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Reinterpreting Models of Slope-Front Recharge in a Desert Basin

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Abstract: Identification of recharge areas in arid basins is challenging due to spatial and temporal variability and complexity of the hydrogeology. This study re-evaluates recharge mechanism in a desert basin where isotopic and geologic data indicated that published conceptual models of recharge are not accurate. A new model of recharge is formulated that is consistent with the unique geologic framework in the basin. In the area of study, the Rio Grande flows across a broad alluvial floodplain, the "El Paso-Juarez Valley", where the river has incised the surface of the Hueco Bolson. The modern Rio Grande floodplain overlies the older basin fill, or "Hueco Bolson deposits", in the valley portion of the area. The lateral contact between the older bolson deposits and the recent alluvial floodplain deposits defines the "slope front". The valley wall along the slope front is penetrated by many arroyos that incise the Hueco Bolson deposits and modern floodplain surface. The presence of a large lens of freshwater at the boundary between the older bolson fill and recent Rio Grande alluvium seemed to suggest to previous researchers that dilute water developed due to runoff drawn in by San Felipe Arroyo, a prominent arroyo at the slope front between the older Hueco Bolson deposits and the recent Rio Grande alluvium. Our follow-up verification work illustrates that this is demonstrably not the case. The testing of groundwater samples for stable water isotopes and radioisotopes showed that the deeper and more dilute waters near San Felipe Arroyo are actually pre-dam waters recharged from the shifting Rio Grande channel.

Keywords: isotope hydrology; groundwater recharge; arid zones; cross-formational flow

1. Introduction

Recharge estimates in desert basins are needed for formulating rules for aquifer development, for developing policy regarding waste disposal, and for setting boundary conditions in digital models. Recharge in arid basins is usually focused in select areas receiving sufficient moisture to allow downward-moving wetting fronts to move beneath plant rooting zones, and in areas of bedrock exposure, where deeply percolating water finds conduits to the groundwater zone [1]. Complexities and challengers in identifying recharge include the lack of well control data, paucity of vadose zone information, and poorly understood basin geology [1]. These factors challenge hydrogeologists who need to develop meaningful estimates or predictions of recharge for the purpose of formulating guidelines for aquifer management [2].

Three important forms of natural recharge in arid basins are recharge in mountain fronts, recharge along mountain blocks, and recharge along slope fronts. Recharge of aquifers in mountains and along mountain fronts has been the subject of research by many groundwater scientists [1,3–9]. Mountain-front recharge describes the contribution of groundwater recharge along alluvial fans and pediments bordering mountains. Mountain-block recharge occurs at higher elevation in mountains through deep percolation of water in bedrock matrix and fractures.

Slope-front recharge is a process that has received considerably less commentary. This type of recharge occurs where ephemeral flows in sand channels move from moderately steep slopes onto less steep sand channels that may or may not extend to rivers or desert playas [10]. It occurs where there are topographic irregularities on a basin floor. The classical type location defining "slope front recharge" is a physiographic setting found in the Upper Rio Grande Basin [10]. There, the modern Rio Grande has dissected older basin fill deposits while cutting down to current base level. Many ephemeral channels extending across level bolson surfaces encounter sharp topographic slopes between the erosional edges of basin floors and the lower lying Rio Grande floodplain. Slope-front recharge occurs at the topographic break between slope and floodplain. This paper addresses anomalies and anecdotal models in a hydrogeological setting, where it was posited that slope-front recharge occurred by internal recharge from precipitation runoff drawn in by arroyos and where new data showed that the source of recharge was from infiltration from a major river that had shifted its course.

