ground water

# Ground Water Budget Analysis and Cross-Formational Leakage in an Arid Basin

by William R. Hutchison[1] and Barry J. Hibbs[2]


## Abstract

Ground water budget analysis in arid basins is substantially aided by integrated use of numerical models and environmental isotopes. Spatial variability of recharge, storage of water of both modern and pluvial age, and complex three-dimensional flow processes in these basins provide challenges to the development of a good conceptual model. Ground water age dating and mixing analysis with isotopic tracers complement standard hydrogeologic data that are collected and processed as an initial step in the development and calibration of a numerical model. Environmental isotopes can confirm or refute a priori assumptions of ground water flow, such as the general assumption that natural recharge occurs primarily along mountains and mountain fronts. Isotopes also serve as powerful tools during postaudits of numerical models. Ground water models provide a means of developing ground water budgets for entire model domains or for smaller regions within the model domain. These ground water budgets can be used to evaluate the impacts of pumping and estimate the magnitude of capture in the form of induced recharge from streams, as well as quantify storage changes within the system. The coupled analyses of ground water budget analysis and isotope sampling and analysis provide a means to confirm, refute, or modify conceptual models of ground water flow.


## Introduction

Ground water budgets or ground water inventories are developed by quantifying all inflows to a system, all outflows from a system, and the storage change of the system over a specified period of time. Literature on the development of ground water budgets dates back to at least the 1930s with the work of Meinzer (1932). Tolman (1937) noted that, at the time, methods to develop ground water budgets had not reached the accuracy necessary to be accepted by all investigators. This was largely due to extensive data collection requirements and the lengthy time needed to observe the range of hydrologic conditions.

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Bredehoeft (2002) reviewed the evolution of analysis of ground water systems. The earliest methods in the 1940s and 1950s revolved around the analysis of flow to a single well. Understanding ground water flow on an aquifer or basin scale became possible with the analog model in the 1950s. Improvements in computer technology in the 1960s and 1970s led to the development of digital computer models or numerical models of ground water flow. By 1980, Bredehoeft (2002) reported that numerical models had replaced analog models in the investigations of aquifer dynamics. The principal objective of such models is to understand the impacts of pumping on the system.

Pumping usually alters the direction and magnitude of hydraulic gradients, induces recharge from (formerly base flow fed) streams, and affects fluxes between hydraulically connected aquifer systems. Bredehoeft (2002) noted that understanding the dynamic response of a ground water system under pumping stress distills down to understanding the rate and nature of "capture" attributable to pumping, which is the sum of the change in recharge and the change in discharge caused by the pumping. A calibrated numerical ground water model of a region is an ideal tool in meeting the objective of understanding capture. Output from the models includes estimates of various components of the water budget.

When combined with stable isotopes and radioisotopes collected in ground water, the calibration and predictive reliability of these models can be greatly improved. If collected with sufficient vertical and horizontal density in an aquifer system, the environmental isotopes can enhance the robustness of the conceptual model. This additional data may allow conceptual models to be confirmed, modified, or refuted. Likewise, model simulations can be used to assist in the interpretation of isotope or other tracer data to develop a more complete understanding of the contemporary and historical movement of ground water.

Such a synergistic application is attempted in this study. In the case of the Hueco Bolson, model output includes annual estimates of water budget components from 1903 (at the beginning of pumping stresses) to 2002. Ground water pumped from the Hueco Bolson represents one supply component for the City of El Paso, Texas, and represents the entire municipal supply for Ciudad Juarez, Chihuahua. A ground water flow model of the area was used to quantify various components of the ground water budget, including the interaction between the overlying surface water system and the Hueco Bolson. This interaction includes the natural recharge and induced inflow caused by historical pumping.

Environmental isotopes were collected for the purposes of testing the reliability of model results. Carbon-14 and tritium data provide information on relative ground water ages and vertical mixing relationships between surface water and ground water. Stable isotopes of oxygen and hydrogen are isotopically distinct across the Hueco Bolson, which allowed identification of predevelopment recharge water (pre-dam Rio Grande water), postdevelopment recharge water (post-dam Rio Grande water), and internally derived precipitation recharge (locally derived water) of both pluvial and modern origins. Model results compare favorably to patterns shown by environmental isotope data. Based on the favorable comparisons, we have confidence in simulations that were done to quantify water balances, evaluate interformational leakage, and analyze induced recharge from the Rio Grande.

## Overview of Hueco Bolson

The Hueco Bolson is the local name for a ground water basin that covers about 6500 km$^2$ in New Mexico, Texas, and Chihuahua (Figure 1). In Texas, the Hueco Bolson overlies portions of El Paso and Hudspeth counties. The Tularosa Basin in New Mexico bounds the Hueco Bolson on the north. The boundary between the Tularosa Basin and the Hueco Bolson is a subtle topographic boundary and does not represent a geologic or hydrologic boundary, and ground water flows from the Tularosa Basin into the Hueco Bolson. The Franklin Mountains bound the Hueco Bolson on the west, the Hueco Mountains are the eastern boundary, and the Sierra Juarez is the southern boundary.

The Hueco Bolson lies within the Rio Grande Rift and is downdropped by normal faults in relation to the

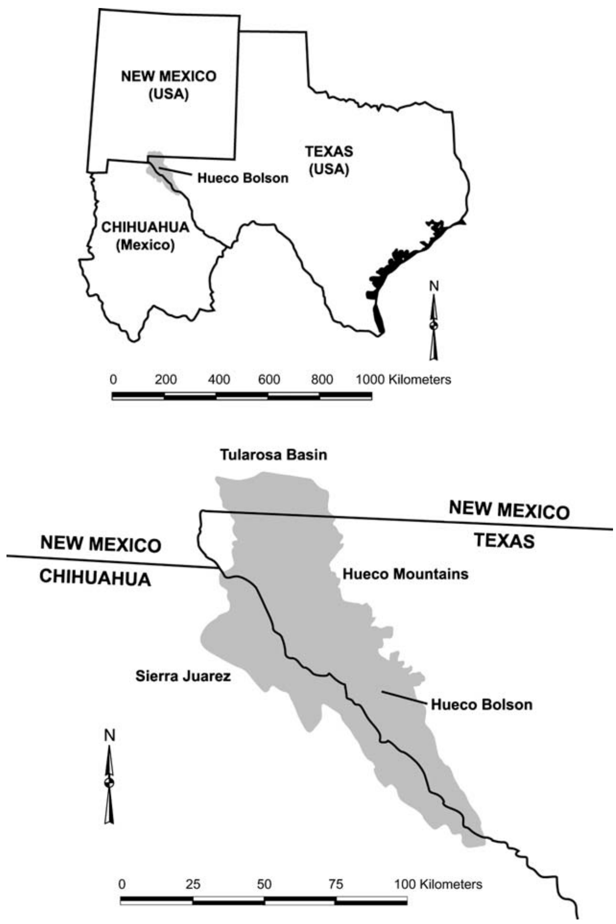



**Figure 1. Location map of Hueco Bolson and surrounding geographic features.**

bounding mountains. Sediments that constitute the Hueco Bolson include Tertiary and Quaternary lacustrine, fluvial, and alluvial deposits of gravel, sand, silt, and clay (Collins and Raney 1991; Heywood and Yager 2003). At its maximum extent, Hueco Bolson deposits are up to 2500 m thick (Knowles and Kenney 1956).

