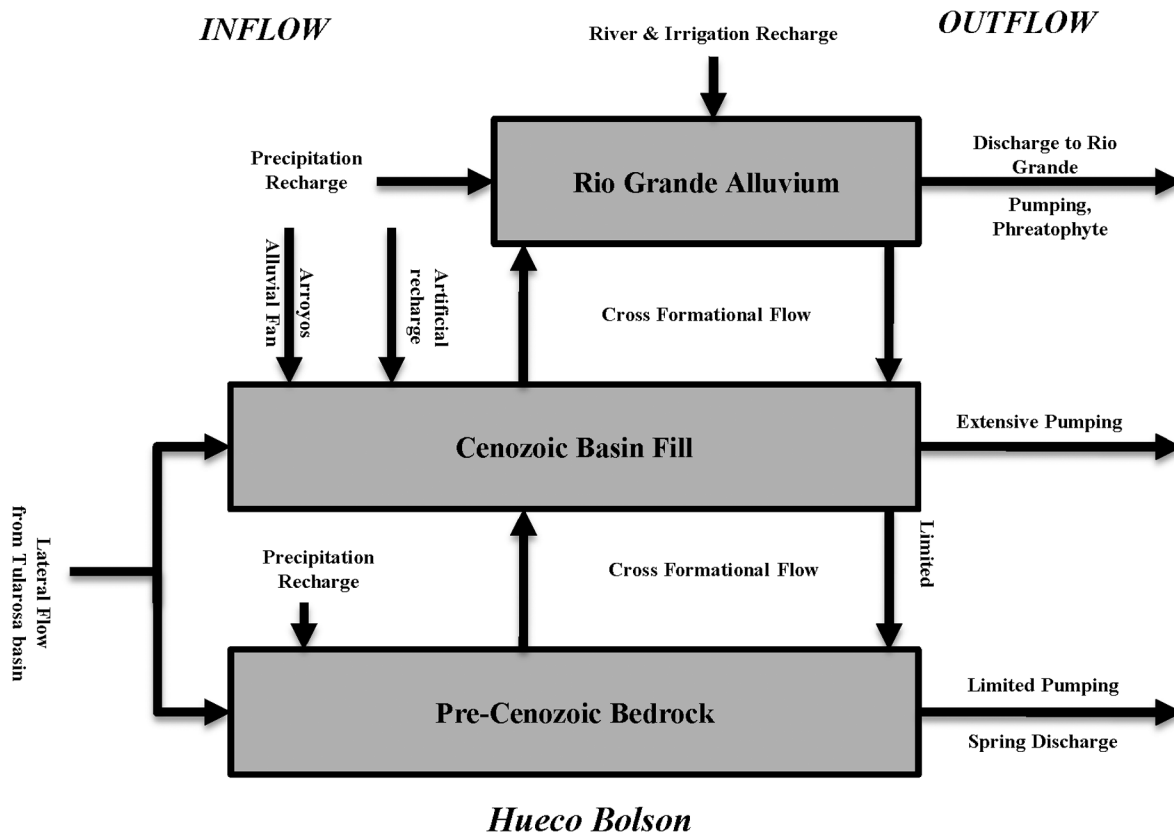


Fig. 2. Major flow components in the Hueco Bolson aquifer system (modified from Hibbs et al. 1997).

noticed that depletion of fresh water storage may be in fact greater than the calculated values because cross-formational flow and interbasin flow contain poor quality water (chloride >250 mg/L). Moreover, if the Rio Grande Alluvium aquifer does not receive the same amount of infiltration as the cross-formational flow, we are also mining groundwater from the Rio Grande Alluvium aquifer.

As a result of groundwater overdraft, the groundwater level has dropped over time. The largest groundwater level drop is up to 46 m at the El Paso Airport wellfield (Hibbs et al. 1997, Sheng and Devere 2005, Hutchison 2006). Cones of depression were formed at pumping centers in both El Paso and Ciudad Juarez and continue to deepen within the pumping centers with recoveries in some areas where pumping has been stopped (Sheng and Devere 2005, Hutchison 2006). The flow patterns across the NM/TX state line and borderline between El Paso and Ciudad Juarez have been changed due to historical

pumping, which further complicates the management of fresh water resources in the aquifer. Across the New Mexico-Texas state line, groundwater generally flows from north to south. Prior to large scale municipal pumping by EPWU in the early 1960s, the average annual groundwater underflow from New Mexico to Texas was approximately 7.4 million m<sup>3</sup> based on a groundwater model simulation (Heywood and Yager 2003, Sheng and Devere 2005). It has been increased to about 20 million m<sup>3</sup>/yr due to pumping in El Paso and Ciudad Juarez (Hutchison 2006). This amount includes both fresh and brackish waters. Prior to about 1960, groundwater flowed from Ciudad Juarez to El Paso. The flow across the border increased from 1.5 million m<sup>3</sup>/year of predevelopment to 6.2 million m<sup>3</sup>/year in the 1930s. Since 1960, increased pumping in Ciudad Juarez caused reversal of the flow direction. In 2002, this flow was about 39 million m<sup>3</sup>/year (Sheng and Devere 2005, Hutchison 2006). However the majority of cross-border

flow is brackish water from vertical flow from the Rio Grande Alluvium aquifer and lateral flow of the deep Hueco Bolson Aquifer.