1.1. Study Area

The case study is presented at the slope front of the San Felipe Arroyo near Fabens, Texas (Figures 1 and 2). In this area, the Rio Grande flows across a broad alluvial floodplain, the "El Paso-Juarez Valley", where the river has incised the surface of the Hueco Bolson (Figure 1). In this paper, modern Rio Grande floodplain refers to the current floodplain surface across which the Rio Grande flows (Table 1). Historical floodplains formed by ancestral versions of the Rio Grande are now buried and make up some of the basin fill units that form the regional Hueco Bolson aquifer (Figure 1). Rio Grande alluvium refers to the recent floodplain deposits formed from deposition by the modern Rio Grande. Rio Grande Aquifer is the recent river alluvium that is saturated. Vadose zone thickness above the Rio Grande Aquifer is usually 5 to 30 feet (1.5 to 9.2 m) thick.
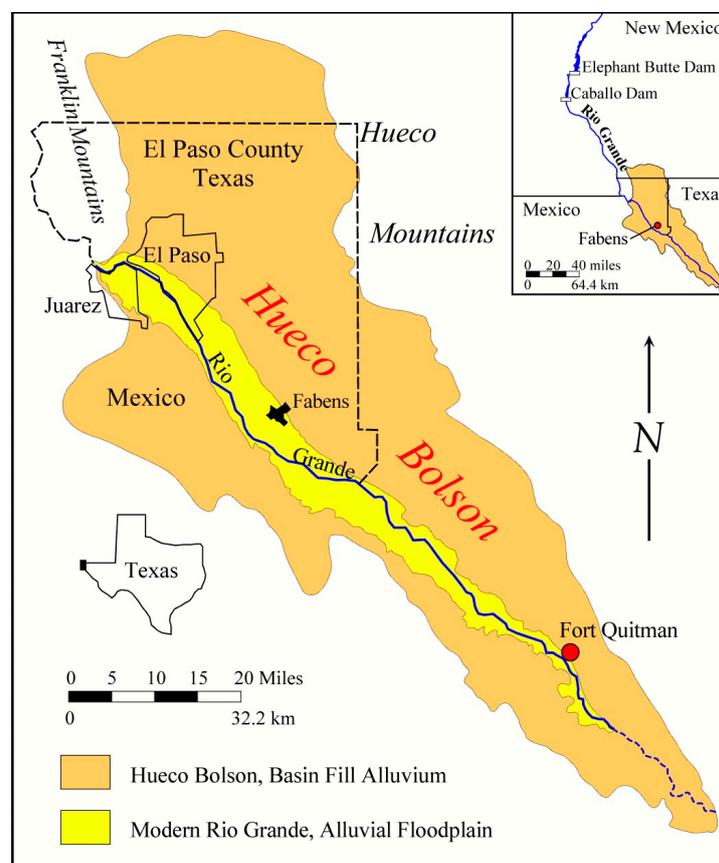

Figure 1. Regional study area map showing the extent of the Hueco Bolson and modern Rio Grande floodplain. The study area is centered near Fabens, Texas.
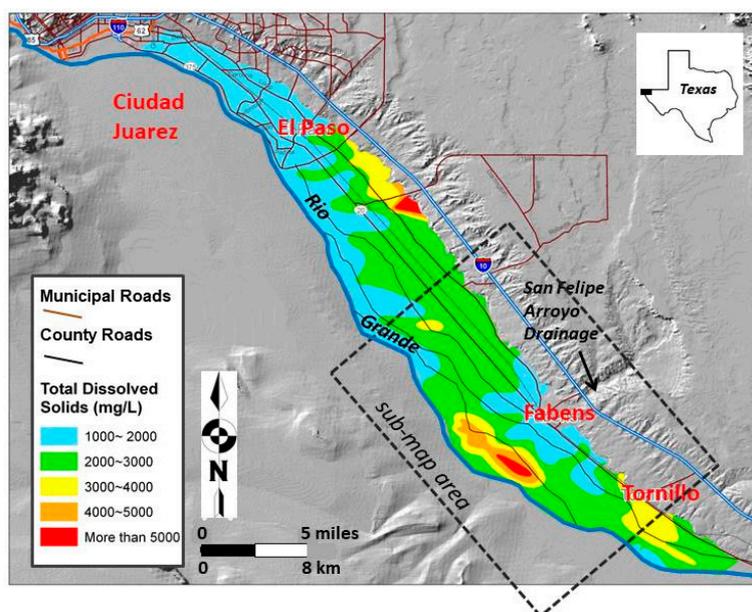
Figure 2. Salinity of the Rio Grande Aquifer in El Paso County, Texas. Alluvial aquifer salinities mapped by Alvarez and Buckner, 1980 using dense well control. The dilute groundwater near San Felipe Arroyo was thought to have formed by slope front recharge from the arroyo. Only the part of the Rio Grande floodplain in the United Section was mapped by Alvarez and Buckner [12]. The Rio Grande marks the southwestern limit of the section of the floodplain in the United States.