The Rio Grande Alluvium overlies the Hueco Bolson deposits in the valley portion of the area (Figure 2). The Rio Grande Alluvium is relatively thin (maximum thickness of about 60 m). The surface water in the Rio Grande and the associated ditches and drains that were constructed for the delivery and removal of agricultural water interact with the ground water in the Rio Grande Alluvium (Land and Armstrong 1985). Ground water in the Rio Grande Alluvium, in turn, interacts with the underlying Hueco Bolson (Hibbs and Boghici 1999).

## Past Analyses of Water Budget and Ground Water/Surface Water Interaction

Slichter (1905) completed an early investigation of ground water conditions in the El Paso area and noted the relative position of the bed of the Rio Grande, ground water elevations near the Rio Grande in shallow wells, and ground water elevations in deep wells north of the Rio Grande. Slichter (1905) observed a gentle slope of the ground water elevation toward the river when deep

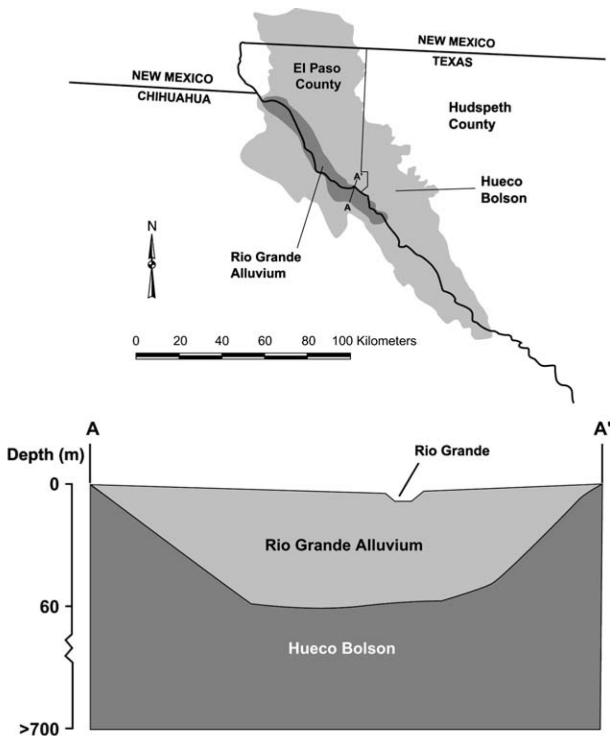



**Figure 2. Location of Hueco Bolson and Rio Grande Alluvium and schematic cross section of relationship between Rio Grande, Rio Grande Alluvium, and Hueco Bolson.**

wells were not pumping and away from the Rio Grande when deep wells were being pumped. He further noted that at times of high flows in the Rio Grande, the river acted as a source of recharge to the shallow ground water. Slichter (1905) also noted the difference in the chemistry of the runoff from the Franklin Mountains and the Hueco Bolson ground water and concluded that the Franklin Mountains are not a significant source of recharge to the Hueco Bolson.

Lippincott (1921) extended the discussion of the interaction of the Rio Grande and the Hueco Bolson. Ground water pumping in the Hueco Bolson began in 1903 with the first of several wells constructed about three miles north of the Rio Grande. After reviewing the history of the ground water level declines and water quality changes in the Mesa wellfield, Lippincott (1921) concluded that the wells were being fed, in part, from the Rio Grande. Lippincott (1921), however, was not able to quantify the rate of inflow.

As pumping continued, more data were collected, and as the science of hydrogeology improved over the decades, the understanding of the ground water–surface water interaction also improved. In a report by the Texas Board of Water Engineers, Smith (1956) provided one of the earliest qualitative discussions. Smith (1956) noted that prior to development, the vertical gradient between the Hueco Bolson and the overlying Rio Grande Alluvium in Texas was upward. Consequently, ground water discharged from the Hueco Bolson to the Rio Grande Alluvium and thence to the Rio Grande as base flow. Increases in pumping resulted in decreased ground water levels in the Hueco Bolson and resulted in a reversal of the vertical gradient between the Rio Grande Alluvium and the Hueco Bolson. As a result, Smith (1956) reported that the alluvium became a source of recharge to the Hueco Bolson rather than a discharge area.

In 1976, a USGS investigation presented a quantitative estimate of the interaction between ground water and surface water. Meyer (1976) recognized that the Rio Grande was a gaining stream until the mid-1930s, after which the Rio Grande began to lose water at a rate that increased as pumping increased. Pumping ground water from the Hueco Bolson induced this recharge from the Rio Grande. Surface water first recharged the Rio Grande Alluvium. Downward vertical gradients between the Rio Grande Alluvium and the Hueco Bolson resulted in cross-formational recharge from the Rio Grande Alluvium into the Hueco Bolson (White 1987). Meyer (1976) estimated that 50% of the pumped ground water was removed from storage, 25% was leakage from the Rio Grande Alluvium, and 25% was derived from natural recharge.

The understanding of ground water in the Hueco Bolson and the Rio Grande Alluvium evolved from qualitatively describing the interaction between the surface water and the ground water to a quantitative understanding of the relationships between pumping, storage decline, natural recharge, and leakage from the alluvium. After 1976, data continued to be collected and studies and interpretations of those data have continued.

## Reanalysis of Ground Water/Surface Water Interaction with Environmental Isotopes

Historical modeling studies confirmed leakage of Rio Grande water into the Rio Grande Alluvium and leakage of Rio Grande Aquifer water into the Hueco Bolson. So long as the alluvial aquifer is itself replenished from recharge from unlined channels, the Rio Grande Aquifer will account for a major component of recharge to the Hueco Bolson. Previous model analyses are dated, however, and new analyses need to be done to provide current leakage estimates based on present hydraulic head relationships in the alluvium and bolson aquifers.

An important part of this study integrates natural isotopic tracers (tritium, carbon-14, and oxygen and deuterium isotopes) with numerical models to try to quantify and determine depth of induced leakage from the Rio Grande Aquifer to the Hueco Bolson. Detailed analysis using such tracers had not been previously completed in the Hueco Bolson except for limited use of more generalized natural tracers such as chloride and sulfate. It is expected that the empirical isotope data may complement numerical model analysis by providing clear evidence of leakage between the Rio Grande Aquifer and the Hueco Bolson Aquifer due to pumping-induced stresses.