Naturally occurring brackish or slightly saline (1,000 to 3,000 mg/L TDS) waters surround the thin freshwater zone of the Hueco Bolson aquifer (Hibbs et al. 1997). The fresh water section thins to less than 30.5 m toward the Hueco Mountains. Brackish water underlies the fresh water zone. Groundwater in the Rio Grande alluvium in the El Paso lower valley is predominantly slightly saline/brackish water in El Paso County, and moderately saline or of poor quality in Hudspeth County (Alvarez and Buckner 1980, Gates et al. 1980). In the city artesian area (downtown of El Paso to Ysleta) at the northern end of El Paso lower valley, the water in the Rio Grande alluvium is of poorer quality than the water in the underlying bolson deposits, but at many locations down the valley, the water in the alluvium is of better quality than the water underlying the bolson deposits. Soluble material in the fine-grained, predominantly playa-lake bolson deposits, and the lack of groundwater circulation at depth probably accounts for the poor-quality water in the basin fill in the El Paso lower valley (Druhan et al. 2008). Brackish water intrusion into the freshwater zone is due to leakage from mud interbeds and artesian-confining beds, cascading waters along well casings and screens, lateral brackish water encroachment, potential upconing of underlying brackish water, and movement of high salinity drain water in the lower valley (Druhan et al. 2008). With continuous pumping from both Ciudad Juarez and El Paso, both cities have experienced water quality degradation due to lateral brackish water intrusion into the fresh water zones in addition to the large water level drawdowns (Eatoe et al. 2008). Heavy pumping decreases hydraulic heads at or near centers of pumpage, which induces the movement of surrounding brackish water into the fresh water zone. In addition, brackish water intrusion from irrigation return flow drains continues to expand laterally and vertically, thereby degrading water quality in the shallow alluvium aquifer along the Rio Grande (Druhan et al. 2008, Eastoe et al. 2008).

Water quality deterioration further reduces the availability of fresh water from the aquifer despite measures that have been implemented

to reduce the rate of deterioration, including reduction of pumpage and artificial recharge into the aquifer. Water quality in the aquifer has been affected by the large water-level declines that have induced flow of poor-quality brackish water into areas of fresh water. Brackish water intrusion into the fresh water zone increases the concentration of TDS, chloride and sulfate in Airport and Northeast wellfields in El Paso to the extent that it exceeds the safe drinking water standards (Sheng and Devere 2005, Druhan et al. 2008). The rate of groundwater quality deterioration in some wells has accelerated with time due to continuous overdraft of the aquifer. A composite graph (Fig. 3) shows measured groundwater quality changes at EPWU well number 84 (Texas State Well No.: JL-49-22-125) in southeast El Paso (Sheng and Devere 2005).

With an increase of groundwater pumping after 1979, TDS concentrations increased from about 800 to 1,200 mg/L after 10 years of pumping. Chloride and sulfate concentrations also increased. They all exceeded the Secondary Safe Drinking Water Standards, i.e., 1000 mg/L for TDS and 250 mg/L for chloride and sulfate. Recent reduction in pumpage and operation of a brackish groundwater desalination plant in El Paso are anticipated to reduce depletion of fresh groundwater storage and slow down intrusion of brackish water into the fresh groundwater zone (Sheng and Devere 2005, Hutchison 2006).

In addition, groundwater overdraft has resulted in land subsidence near the Chamizal Park in El Paso (Land and Armstrong 1985, Heywood 1995, 2003). The observed subsidence reached 0.3 m in El Paso, Texas. Land subsidence could further limit the recoverable volume of fresh groundwater. Therefore future groundwater availability is no longer a simple groundwater budget issue because of the impacts of groundwater pumping on water quality and environment as mentioned above. Understanding these impacts and cost of pumping will be a key to solution for determination of future groundwater availability.

#### *Mesilla Basin aquifer system*

*Aquifer characterization.*—The Mesilla Basin aquifer system extends south from southern New Mexico to Far West Texas and northern Chihuahua, Mexico, with a surface drainage area