Table 1. Unconsolidated Rocks in the Hueco Bolson (from Gates and Stanley [11]).

Age	Unit		Characteristics
Holocene and Pleistocene	Rio Grande Alluvium		Mostly fluvial sand and gravel deposited along the modern course of the Rio Grande
Pleistocene, Pliocene, and Miocene (?)	Camp Rice Formation of Strain (1966) Fort Hancock Formation of Strain (1966)	Bolson Deposits	The Camp Rice is fluvial sand and gravel deposited along ancient courses of the Rio Grande. The Fort Hancock and older bolson deposits are mostly coarse-grained alluvial-fan material deposited around the margins of the bolson and fine-grained playa deposits along the axis of the bolson

The Hueco Bolson is a Tertiary and Quaternary basin fill system and is a primary source of water supply for the cities of El Paso, Texas and Juarez, Mexico. The basin fill of the Hueco Bolson includes ancestral Rio Grande deposits and alluvium and colluvium formed from weathering and erosion of the flanking mountains (Table 1). Modern Rio Grande alluvium overlies the Hueco Bolson deposits in the valley portion of the area (Figure 1). Near El Paso, the El Paso Valley is approximately 6 to 8 miles (9.7 to 12.9 km) wide and is a little more than 200 ft (61 m) deep [12]. The valley trends nearly 90 miles (145.2 km) east-southeast to Fort Quitman, where the valley is constricted between the Sierra de La Cieneguilla and the Quitman Mountains. The valley deepens along its course and is almost 330 ft (100.6 m) deep near Fabens, 30 miles (48.4 km) below El Paso. The valley wall is penetrated by many arroyos that incise the Hueco Bolson and floodplain surfaces. San Felipe Arroyo is one of many such arroyos extending along the slope front between older basin-fill and the modern Rio Grande floodplain (Figures 1 and 2).

The Hueco Bolson deposits lie comfortably beneath the Rio Grande alluvium. Basin fill sediments in the Hueco Bolson are usually weakly consolidated, heterogeneous materials that overlay Precambrian

through Tertiary rocks [13]. Fort Hancock deposits in the Hueco Bolson include lacustrine muds, interbedded with layers of bentonitic claystone and siltstone and some discontinuous sand lenses (Table 1). Overlying the Fort Hancock Formation is the Camp Rice Formation, a Pliocene unit consisting of stream-channel and floodplain deposits that are the most prolific in terms of water supply (Table 1). Camp Rice deposits are juxtaposed against fanglomerates that flank the margin of the basin [14]. Deposits in the Camp Rice Formation include predominantly gravels and sands, interbedded with muds, volcanic ash, and caliche [13,15]. Camp Rice deposits were formed by ancestral channels of the Rio Grande.

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 Rio Grande Aquifer. Groundwater in the alluvium interacts with the deeper Hueco Bolson Aquifer. Ample fluid exchange has been recorded between the Hueco Bolson Aquifer, Rio Grande Aquifer, and Rio Grande [16,17].