## Field and Laboratory Methods

Regional and site-specific ground water sampling was performed in the Hueco Bolson and Rio Grande Alluvium. Regional sampling was done primarily in high-capacity municipal and irrigation wells, and site-specific sampling was done in nested monitoring wells.

Before sampling ground water, water wells and piezometers were first purged and stabilized. To purge wells, the well was pumped until at least three casing volumes of water were pumped before sampling. Purging wells with dedicated pumps was accomplished by sampling when wells were pumping continuously or by turning the pumps on for the necessary period of time to vacate at least three casing volumes. Observation wells without dedicated pumps were purged and samples were collected using a Grundfos pump.

All samples for isotopic analyses were collected in new high-density polyethylene bottles and then sealed with tight-fitting caps leaving no bubbles or headspace. Sample containers were clearly labeled with the well identification number, date of collection, type of parameters to be analyzed, and preservation used. The sample was sealed so that opening the sample container without breaking the seal is impossible. The seal adhered to both the cap and the sample container and encompassed the entire perimeter of the mouth of the container.

Ground water samples were collected for O-H stable isotopes ($^{2}H$ and $^{18}O$), tritium, and carbon-14 analyses. Stable isotope measurements were made at the Laboratory of Isotope Geochemistry at the University of Arizona. The hydrogen and oxygen isotopic composition of water was determined using a Finnigan Delta-S isotope ratio mass spectrometer following reduction with Cr (Gehre et al. 1996) or $CO_2$ equilibration (Craig 1961a, 1961b), respectively. Results were expressed as $\delta^{2}H$ and $\delta^{18}O$ in per mil (‰) relative to the standard Vienna Standard Mean Ocean Water (Gonfiantini 1978) with analytical precisions of 0.9‰ and 0.08‰, respectively.

Tritium samples were enriched ninefold through electrolytic enrichment to concentrate the sample and then analyzed by liquid scintillation counting with a LBK Wallac Quantulus 1220. Results are reported in tritium units (TU) (1 TU = ~3.2 pCi/L) with the detection limit ranging from 0.6 to 0.9 TU. Tritium was analyzed at the Laboratory of Isotope Geochemistry at the University of Arizona.

To analyze for carbon-14, dissolved inorganic carbon in the water sample was extracted as gaseous $CO_2$ by acid hydrolysis on a vacuum line. The $CO_2$ was then analyzed by accelerator mass spectrometry (AMS) at the University of Arizona AMS Lab. Results are reported in percent modern carbon relative to the NBS oxalic acid I and II standards.

## Numerical Methods

The USGS developed the most recent ground water flow model of the Hueco Bolson (Heywood and Yager 2003). The objectives of the model were to develop a tool to assist in the understanding of ground water flow and to evaluate potential ground water management strategies. The model area extends slightly into the Tularosa Basin in New Mexico, and covers most of the Hueco Bolson in Texas and most of the Hueco Bolson in Chihuahua.

The model code used was a modified version of MODFLOW-96, the modular finite-difference ground water flow model developed by the USGS (Harbaugh and McDonald 1996). As described in Heywood and Yager (2003), the streamflow routing and multiaquifer well (MAW) packages were modified in order to deal with the large magnitude of historical drawdown that has been observed in the area and the consequential issue of dried model cells in the upper layers of the model. The MAW package was previously developed by McDonald (1984) and is not included as part of MODFLOW-96 as distributed by the USGS.

The model grid consists of 10 layers of 165 rows and 100 columns in a variable grid of 500 × 500 m to 1000 × 1000 m, with the finer grid in the area of interest in the El Paso and Juarez area. The model was calibrated with data from 1903 to 1996.

Heywood and Yager (2003) calibrated the model by adjusting parameter values representing aquifer properties and specified boundary conditions using nonlinear regression techniques to minimize the difference between measured data and model-estimated data. Calibration relied

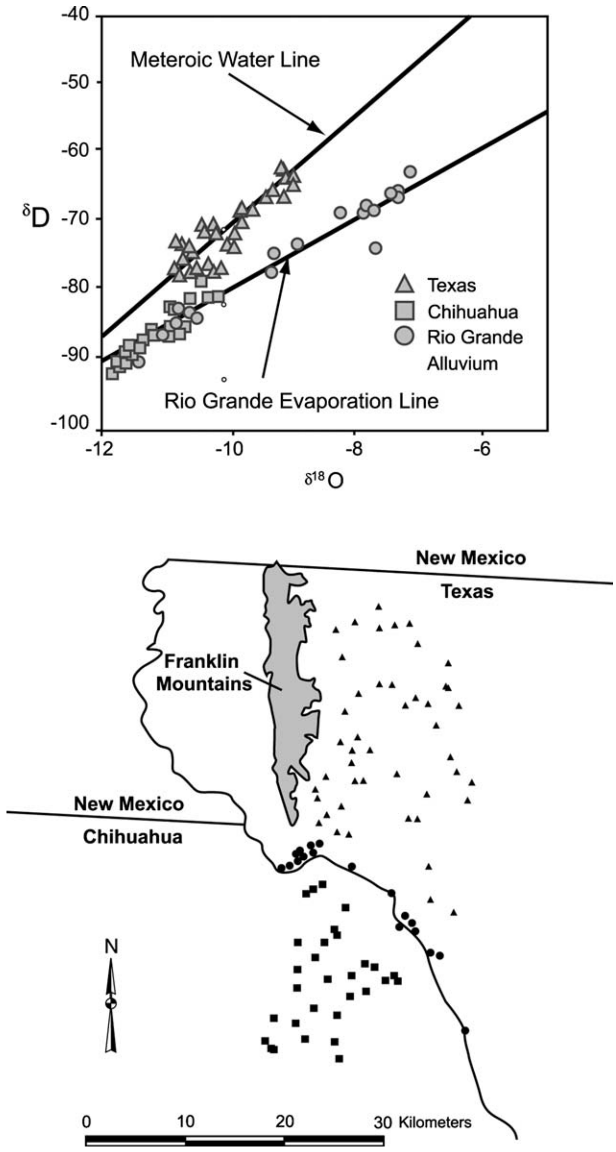



**Figure 3. Isotopic signatures of Hueco Bolson ground water in Texas and Chihuahua and Rio Grande Alluvium ground water and location of sampling points.**

on comparisons between actual and estimated ground water elevation data and selected surface water flows. More recently, El Paso Water Utilities updated the model to include input data from 1997 to 2002 (Hutchison 2004).