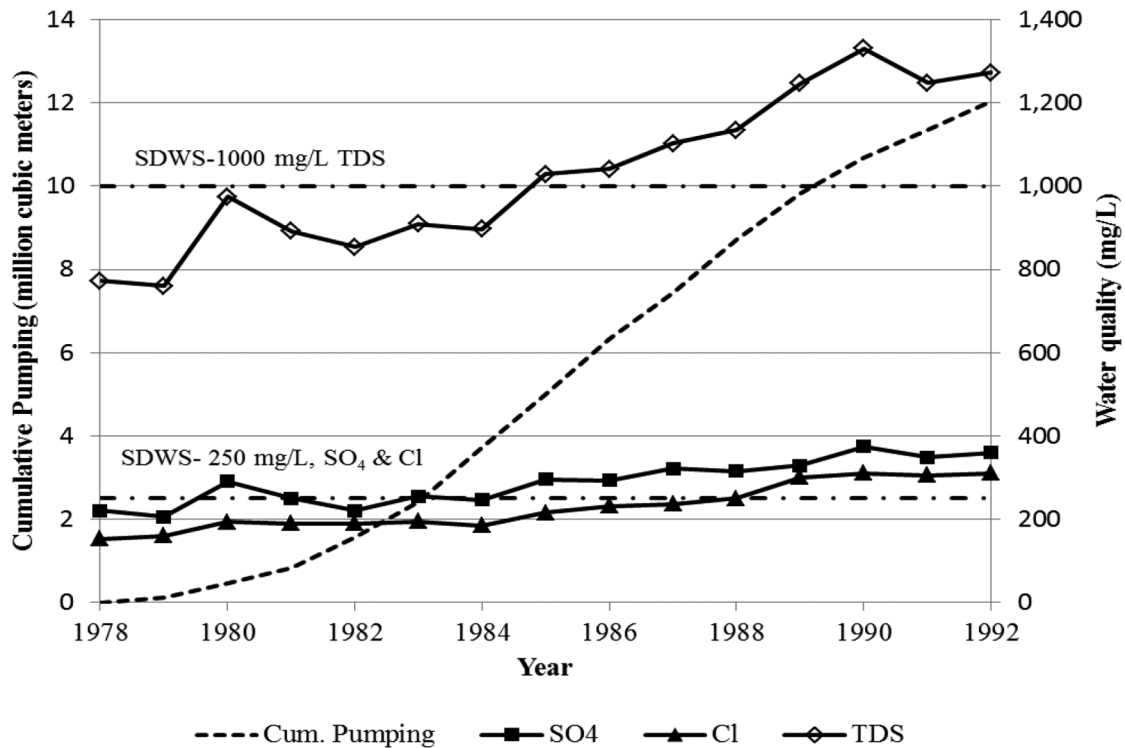


Fig. 3. Measured water quality changes with groundwater pumping for the EPWU Well #84 (JL-49-22-125) (modified from Sheng and Devere 2005).

of 28,500 km<sup>2</sup> (Hibbs et al. 1997, Hawley and Kennedy 2004) as shown in Fig. 1 and Table 2. The Mesilla Basin aquifer system is an extensive intermountane aquifer system. On the east it is bounded by the Organ-Franklin-Juarez Mountain chain, on the west it is bounded by fault-blocks and volcanic uplands that extend northward from the East Potrillo Mountains and West Potrillo basalt field to the Aden and Sleeping Lady Hills blocks. The Robledo and Doña Ana Mountains form the northern boundary of the Mesilla Basin, while the northeastern boundary is transitional with the Jornada del Muerto Basin (Seager et al. 1987). Finally, the Mesilla Basin is bounded on the south by the Bolson de los Muertos in north-central Chihuahua. The entrenched Mesilla Valley of the Rio Grande crosses the eastern part of the larger Mesilla Basin (Hawley and Kennedy 2004). The topographic and structural gaps between the Franklin Mountains and Sierra Juarez separate the Mesilla Basin from the Hueco Bolson.

The major productive formation in the Mesilla

Basin aquifer system is basin fill sediments, consisting of unconsolidated and heterogeneous materials of late Pleistocene to Holocene-age Rio Grande alluvium deposits, and the upper Tertiary and Quaternary deposits of Santa Fe Group (Vanderhill 1986, Hibbs et al. 1997). The floodplain alluvium and basin fill deposits within the Mesilla Valley, consisting of a mixture of gravel and coarse sand, form the shallow zone. The Santa Fe Group formation below the floodplain alluvium includes alternating layers of silty clay, fine to coarse-grained sand, and some gravel. The deep zone of the Santa Fe Group aquifer consists of more uniform fine- to medium-grained silt and clay (Nickerson 1989). The Santa Fe Group is subdivided into three hydrostratigraphic units (HSUs): upper, middle and lower (Frenzel 1992, Hawley and Kennedy 2004).

The most-productive aquifer zones vary in thickness from about 91 m in the northern and southernmost parts of the basin to over 610 m in and near the eastern basin sector, which underlies the Mesilla Valley corridor from the Las

Cruces metropolitan area to near Canutillo, Texas and La Union, New Mexico (Hibbs et al. 1997, Hawley and Kennedy 2004). The alluvium deposits are about 18 to 24 m thick below the intervalley floor, which is locally as much as 8 km wide. In many places, the fluvial facies extend laterally for hundreds of meters beyond the valley floor. The basal-channel gravel and sand layer, which is as much as 9 to 12 m thick, was deposited during the interval of maximum valley incision near the end of the Late Pleistocene ice age (Wilson and White 1984, Hawley and Kennedy 2004). The Rio Grande alluvium aquifer is unconfined, while the Santa Fe Group is a leaky-confined aquifer. Regional groundwater and surface water flow toward “El Paso del Norte”.

*Groundwater budget.*—The majority of recharge to the floodplain alluvium is provided by seepage from the Rio Grande and its tributaries and percolation from applied irrigation water. A small amount of underflow probably recharges the alluvium at Selden Canyon adjacent to the northern end of Mesilla Basin (Frenzel 1992, Hibbs et al. 1997). Recharges from precipitation and interbasin groundwater inflow are considered minor (Wilson et al. 1981). Mountain front recharge from Franklin Mountains and West Mesa was estimated at 3.1 million m<sup>3</sup> per year by assuming that most mountain-front and slope recharge occurs as infiltration from ephemeral stream beds in response to local rain storms (S.S. Papadopulos and Associates 2007). The net recharge to the aquifer is directly related to the Rio Grande streamflow and the volume of river water used for irrigation (Nickerson and Myers 1993).