Salinity maps prepared for the Rio Grande Aquifer showed distinct variations and generally moderately high salinity of 2000 to 5000 mg/L total dissolved solids (TDS) between the cities of El Paso and Tornillo, Texas (Figures 2 and 3). In the upper part of El Paso Valley, salinity of the alluvium is usually between 1000 and 2000 mg/L TDS near the Rio Grande, as a result of pumping induced infiltration of better quality river water into the river alluvium [12,16,17]. In the study area near Fabens, the presence of a large but isolated lens of dilute water at the boundary between older basin fill and Rio Grande alluvium led many analysts to conclude that the dilute water developed due to runoff drawn in by San Felipe Arroyo (Figures 2 and 3). Recharge is believed to have occurred at the slope break between older valley fill and floodplain alluvium. Several authors cited slope-front recharge at the San Felipe Arroyo due to runoff in the arroyo:

"In the valley downstream of El Paso most wells are relatively shallow and the water, with the exception of the public supply at Fabens, is in general more or less highly mineralized". [18]

"Between Socorro and the El Paso-Hudspeth County line, most of the water in the alluvium contains more than 2500 mg/L dissolved solids. In the area near Fabens, the improved water quality probably results from inflow from arroyos entering the valley in this vicinity". [19]

" . . . .an influx of fresh-water near Fabens which is probably a result of recharge from San Felipe Arroyo". [12]

"An alluvial fan from the [San Felipe] arroyo spreads out over Recent alluvium. Such fans are loci for ground-water recharge from surface-water flows in the arroyos". [20]

The working hypothesis in these studies presumes that dilute groundwater near San Felipe Arroyo is caused by local runoff and slope-front recharge at the basin fill/floodplain margin. The data presented in this paper establish that this model of recharge does not accurately define the actual recharge process near San Felipe Arroyo. The model presented in this paper is developed on the basis of environmental isotopes tested in shallow and deep groundwater at and near the dilute groundwater lens near Fabens. Local hydrogeological complexities of the Hueco Bolson and associated Rio Grande floodplain accounts for a completely different conceptual model of recharge. This work shows that recharge occurred primarily by infiltration of water from the pre-dam Rio Grande water, and not from local runoff within the Hueco Bolson.
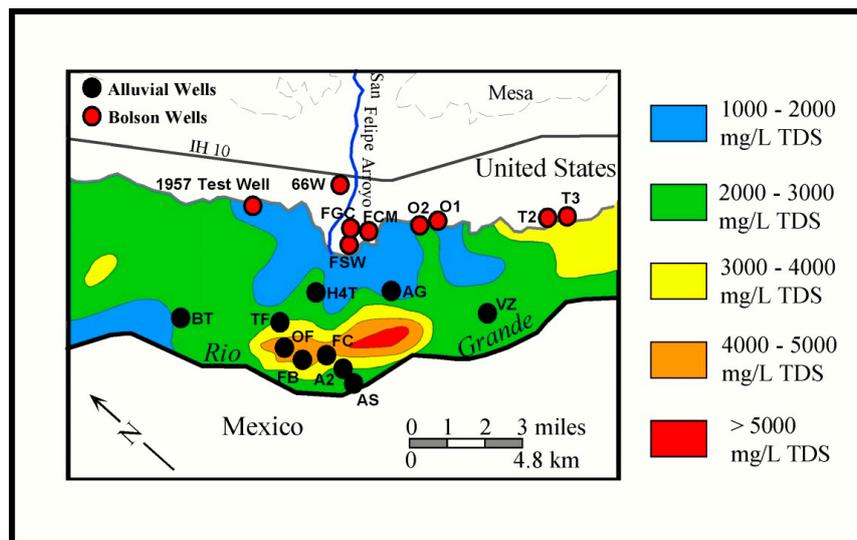
Figure 3. Study area map showing salinity of the Rio Grande Aquifer in the vicinity of Fabens, Texas showing that the most dilute water in the area is near San Felipe Arroyo. This figure also shows wells sampled in this study (alluvial aquifer salinities mapped by Alvarez and Buckner [12]; index map location shown in Figure 2).