## Results

### Isotopic Evidence of Ground Water/Surface Water Interaction

Regional work summarized by Eastoe et al. (2008) and Hibbs et al. (2003) provided isotopic evidence of interaction of ground water and surface water in different parts of the Hueco Bolson. Eastoe et al. (2008) identified differences in isotopic signatures in ground water sampled in the Rio Grande Alluvium, the Texas portion of the Hueco Bolson, and the Chihuahua portion of the Hueco Bolson. Eastoe et al. (2008) found that Rio Grande surface water and most ground water in the Rio Grande Alluvium have been affected by evaporation in upstream reservoirs in New Mexico. Ground water in the Texas portion of the Hueco Bolson has isotopic signatures consistent with recharge from the Franklin Mountains and Sacramento Mountains to the west and north. Ground water in the Chihuahua portion of the Hueco Bolson has isotopic signatures that are consistent with pre-dam snow melt from southern Colorado and northern New Mexico, the source area for the Rio Grande, which is a higher elevation area than the local mountain ranges. A general depiction of this pattern is shown in Figures 3 and 4. Figure 3 presents the isotopic signature of ground water over a major part of the basin. Figure 4 shows a conceptual representation of predevelopment conditions and postdevelopmental changes in the flow system. Induced leakage from the Rio Grande and reversal of the cross-formational leakage between the Rio Grande Alluvium and the Hueco Bolson are denoted on the U.S. side of the international border.

Site-specific testing of the nested observation wells was done primarily to support the modeling study discussed in this paper. Induced flows between the Rio Grande, Rio Grande Alluvium, and Hueco Bolson are indicated by isotopic and hydraulic head data collected at

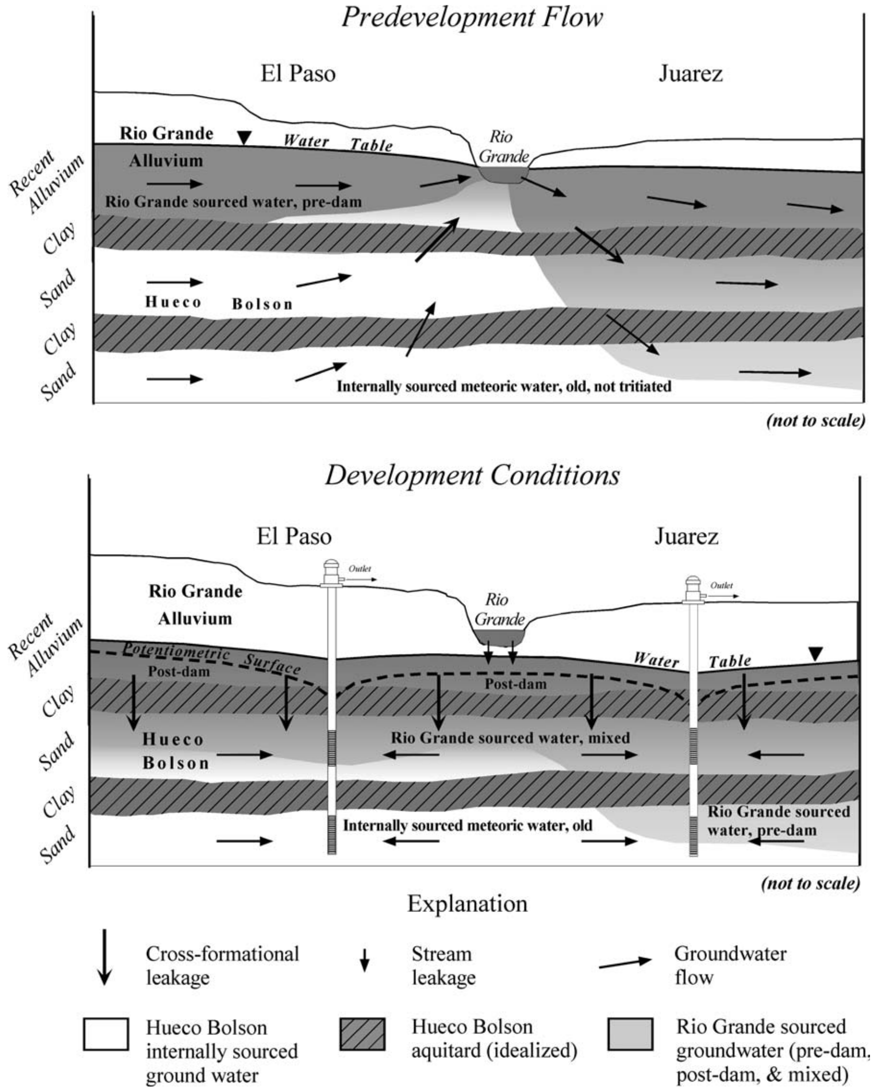



**Figure 4. Conceptual model showing predevelopment conditions and associated recharge and discharge characteristics and postdevelopment conditions, including pumping-induced recharge and downward cross-formational flow.**

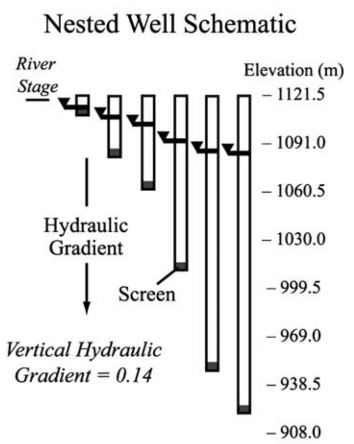
the multilevel well nest. The Rio Grande is unlined at this location. Wells screened above 60 m are installed in the Rio Grande Alluvium and wells screened below 60 m are installed in the Hueco Bolson. The hydraulic head gradient is oriented vertically downward (Figure 5). Mixing between Rio Grande water, Rio Grande Alluvium water, and Hueco Bolson water is indicated by stable isotope data (Figure 6). Wells at intermediate depths show stable isotope signatures that are intermediate between the isotopically heavy water from the shallowest well in the Rio Grande Alluvium (JL-49-21-324) and the isotopically lighter water at the deepest well (JL-49-21-322).

Tritium ($^3H$) data provide clues to the distribution of recharge and relative ages of ground water. Pre-1950 values for tritium in northern hemisphere precipitation were about 5 TU, where 1 TU is equal to one atom of $^3H$ in $10^{18}$ atoms of hydrogen. Tritium has a half-life of 12.3 years (Mazor 1991), and $^3H$ values less than about 0.5 TU usually indicate ground water recharged before 1952, provided that extensive dilution by older ground water has not occurred. Tritium in northern hemisphere precipitation increased to more than 2000 TU as a result of aboveground testing programs for nuclear weapons in the 1950s and 1960s. Tritium has decreased to near-background levels.

Tritium is highest in intermediate wells screened between 55 and 109 m (Figure 6), indicating residual "bomb" tritium probably recharged between 1960 and 1985. At this distance from the natural recharge areas in the mountains, any tritiated water must have come from the Rio Grande. Post-1952 and tritiated ground water penetrates to a depth of at least 183 m below ground surface at the well nest (Figure 6), which suggests induced infiltration from the Rio Grande Alluvium. The hydrogeologic data indicate downward vertical flow and recharge to the Hueco Bolson Aquifer from the Rio Grande Alluvium and the Rio Grande. Carbon-14 data at the well nest are in agreement with the tritium and stable isotope data (Figure 6). Carbon-14 data imply old water at depth and progressively younger Rio Grande water at shallower intervals.