Most groundwater discharge from the Mesilla Basin aquifer takes place in the vicinity of the valley-margin and floodplain surfaces (Nickerson and Myers 1993). The discharge from the Mesilla Basin includes: flow to agricultural drains; discharge to the Rio Grande in the gaining reaches of the stream; well pumpage; evapotranspiration; and discharge as interbasin groundwater outflow (Wilson et al. 1981). When the water table in the floodplain alluvium aquifer intersects a drain channel, discharge to the channel occurs. Some drains flow year round, while others flow periodically, varying with water levels in the shallow water table. Much of

the irrigation water that infiltrates to the water table is thus returned by drains to the river (Nickerson and Myers 1993). Discharge to the Rio Grande from the shallow aquifer in the gaining reaches of the river occurs when the potentiometric surface of the aquifer rises above the river stage. Seepage investigations show that the Rio Grande is usually a losing stream through most of the Mesilla Valley. Portions of the river, however, are gaining. Gains have been reported between Leasburg Dam and Las Cruces (Wilson et al. 1981) and immediately upstream from the El Paso Narrows in the southern end of the Mesilla Valley. Groundwater is the primary source of irrigation water for about 2025 ha in the Mesilla Valley, and is a supplemental source of supply for about 28,350 ha that receive surface water supplies from Elephant Butte Irrigation District, and, presumably, for some irrigated lands in Texas (S.S. Papadopulos and Associates 2007). The Mesilla Basin aquifer system also provides groundwater for municipal and industrial supplies and is a primary source of domestic use for the cities of Las Cruces, New Mexico and El Paso, Texas as well as several smaller towns (Hibbs et al. 1997, S.S. Papadopulos and Associates 2007). Consumptive uses of groundwater by phreatophytes such as tamarisk account for another type of discharge of the aquifer.

*Groundwater quality.*—Water quality in the Mesilla Basin varies both areally through the valley as well as vertically through the aquifer layers. Gelhar and McLin (1979) showed that groundwater TDS at the base of the alluvium ranges from 1,000 mg/L in the northern part of valley to more than 8,000 mg/L in the southern portion. The Santa Fe group formation yields much better quality water at approximately 500 to 700 mg/L (Conover 1954).

Witcher and others (2004) conducted an investigation of salinity sources by using a combined interpretation of groundwater isotopic signatures and major cation and anion compositions. The results show that saline and brackish water from deeper HSUs and geothermal water have Cl/Br ratios greater than 600 to 800, <sup>87</sup>Sr/<sup>86</sup>Sr ratios greater than 0.710, and heavier isotopes deuterium (δD) and <sup>18</sup>O (δ<sup>18</sup>O) than upper HSUs non-thermal water. However groundwater in the deeper HSUs and geothermal water have lighter δD and δ<sup>18</sup>O than the water from the Rio Grande.

The salinity balance in the Rio Grande during the last 40 years for the Mesilla Basin is positive, meaning that more salts are entering the basin than are transported by the Rio Grande out of the basin at El Paso (Witcher et al. 2004, Sheng et al. 2010). Higher salinity in shallow groundwater and the Rio Grande in the southern and southeastern Mesilla Basin is probably dominated by structurally forced upwelling of brackish and saline water from deep HSUs and by upflow of geothermal water from shallow bedrock structures and bedrock boundaries (Witcher et al. 2004). The brackish groundwater from the shallow aquifer is discharged into the irrigation drains and flows back into the Rio Grande. This leads to an increase in salinity of the river water as it flows through the Mesilla Basin and Hueco Bolson (Hernandez 1978). Additionally, pumping in the intermediate and deep Mesilla Basin aquifers has affected groundwater flow by causing the downward migration of brackish groundwater from the shallow aquifer. The migration of this water will eventually cause degradation of the intermediate aquifers (Walton et al. 1999).

*Groundwater availability and historic groundwater uses.*—The volume of fresh groundwater in storage beneath the Mesilla Valley has been estimated by the product of a specified saturated thickness of the aquifer, a surface extent of the aquifer, and a specific yield of the aquifer. Wilson and others (1981) estimated a total of 81 billion  $m^3$  of freshwater in storage within the thickest zone generally following the present course of the Rio Grande and an additional 42 billion  $m^3$  beneath the West Mesa. Avalos (1994) estimated a total of 106 billion  $m^3$  by assuming the freshwater to be limited to the top two layers of the aquifer, with an average thickness of 213 m and an surface extend of about 247,860 ha and a specific yield of 0.2 (Frenzel and Kaehler 1990).

The degree of groundwater pumping within the Mesilla Basin aquifer system, largely for agriculture, varies depending on the availability of surface water. For example, in 2004 surface water releases from Elephant Butte Dam were reduced due to drought conditions and supplemental groundwater was increased up to 190 million  $m^3$ , more than double its long-term average of 86 million  $m^3$ /year (S.S. Papadopoulos and Associates 2007). Groundwater pumping for

municipal supplies has also been continuously increased since the 1950s. In 2004, New Mexico M&I and domestic users used a total of 53 million  $m^3$  of groundwater; while El Paso Water Utilities in Texas pumped a total of 32 million  $m^3$ . A total of 275 million  $m^3$  of groundwater were pumped for both agricultural applications and urban water supplies in 2004 (S.S. Papadopoulos and Associates 2007). Based on budget estimate from a groundwater model simulation (S.S. Papadopoulos and Associates 2007), in 2004 the aquifer received seepage of 138 million  $m^3$  and deep percolation of 105 million  $m^3$  as well as reduced natural recharge due to drought. As a result, groundwater storage in the aquifer was used to compensate the remainder of the pumped volume of 32 million  $m^3$ . It should be noted that the evapotranspiration of riparian vegetation will cause further depletion of the aquifer storage.