1.2. Basinwide Water Types

In order to define water types in the San Felipe Arroyo/Fabens/Tornillo area, it is necessary to identify basinwide water types in surface water and groundwater in the Hueco Bolson. Regional studies by numerous authors [17,21–24] provided isotopic evidence of interaction of groundwater and surface water in different parts of the Hueco Bolson. Eastoe et al. [24] identified differences in isotopic signatures in groundwater sampled in the Rio Grande Aquifer, in the Texas portion of the Hueco Bolson, and in the Mexican portion of the Hueco Bolson. They found that Rio Grande water and most groundwater in the Rio Grande Aquifer has been affected by evaporation in upstream reservoirs in New Mexico, the largest of which, Elephant Butte Dam, was completed in 1916 (Figure 1). Groundwater 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. Groundwater in the Mexican portion of the Hueco Bolson has isotopic signatures that are consistent with pre-dam snow melt from Colorado and northern New Mexico, the source area for most of the flows of the Rio Grande. A general shaded depiction of these isotopic types is shown in Figure 4. These patterns represent the general isotopic signature of groundwater over a major part of the Hueco Bolson [24]. The main water types that are pertinent are the Franklin Mountain water type plotting near the Global Meteoric Water Line, and pre-dam and post-dam Rio Grande water types plotting along the Rio Grande Evaporation Line (Figure 4). The Rio Grande Evaporation Line was defined by previous investigators based on runoff into the Rio Grande from snow melt and precipitation in Colorado and northern New Mexico [24]. Aquifers in the Rio Grande Basin that are recharged by Rio Grande water plot near the Rio Grande Evaporation Line because the aquifers were replenished by infiltrating river water. Aquifers in the Rio Grande Basin in southern New Mexico and western Texas that are recharged by local precipitation usually plot in isotopically distinct ranges because of different isotopic signature of precipitation in southern latitudes [25]. Consequently, it is often possible to distinguish local sources of recharge from river recharge in this area [24].
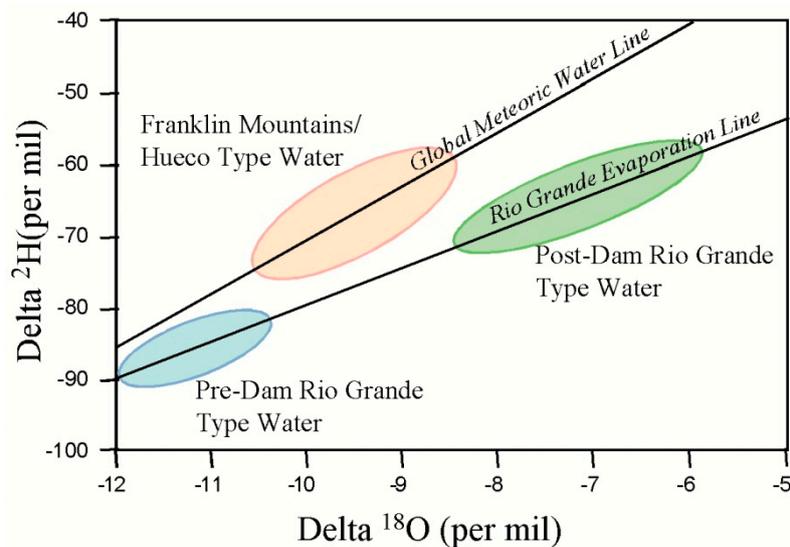
Figure 4. Major regional water types in the Hueco Bolson and stable water isotopes plotted for alluvial and bolson water wells sampled in this study. Regional water types include local recharge waters that characterize the Franklin Mountains/Hueco-type water and pre-dam and post-dam Rio Grande water.