Nested Monitoring Well Data

| Well Number | Screen Interval | Hydraulic Head |
|---|---|---|
| JL-49-21-324 | 8.5 - 11.6 m bgs | 1115.85 m |
| JL-49-21-320 | 34.7 - 37.8 m bgs | 1110.94 m |
| JL-49-21-319 | 55.1 - 58.2 m bgs | 1107.95 m |
| JL-49-21-318 | 106.0 - 109.1 m bgs | 1093.58 m |
| JL-49-21-323 | 172.5 - 175.6 m bgs | 1089.15 m |
| JL-49-21-322 | 200.8 - 203.9 m bgs | 1088.41 m |



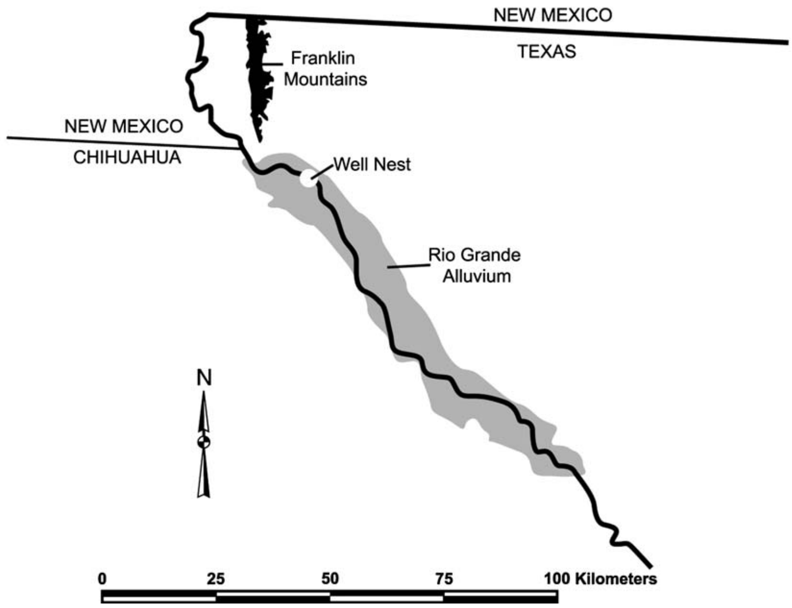




**Figure 5. Hydraulic head data collected from a well nest near an unlined segment of the Rio Grande. The well nest is located approximately 61 m from the Rio Grande. Data indicate downward hydraulic head gradient between the Rio Grande, Rio Grande Alluvium (up to 60 m below ground surface [bgs]), and Hueco Bolson (60 m and more bgs).**

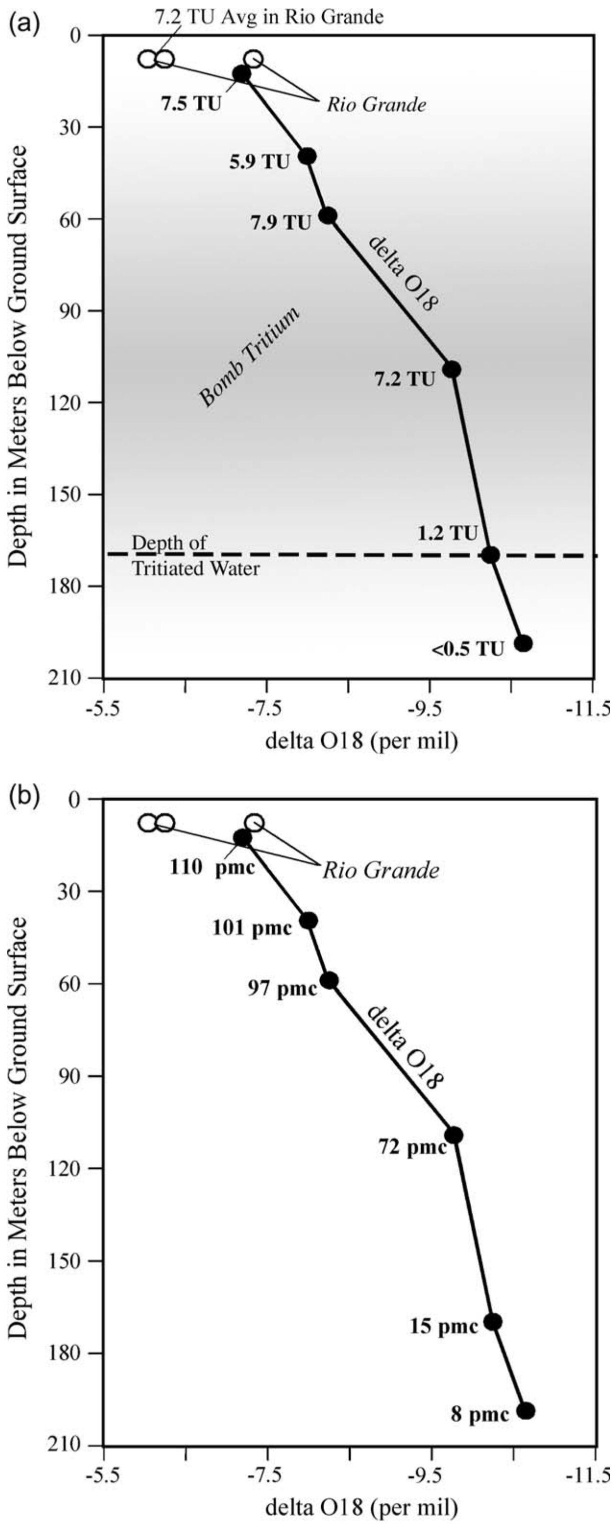



**Figure 6. Stable isotope and tritium data collected from the well nest near the Rio Grande. (a) Tritium at depths of at least 183 m indicates cross-formational leakage from the Rio Grande Alluvium to the Hueco Bolson, and (b) carbon-14 date show similar results and imply old and isotopically lighter water at depth and progressively younger Rio Grande–fed water at shallower intervals.**

The isotope data that establish induced recharge are site specific and do not provide quantitative estimates of recharge. Modeling studies are therefore employed to provide a regional and quantitative estimate of induced recharge.

### Overall Model Area Ground Water Budget

Ground water budget analysis began with an examination of the entire model domain (Figure 7). Model output includes annual estimates of water budget components from 1903 (at the beginning of pumping stresses) to 2002. In addition, it is possible to develop subregional budgets using the model output from 1903 to 2002 to further characterize and quantify historical and current interaction between ground water and surface water using ZONEBUDGET (Harbaugh 1990).