*Impacts of historic groundwater development.*—Municipal pumping has caused localized cones of depression in the Las Cruces and Canutillo wellfields in the Mesilla Basin, which has a significant regional impact on the direction of groundwater flow (Hibbs et al. 1997). Trends in water level changes vary for different aquifer layers (alluvium aquifer, upper Santa Fe group, middle Santa Fe group, and lower Santa Fe group) as shown by monthly water level monitoring data (Nickerson 2011) at the Canutillo wellfield nested well monitoring site CWF1 (Fig. 4). At this site the water level in the shallow alluvium aquifer (CWF1A, blue dash line in Fig. 4) has remained unchanged since 1985 with the exception of some seasonal variations, which demonstrate the close hydraulic connection with surface water. The water level in upper Santa Fe Group (CWF1B, black line in Fig. 4) shows a few meters of drawdown with a seasonal variation of several meters over 25 years. The water level in the middle Santa Fe Group (CWF1C, green line in Fig. 4) shows a clear trend of drawdown (greater than 6 m over the last 25 years) with a greater seasonal variation (greater than 15 m between irrigation and non-irrigation seasons). Water levels in the lower Santa Fe Group also show a clear trend of drawdown (greater than 3 m over 25 years) with a large seasonal variation (greater than 18 m of seasonal variation). The largest drawdown occurs in summer when

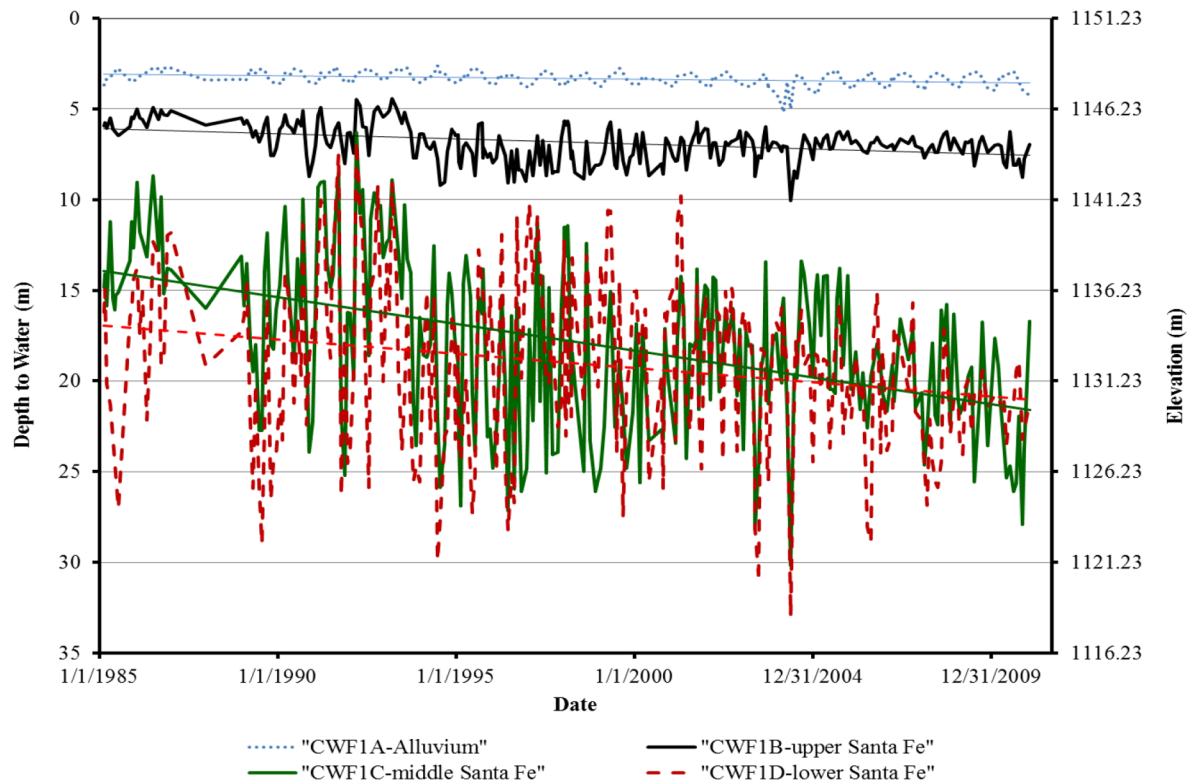


Fig. 4. Water level changes with time at the nested monitoring site CWF1 in Mesilla Basin (Nickerson 2011). CWF1A screened at depth from 13.72 to 15.24 m; CWF1B screened at depth from 45.42 to 46.94 m; CWF1C screened at depth from 99.67 to 101.19 m; CWF1D screened at depth from 242.62 to 244.14 m.

municipal wells pump at their high capacity to meet high water demand, and groundwater levels recovers in the late fall and winter. Based on the difference between hydraulic heads in different aquifer layers, one can conclude that groundwater may move downward from the alluvium aquifer to the upper Santa Fe Group aquifer through leaky confining layer. Groundwater continues its vertical movement downward into the middle Santa Fe Group through leaky confining layer. The exchange between the middle Santa Fe Group aquifer layer and the lower Santa Fe Group layer shows a more complex pattern, such as large variations in hydraulic heads and frequently reversed flow directions occurring within the season.

Walton and others (1999) studies groundwater quality in different aquifers, and concluded that pumping in the intermediate and deep Mesilla Basin aquifers has affected ground-water flow by causing the downward migration of brackish

ground water from the shallow aquifer. The migration of this water will eventually cause degradation of the intermediate aquifers. Szykiewicz and others (2011) identified zones of mixing between recharging irrigation water and groundwater within the depth range of ~50–200 m below the land surface in the Mesilla Basin based on the  $\delta^{34}\text{S}$  of dissolved  $\text{SO}_4$  in the Rio Grande. The results also indicated that Na-K-Cl concentrations in the aquifer were largely attributable to geological sources, and  $\text{SO}_4$ -Mg-Ca concentrations to anthropogenic sources. No land subsidence and other detrimental environmental impacts have been reported for the Mesilla Basin aquifer system yet. It is worth noting that in 2010 Ciudad Juarez started to pump groundwater from its wellfield in the Conejos Medanos aquifer, which is hydraulically connected to the Mesilla Basin. The impacts of future pumping by Ciudad Juarez on the groundwater flow along the borderline and

groundwater availability should be further evaluated.