Pre-dam water is temporally referenced water because it is water that flowed down the Rio Grande before large dams were constructed in the Rio Grande Basin. Pre-dam water is not as evaporated as post-dam water because it was not retained in reservoirs. Post-dam water is withheld in reservoirs and is consequently much more evaporated. Water residence time in Elephant Butte dam is approximately 2.2 to 2.5 years and retention in the reservoir leads to evaporative enrichment of stable water isotopes. Post-dam water is easily distinguished from pre-dam water because it is evaporated and of younger age (Figure 4). Average pre-dam water is −10.5 to −12.0 per mil $\delta^{18}O$ while that of post-dam water, which is much more evaporated, is −5.7 to −8.5 per mil $\delta^{18}O$ (Figure 4). Readers unfamiliar with isotopic age dating and water isotope fractionation may refer to Eastoe et al. [24] and Clark and Fritz [25] for general details.

2. Methods

Regional groundwater sampling for isotopic analysis was previously conducted in the Hueco Bolson and Rio Grande Aquifers in the United States and Mexico. Over 200 water wells were sampled [21–24]. These studies defined regional isotopic variations and distinct types in surface water and groundwater in the Hueco Bolson [24]. Groundwater sampling was performed across the area near and adjacent to San Felipe Arroyo. High capacity municipal and irrigation wells, shallow domestic wells, and two single hand-installed piezometers were sampled (Figure 3). Deeper bolson wells in the Fabens/Tornillo area have total depths usually between 160 and 350 feet (48.8 and 106.7 m) below land surface (Table 2). Shallow wells sampled in Rio Grande alluvium were less than 120 feet (36.6 m) deep (Figure 3). Unfortunately, well screen intervals are not known for virtually all of these shallow wells in the Rio Grande alluvium. It is customary to install single perforated screens of 10 to 80 ft (3.0 to 24.4 m) in length in these shallow wells. The bottom of the screen is almost always installed at the bottom of the well.

Prior to sampling groundwater, water wells were purged and stabilized. To purge wells, the well was pumped until at least three casing-volumes of water were evacuated prior to 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 evacuate at least three casing volumes. Wells without dedicated pumps were purged, and samples were collected using a Grundfos or whaler pump.

Table 2. Information on water wells sampled in the study area, including map well index, environmental isotope data, and water type identified as pre-dam, post-dam, or mixed pre- and post-dam (Figure 3 shows well locations).

Well ID	Map Well Symbol	Well Depth (ft)	Date Sampled	Water-Bearing Strata	$\delta^{18}O$ per mil	δ^2H per mil	Tritium (TU)	C-14 (pMC)	Water Type
Tornillo Well 2	T2	257	9/19/2002	Bolson Fill	−11.5	−89	<0.5	62.6	Pre-Dam
Tornillo Well 3	T3	284	8/22/2002	Bolson Fill	−11.5	−90	<0.5	68.5	Pre-Dam
Fabens 10th Street Well	FSW	328	11/13/2002	Bolson Fill	−11.1	−86	<0.6	NA	Pre-Dam
Fabens CM Well	FCM	315	11/13/2002	Bolson Fill	−10.9	−82	5.2	91.9	Pre-Dam
Fabens GC Well	FGC	350	11/13/2002	Bolson Fill	−11.0	−86	2.8	81.4	Pre-Dam
* Oro-Well 2	O2	~160	7/26/2006	Bolson Fill	−11.1	−86	<0.4	62.1	Pre-Dam
* 66 Well	66W	183	8/22/2005	Bolson Fill	−10.5	−84	NA	NA	Pre-Dam
* Oro-Well 1	O1	~120	7/26/2006	Bolson Fill	−9.6	−76	2.9	97.4	Mixed Pre- and Post-Dam
Hansen 4T Well	H4T	<120 est	7/14/2014	River Alluvium	−8.8	−73	5.2	102.8	Mixed, Mostly Post-Dam
Aliens 2000 ft Well	A2	10	5/5/2004	River Alluvium	−8.7	−70	3.8	97.3	Mixed, Mostly Post-Dam
Augustine Well	AG	116	5/4/2004	River Alluvium	−8.4	−72	6.5	99.8	Post-Dam
Thief Well	TF	<120 est	3/22/2004	River Alluvium	−8.2	−68	6.3	110.0	Post-Dam
Aliens Shallow Well	AS	8.9	12/3/2003	River Alluvium	−8.2	−69	NA	101.9	Post-Dam
Blue Thief Well	BT	<120 est	4/3/2004	River Alluvium	−8.1	−68	10.5	104.6	Post-Dam
Vasquez Well	VZ	50	5/5/2004	River Alluvium	−8.0	−69	12.2	113.9	Post-Dam
Orlando Flores Well	OF	38	5/4/2004	River Alluvium	−7.8	−68	11.1	107.1	Post-Dam
Francione Well	FC	24	12/10/2003	River Alluvium	−7.7	−67	NA	113.7	Post-Dam
Fabens Church Well	FB	97	3/21/2004	River Alluvium	−7.5	−66	8.1	106.6	Post-Dam