The ground water budget for the entire model domain based on the calibrated model is summarized in Figures 8a (inflow), 8b (outflow), and 8c (storage change). Inflow to the system is from surface recharge (precipitation, irrigation return flow, leaking water distribution pipes, and sewer lines), boundary inflows, and net surface water inflows from the Rio Grande and various canals that carry diverted Rio Grande water to irrigated fields (Figure 8a). From 1903 to about 1940, ground water discharged to the surface water system in some areas. However, since about 1940, the surface water system has been a net source of recharge to the ground water system within the model domain.

Note that for purposes of this analysis, surface recharge and boundary inflows are combined. Over the period of interest, surface recharge has increased slightly due to increases associated with irrigation return flow. This is a result of increases in irrigated agriculture made possible by the Rio Grande Project, which delivers Rio Grande water to the area after storage in Elephant Butte Reservoir. Surface water inflows were relatively constant from 1903 to 1920. After the construction of Elephant Butte Dam in 1916, the surface water inflows decreased slightly apparently as a result of regulated surface flows into the area. Surface water inflow to the ground water system dropped significantly in the 1950s due to a prolonged drought. Since the 1960s, surface water inflows to the ground water system have steadily increased, possibly as a result of increased drawdown caused by ground water pumping.

Outflow from the system is to agricultural drains, evapotranspiration, and pumping (Figure 8b). Outflow to drains and through evapotranspiration decreased slightly from 1903 to 1950, dropped significantly during the drought of the 1950s, and then increased and was relatively constant from 1960 to 2002 but at a level that was lower than the early part of the period of interest. The lack of recovery to earlier rates of discharge is due to lowered ground water levels due to ground water pumping. Pumping increased from 1903 to 1950 and then increased more rapidly from 1951 to 1990.

Storage change in the Hueco Bolson is summarized in Figure 8c. Storage changes were relatively insignificant from 1903 to 1940. As a result of increased pumping, storage began to decline significantly after 1940. Note that the trend of increasing storage declines reversed from 1990 to 2002 due to decreasing pumping in El Paso.

Pumped ground water is derived from a combination of storage decline and "capture" (the sum of the change in recharge and the change in discharge caused by the pumping). Figure 9 depicts the summary of the analysis of

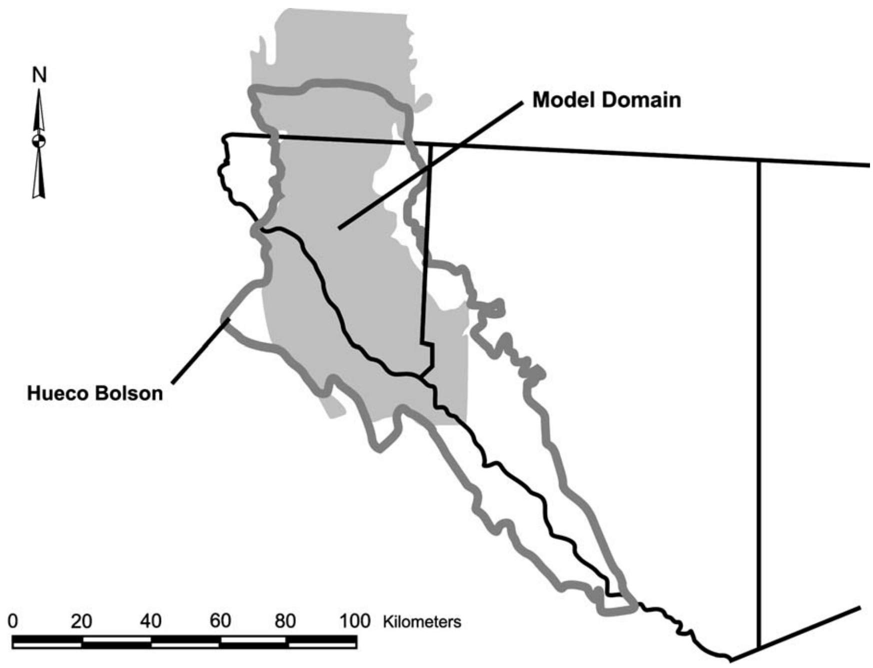



**Figure 7. Domain of ground water flow model of Heywood and Yager (2003).**

storage decline and capture. In this case, capture is estimated by subtracting the "natural outflow" (outflows from agricultural drains and evapotranspiration as shown in Figure 8b) from the sum of the inflow components of Figure 8 a (surface recharge, boundary inflows, and surface water inflow). Note that from 1921 to 1950, pumping resulted in a large capture relative to storage decline. After 1951, storage decline dominated capture. The significant increases in pumping in the 1960s, 1970s, and 1980s coincided with large storage declines. From 1990 to 2002, capture increased and storage decline decreased relative to 1981 to 1990 when increases in pumping had been substantially reduced.

The analysis of the ground water budget of the entire model domain illustrates the concepts outlined by Bredehoeft (2002) with respect to the dynamic response of pumping and the concept of capture. However, the analysis provides little insight into the significant differences in isotopic signature of the ground water as reported by Eastoe et al. (2008). The analysis, therefore, needs to be extended by considering ground water budgets of regions within the model domain.

### Rio Grande Alluvium Ground Water Flow to and from the Hueco Bolson

For purposes of this analysis, the Rio Grande Alluvium was subdivided into an "urban alluvium" area and a "rural alluvium" area (Figure 10). The urban alluvium area was defined generally as the area significantly affected by historical pumping based on a comparison of ground water flow patterns in 1903 and 2002. The rural alluvium area was defined generally as the area not significantly affected by pumping based on a comparison of ground water flow patterns in 1903 and 2002.

The analysis was further extended by considering the ground water flow from the urban alluvium and rural alluvium into and out of the Texas and Chihuahua portions of the Hueco Bolson. There was also minor flow between the urban and the rural alluvium that is not discussed in this analysis. The ground water budgets for this analysis were developed using ZONEBUDGET (Harbaugh 1990).

Figure 11 summarizes the flow between the urban alluvium and the rural alluvium and the Texas and Chihuahua portions of the Hueco Bolson. Note that positive values represent downward flow from the Rio Grande Alluvium into the underlying Hueco Bolson. Negative values represent upward flow from the Hueco Bolson to the overlying Rio Grande Alluvium.

Between 1903 and about 1940, ground water in the Texas portion of the Hueco Bolson moved upward into the urban and the rural alluvium. Pumping during these years did result in a decreasing rate of discharge into the urban alluvium. Overall, however, the Rio Grande Alluvium acted as a discharge area for the Texas portion of the Hueco Bolson. Note that in the earliest years, discharge from the Hueco Bolson was slightly higher in the urban alluvium than in the rural alluvium. After about 1940, ground water in the urban alluvium began to recharge the Hueco Bolson in Texas. The rate of this recharge increased until about 1990 when pumping in Texas decreased. The decrease in pumping in Texas resulted in a decrease in the rate of inflow from the alluvium.