### LEGAL CONSTRAINTS ON GROUNDWATER AVAILABILITY

Groundwater in these selected aquifers flows across the state line and international border. Therefore its use is regulated by different water laws, regulations, and institutions. Like most western states, New Mexico water law is based on the doctrine of prior appropriation or “first in time—first in right”. All waters in New Mexico are declared to be public and subject to appropriation for beneficial use, which is the “basis, the measure, and the limit” of the right to use water. Under this doctrine, the first user in time of water (senior appropriator) has the right to take and use the water against subsequent users (junior appropriator) during periods of drought when there is not enough water to supply water for all appropriators (NMOSE 2005, Franks 2007). In 1931 the New Mexico legislature enacted the groundwater code and extended the state engineer’s responsibility to include the administration of groundwater only within declared groundwater basins. The groundwater code states that groundwater will be subject to State Engineer jurisdiction only after the State Engineer issues an order declaring a groundwater basin that has reasonably ascertainable boundaries. Prior to the declaration of a groundwater basin, basic common law principles, such as priority of right and beneficial use as the basis, measure, and limit of right, govern the use of groundwater. In 1950s new groundwater appropriations caused depletion of surface water from the streams that are hydraulically connected with the underlying aquifer. As a result “surface water offsets” are required to address such depletion. A key issue in the lower Rio Grande Basin (including Mesilla and Rincon valleys) is the priority date assigned to groundwater users in the pending adjudication as it will determine their requirement to obtain “offset water” for effects that groundwater users have on the Rio Grande in the event that they have priorities junior to 1906 (NMOSE 2005).

Groundwater law in Texas is based on the English common law rule of “absolute ownership.” Texas follows the Rule of Capture in

determining ownership of groundwater (Kaiser 1986, Kaiser and Skillern 2001, Kaiser 2005). Under this rule groundwater belongs to the owners of the land above it. Recent passed Senate Bill 332 clearly stated that the landowners have a vested ownership interest in the groundwater beneath their property. It granted that the landowner may withdraw groundwater without limitations and without being liable to neighboring landowners for any harmful effects resulting from the withdrawal. Texas groundwater law has often been called the “law of the biggest pump”, i.e., the deepest well and most powerful pump get the water. Even though the Texas Legislature has the ultimate regulatory authority over groundwater management, it has delegated this responsibility to local groundwater conservation districts (Kaiser 2005). To date, 98 local groundwater conservation districts have been established throughout the state and one more are awaiting for confirmation (TCEQ 2011). Chapter 36 of Texas Water Code (TCEQ 2011) gives these districts extensive legal authorities that enable them to manage groundwater resources, including permitting water wells, developing a comprehensive management plan, and adopting the necessary rules to implement the management plan. They can register and permit wells, keep drilling and well records, regulate well spacing and production, require a permit for water transfers, buy and sell water, undertake aquifer storage and recovery projects, levy taxes and pumping fees, and generally engage in projects to conserve and protect the aquifer (Kaiser 2005, TCEQ 2011).

The main law governing water resources management in Mexico is the National Water Law of 1992, revised on April 29, 2004 (Wilder and Lankao 2006). In Mexico ownership of the lands and waters within the boundaries of the national territory is vested originally in the Nation, which has had, and has the right to transfer title thereof to private persons, thereby constituting private property. Groundwater may be pumped by wells or other methods and utilized by the surface owner. However the Mexican Federal Executive may regulate groundwater extraction, and even establish prohibited areas if the public interest requires or use of groundwater by others is affected. According to the Law key functions in the sector are the



responsibility of the federal government, through the National Water Commission (CONAGUA or CNA). CONAGUA's mission is to "manage and preserve national water resources, with the participation of the society, to reach a sustainable use of the resources." Two key instruments of water resources management at the disposal of the CONAGUA are permits and abstraction charges. The 2004 amended National Water Law aims to restructure CONAGUA key functions through the transfer of responsibilities from the central level to subnational entities: the Basin Authorities (BAs) and Basin Councils (BCs). Under the guidance of BCs and CONAGUA, BAs are expected to be responsible for formulating regional policy, designing programs to implement such policies, conducting studies to estimate the value of the financial resources generated within their boundaries (water user fees and service fees), recommending specific rates for water user fees, and collecting them (Wilder and Lankao 2006, Scott and Banister 2008).

#### CLIMATE CHANGE IMPACTS ON GROUNDWATER RESOURCES

The warming rate in the Southwest (four corners region) over the last 50 years is 0.21°C per decade, which is almost double that over the last 100 years (Karl et al. 2009). In the past 30 years, the southwest warming rate has increased to 0.37°C per decade. Apparently, in the past 30 years, the southwest warming rate is higher than that of the contiguous U.S.'s (0.31°C per decade), which is higher than the global warming rate (Karl et al. 2009). As of 2009, much of the Southwest and the West remains in a drought that began around 1999 (Karl et al. 2009). Seager and others (2007) showed that there is a broad consensus among climate models that the Southwestern North America will be drier in the 21st century and that the transition to a more arid climate should be under way. McCabe and Wolock (2007) showed that if future warming occurs in the Colorado River basin and is not accompanied by increased precipitation, the basin is likely to experience periods of water supply shortages more severe than those inferred from the long-term historical tree-ring reconstruction. Barnett and others (2008) analyzed

water supplies in the western United States using a high-resolution hydrologic model forced by a global climate model. The results show that up to 60% of the climate-related trends of river flow, winter air temperature, and snow pack between 1950 and 1999 are human-induced. They further forecast water shortages, lack of storage capability to meet seasonally changing river flow, transfers of water from agriculture to urban uses, and other critical impacts of climate variations.

In arid and semiarid regions such as the study area, we simply live in drought all the time. Groundwater from the regional aquifers serves as sole source of water supplies or supplements to limited surface water resources. In addition to impacts of groundwater pumping, a prolonged drought period can further lower groundwater level to the point at which shallow wells may go dry and result in non-reversible effects such as land subsidence. Therefore use of groundwater resources for mitigating effects of droughts is likely to be more effective with advance planning for drought contingency. Both Texas and New Mexico have been continuing their efforts in developing regional water plans (NMOSE 2006, FWTWPG 2011).

#### *Impacts on water quantity*

No specific study has been conducted to assess impacts of recent global warming on recharge and discharge in the Hueco-Tularosa aquifer system. As discussed in the previous section, widespread water-table declines accompanied urban development and agricultural production during the twentieth century, demonstrating that sustainable groundwater supplies are not guaranteed when part of the extracted resource represents paleorecharge. For example, the carbon 14 dating of groundwater samples showed that groundwater is 12,000 year old near the New Mexico/Texas state line (Anderholm and Heywood 2003). Therefore, we are mining ancient groundwater. Groundwater recharge in the arid and semiarid southwestern United States is a sensitive function of the climatic factors, local geology, topography, and land use across widely ranging spatial and temporal scales. Climatic controls on groundwater recharge range from seasonal cycles of summer monsoonal and winter frontal storms to multimillennial cycles of glacial and interglacial periods. Precipitation patterns

reflect global-scale interactions among the oceans, atmosphere, and continents. Large-scale climatic influences associated with El Niño and Pacific Decadal Oscillations strongly, but irregularly, control weather in the study area, so that year-to-year variations in precipitation and groundwater recharge are large and difficult to predict. Any anthropogenically induced climate change will likely reduce groundwater recharge through diminished snowpack at higher elevations in arid regions (Stonestrom et al. 2007).

It is difficult to quantify groundwater recharge in arid settings due to its low amount, its spatially and temporally spotty nature, and the lack of techniques for directly measuring fluxes entering the saturated zone from the unsaturated zone. Deep water tables in arid alluvial basins correspond to thick unsaturated zones that produce up to millennial time lags between changes in hydrologic conditions at the land surface and subsequent changes in recharge to underlying groundwater. Analysis of recharge patterns shows that large expanses of alluvial basin floors are drying out under current climatic conditions, with little to no recharge to underlying groundwater (Walvoord et al. 2004). Groundwater recharge occurs mainly beneath upland catchments in which thin soils overlie permeable bedrock, along ephemeral channels in which flow may average only several hours per year, and in active agricultural areas (Stonestrom et al. 2004, Stonestrom et al. 2007). If the surface water delivery were affected by global warming droughts in the near future (NMOSE 2006, TWDB 2008), the deep percolation from the irrigation field and seepage from the river and irrigation canals and laterals would be reduced, in turn causing reduction in inflow terms in groundwater budget and probably affects long-term groundwater availability. Variations in aquifer recharge not only change the aquifer yield or discharge, but also modify the groundwater flow network, e.g., gaining stream may suddenly become losing streams, and groundwater divides may move position. Dry drain beds during the drought in the region and changes in interaction patterns between the Rio Grande and shallow alluvium aquifer have demonstrated such effects. Groundwater discharge is another key element in the water cycle which includes loss of water from the aquifer to

surface water, to the atmosphere and abstraction for human needs. The global warming droughts could reduce surface water delivery and in turn increase groundwater pumpage to supplement surface water shortage.

#### *Impacts on water quality*

Climate change is expected not only to affect input (recharge) and output (discharge), but also influence the quality of the groundwater. For example, water recharged during a dry period may have a higher concentration of salts and hence higher TDS, while during a wet period the converse may occur (Sukhija et al. 1998). To assess such impacts long-term monitoring of rainfall and groundwater quality is required. It is also possible to link the occurrence of certain ions in groundwater to particular water-rock process that occurred during specific past climate periods. As discussed in a previous section, Eastoe et al. (2008) used O and H isotopic data to identify different recharge sources, which could help to identify unrecognized water resources. Druhan and others (2008) used isotopic data to identify two recharge sources and explain the mechanisms of chloride salinity originated from the dissolution of halite.