In contrast, ground water from the Texas portion of the Hueco Bolson continues to discharge into the rural portion of the Rio Grande Alluvium. The rate of discharge has been slightly affected but the rural alluvium remains a discharge area for ground water from the Hueco Bolson.

The Chihuahua portion of the Hueco Bolson has been recharged from both the urban and the rural alluvium since 1903. Note that the rate of recharge before significant pumping (about 1940) was higher in the urban

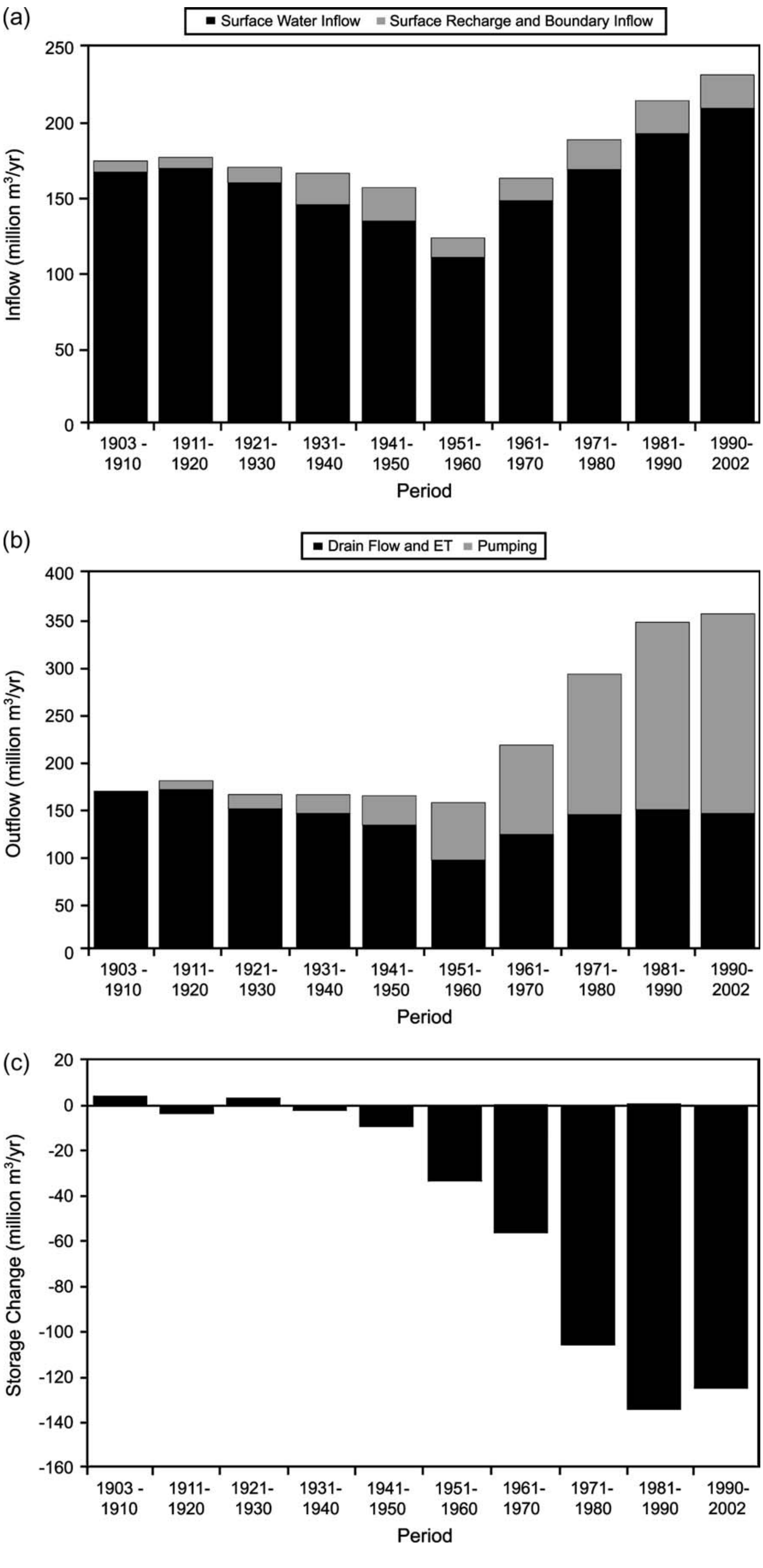



**Figure 8. (a) Inflows to the Hueco Bolson, (b) outflow from the Hueco Bolson, and (c) Hueco Bolson storage changes.**

alluvium than in the rural alluvium. After the significant increase in pumping, the rate of recharge increased dramatically in the urban alluvium but remained relatively constant in the rural alluvium. The rural alluvium acted as a minor discharge area of the Chihuahua portion of the Hueco Bolson during the drought of the 1950s but then

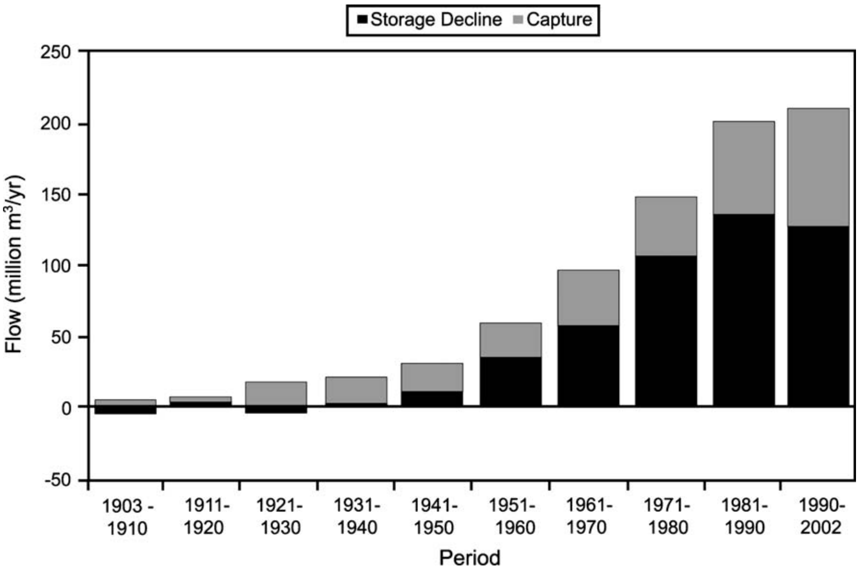



**Figure 9. Storage decline and capture in the Hueco Bolson.**

returned as a recharge source subsequent to the end of the drought.

### Comparison of Isotopic Data and Ground Water Budget Analyses

As previously described and shown in Figure 3, the isotopically lighter water in Chihuahua has been interpreted as being derived from high-elevation snow melt in southern Colorado and northern New Mexico. The ground water budget analysis suggests that surface water recharges the alluvium, which, in turn, recharges the Chihuahua portion of the Hueco Bolson. In contrast, ground water in the Texas portion of the Hueco Bolson is isotopically heavier than ground water in the Chihuahua portion of the Hueco Bolson. The Texas portion of the Hueco Bolson is recharged from precipitation at lower elevations in the Franklin and Sacramento Mountains to the west and north. Prior to pumping, ground water in the Texas portion of the Hueco Bolson flowed into the Rio Grande Alluvium. The Rio Grande Alluvium thus acted as a sink for Hueco Bolson ground water in Texas and acted as a recharge source to the Chihuahua portion of the Hueco Bolson. The isotopic signature of the Rio Grande Alluvium is consistent with evaporated ground water from the Texas portion of the Hueco and/or evaporated water from the Rio Grande after construction of Elephant Butte Dam in 1916 (Figures 5 and 6).

The presence of tritium and lower hydraulic head in deeper segments of a nested well cluster in the Texas portion of the Hueco Bolson is consistent with the ground water budget analysis (Figures 5 and 6). Ground water pumping in both Texas and Chihuahua has resulted in lowered ground water levels, which have reversed the vertical gradient in Texas and increased the vertical gradient in Chihuahua. The ground water budget suggests that this reversal in gradient in Texas has resulted in the movement of surface water into the alluvium and alluvial water into the Hueco Bolson. The presence of tritium is consistent with this finding and suggests that the recharge has

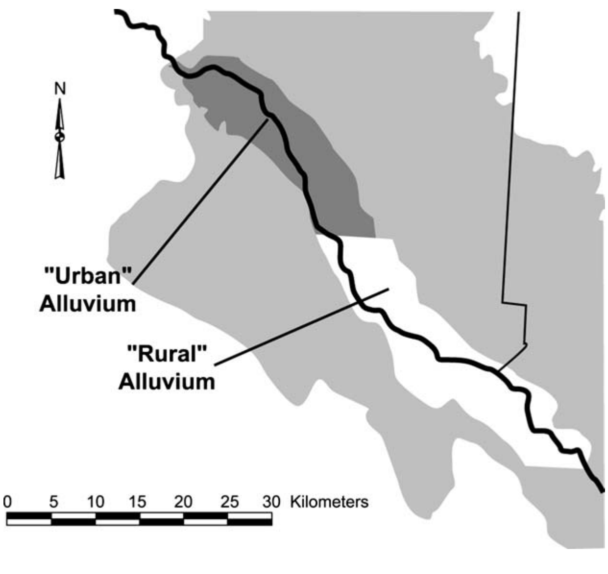



**Figure 10. Location of "urban" and "rural" alluvium.**

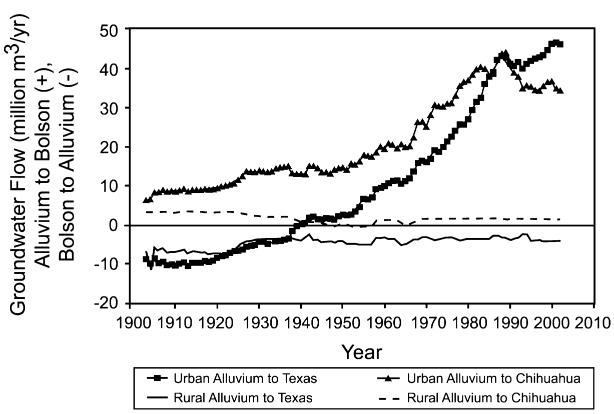



**Figure 11. Flow between Rio Grande Alluvium and Hueco Bolson in Texas and Chihuahua.**

resulted in movement of surface water to a depth of at least 183 m since 1960.

Environmental isotopes and numerical models verify induced infiltration from the Rio Grande Alluvium to the Hueco Bolson. The amount of induced infiltration is substantial, amounting to more than 25% of current municipal pumping from El Paso and Juarez. So long as sections of the Rio Grande channel and agricultural channels remain unlined within and below the El Paso-Juarez corridor, the amount of leakage from the Rio Grande/Rio Grande Alluvium to the Hueco Bolson will continue to account for much of the current recharge to the bolson. Complementary use of environmental isotopes and numerical models also provided synergistic hydrogeologic analyses.

## Conclusions

The ground water budget derived from the numerical flow model of the entire Hueco Bolson is useful to understand the dynamic response of the Hueco Bolson to ground water pumping that started in 1903. In general, ground water pumping is supplied by a combination of storage decline and capture. Capture is defined as the sum of increases in inflow to the ground water system attributable to pumping and decreases in natural outflow attributable to pumping. Initially, ground water pumping in the Hueco Bolson was supplied more by capture than by storage decline. As pumping increased, storage declines were the dominant supply of the pumping.

Understanding the dynamics of capture and storage decline through the use of the ground water budget of the entire model domain, however, does not provide any insight as to the unique isotopic signature of ground water in the three areas of interest: the Texas portion of the Hueco Bolson, the Chihuahua portion of the Hueco Bolson, and the Rio Grande Alluvium, which overlies the Hueco Bolson on both sides of the Rio Grande. The analysis was therefore extended to include the development and evaluation of ground water budgets for each of these areas of interest. The Rio Grande Alluvium was further subdivided into two parts based on the historical impacts of pumping to ground water flow patterns.

Based on ground water budgets of each of the areas of interest, it was concluded that ground water in the Texas portion of the Hueco discharged into the Rio Grande Alluvium until pumping caused a gradient reversal. Once the gradient was reversed, the Rio Grande Alluvium in the urban area acted as a source of recharge to the Texas portion of the Hueco Bolson. In the rural area that has not been significantly affected by pumping, the alluvium continues to act as a discharge area for the Texas portion of the Hueco Bolson.

Ground water in the Rio Grande Alluvium has always acted as a source of recharge to the Chihuahua portion of the Hueco Bolson. Increased pumping has resulted in increases in the rate of recharge in the urban area. However, the increased pumping in the urban area has resulted in no significant change to the rate of recharge in the rural area of Chihuahua.

The estimates of cross-formational flow derived from the ground water budgets are consistent with recent isotopic data collected from the Texas portion of the Hueco Bolson, the Chihuahua portion of the Hueco Bolson, and the Rio Grande Alluvium. The isotopically light water is found in Chihuahua, which is consistent with the Rio Grande acting as a source of recharge, even in predevelopment times. The isotopically heavier water is found in Texas, which is consistent with a recharge source of lower elevation. Rio Grande Alluvium ground water has isotopic signatures consistent with evaporation of surface water. This consistency provides confirmation of the conceptual model that was used to develop the numerical model and provides confidence that the model is useful for regional evaluations of the impacts of pumping and the management of ground water in the region. Integrated use of environmental isotopes and numerical models is strongly encouraged in other arid hydrogeological basins.

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