Szynkiewicz and others (2009) tried to reconstruct paleo-environmental conditions for the saline playa lakes of the Rio Grande Rift by identifying sediment sulfate sources using sulfur isotope compositions of dissolved  $\text{SO}_4^{2-}$  ions in modern surface water, groundwater, and  $\text{SO}_4^{2-}$  precipitated in the form of gypsum sediments deposited during the Pleistocene and Holocene in the Tularosa Basin. The results indicated that in the Tularosa Basin there was negligible effect of microbial sulfate reduction on the  $\delta^{34}\text{S}$  values of the gypsiferous sediments due to higher annual temperatures (15–33°C) and lower organic carbon content (median 0.09%) in those sediments than other source of recharge. This condition leads to efficient oxidation of  $\text{H}_2\text{S}$  and/or small rates of sulfate reduction (Szynkiewicz et al. 2009). The White Sands region of the Tularosa Basin has high temperatures of groundwater (33.3°C) and high  $\delta^{18}\text{O}$  values (1.1‰). They are controlled predominantly by seasonal evaporation rather than the modern influx of hydrothermal fluids. High evaporation rates and groundwater recharge associated with salt-rich

sedimentary rocks can increase the solute content of rivers and shallow aquifers; however, agricultural activity, including evapotranspiration and the application of fertilizers, can also degrade water quality and increase salinity.

### NEED FOR RESEARCH

Climate change is inevitable. Some of aquifers have been greatly stressed by human groundwater uses, while others have not been fully developed. All aquifers may have been impacted by climate variability in one way or another, for example, prolonged drought may have resulted in deterioration of groundwater quality in shallow aquifers, stopped the spring discharge from some aquifers, and reduced groundwater storage. Historical groundwater overdraft in El Paso and Ciudad Juarez has caused large groundwater drawdowns, deterioration of groundwater quality, and land subsidence in Hueco Bolson. Measures have been taken to control the groundwater pumpage, in hopes of sustaining groundwater availability for future water supplies. Depletion of groundwater storage will continue until alternative water sources become available and the pumpage from this aquifer system is reduced. Similar impacts have been observed across southwest and other arid regions around world (Zektser et al. 2004, Ma et al. 2005, Barnett et al. 2008).

To develop adaptive management strategies for climate variability, we need to have a good understanding of hydrologic process in the regional aquifer system, groundwater availability in terms of quantity and quality, and impacts of climate change on groundwater availability. We need to develop tools/water management strategies to address issues related to groundwater availability and climate variability. Currently, the United States-Mexico Transboundary Aquifer Assessment Program is being conducted by Water Resources Research Institutes in Arizona, New Mexico and Texas in partnership with the U.S. Geological Survey (USGS) and in collaboration with appropriate federal, state agencies, and stakeholders as well as Mexican counterparts through International Boundary and Water Commission. The purpose of this Program (Michelsen et al. 2010) is to conduct binational scientific research to systematically assess priority trans-

boundary aquifers, namely Hueco Bolson and Mesilla Basin-Conejos Medanos in New Mexico, Texas and Chihuahua. The results of this program are providing essential new information and a scientific foundation for state and local officials to address pressing water resource challenges in the U.S.-Mexico border region (Michelsen et al. 2010).

In addition to the transboundary aquifer assessment, the Rio Grande Salinity Management program sponsored by U.S. Army Corps of Engineers and the states of New Mexico and Texas aims to developing cost-effective strategies to control river water salinity in the Rio Grande. It is anticipated to provide benefits to both agricultural water users and urban water suppliers (Michelsen et al. 2009). If salinity control strategies are implemented, surface water quality will be improved. As a result, groundwater availability will be enhanced since surface water is one of the major recharge sources to regional aquifers.

To enhance the ongoing research programs in the region, the following research needs are identified:

- Monitor water levels and water quality in the regional groundwater systems in response to development and changes in climate on a regular basis so groundwater flow paths can be identified and the amount of water available for use and the ramifications of using the resource can be quantified; Integrate historic pumping data and monitoring data into a coordinated water resources database, which can be accessed for timely data sharing and decision making.
- Assess interactions among groundwater, surface water and atmospheric water near the river corridor. Vadose zone hydrologic process near the river corridor as well as soil characteristics in this region needs to be analyzed by both field investigation and model simulations. Such analysis will advance our understanding of flow and solute exchanges among those three water systems, and allow us to identify factors that control such exchanges and their impacts on the groundwater availability.
- Analyze water quality data to characterize impacts of human activities (pumping and

contamination) and climate change on groundwater salinity, including trend in water quality, sources of contamination, residence time and solute transport using isotopic analysis and geophysical approaches. Delineate zones of groundwater with different qualities for all aquifers, namely fresh water, slightly saline, and saline waters, of which the latter two can serve as an alternative source of water supply by desalination. Develop strategies for recharge zone protection, wellhead protection, reduction of other potential sources of contaminations, and salinity management for both groundwater and surface water.

- Downscale climate change model results to generate information needed to simulate impacts of climate change and future pumping on groundwater availability in regional aquifers. Existing groundwater models do not address climate changes explicitly, and can be upgraded with new data to assess impacts of future groundwater pumping and climate changes on groundwater flow as well as groundwater availability. The solute transport models are needed to simulate the brackish water intrusion, analyze the salinization of the shallow aquifers, estimate the recoverable storage of brackish and saline groundwater, and assess alternative salinity management scenarios.
- Develop decision support systems to evaluate groundwater availability under the uncertain climate conditions and assess alternative management strategies for conjunctive uses of regional surface water and groundwater, such as managed aquifer recharge, water conservation, desalination of brackish groundwater, interbasin transfer, water sharing among competitive entities and others.

Public outreach will also need to be included in future research programs so that research findings can be disseminated and data and information can be shared for adaptive management of regional water resources in changing climate, such as protection of recharge zones, wellhead protection to prevent contamination, and water conservation. Research findings will not only provide information needed for regional stake-

holders to secure future water supplies, but also provide benefits to other similar arid regions through advances in groundwater hydrology, transfer of innovative technology, and improvement in management policy and decision making process.

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