NA—not available; * post-audit well.

All samples for isotopic analyses were collected in new high density polyethylene HDPE bottles and 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.

Groundwater samples were collected for general minerals, halides, O-H stable water isotopes (δ^2H and $\delta^{18}O$), sulfur isotopes, tritium, and carbon-14 analyses. Only stable water isotope and radioisotope data are discussed in this paper. Stable water 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 (IRMS) following reduction with Cr [26] or CO_2 equilibration [27,28], respectively. Results were expressed as δ^2H and $\delta^{18}O$ in per mil (‰) relative to the standard VSMOW [29] with analytical precisions of 0.9 ‰ and 0.08 ‰, respectively.

Tritium samples were enriched nine-fold 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 (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 carbon-14, approximately 2 cm^3 of gaseous CO^2 from water sample dissolved inorganic carbon was extracted 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 (pMC) relative to the NBS oxalic acid I and II standards.

3. Isotope Results and Discussion

3.1. Study Area Water Types

Groundwater data collected in the Fabens and Tornillo area from wells T2, T3, FSW, FCM, and FGC (Table 2) are plotted in the overlapping isotopic ranges determined by Eastoe et al. [24]. (Figure 5). Groundwater samples collected from deeper municipal wells in Fabens and Tornillo, near San Felipe Arroyo, and groundwater collected from shallow wells in the Rio Grande Aquifer indicate that all groundwater samples are river water of different age. All data plot along the Rio Grande Evaporation Line. The testing of groundwater samples for stable water isotopes shows that the deeper and more dilute waters near San Felipe Arroyo in Fabens and Tornillo are pre-dam waters recharged from the pre-dam Rio Grande (Figure 5). Waters in the isotopic range of lighter than -10.5 per mil $\delta^{18}O$ were shown in earlier studies in the Hueco Bolson to originate from highlands in Colorado and Northern New Mexico [24]. Such isotopically light groundwaters could not have been sourced from any local meteoric input in the Hueco Bolson, nor from any of its surrounding highlands. These are pre-dam waters from the Rio Grande. Samples collected from the Rio Grande Aquifer usually plot in the range of post-dam Rio Grande water (Figure 5).

Radioisotope data offer clues to the age of groundwater the pre-dam and post-dam Rio Grande ranges (Table 2). Pure pre-dam Rio Grande water typically has no detectable tritium and carbon-14 usually less than 70 pMC. Post-dam Rio Grande water always contains tritium above 0.5 tritium units (TU) and carbon-14 usually greater than 100 pMC (Table 2). Tritium greater than 0.5 to 0.8 tritium units (TU) typically indicates post-1952 water is present [24,25]. Mixing of pre-dam and post-dam water will provide tritium and carbon-14 less than approximately 90 pMC. Radioisotope ranges for pre-dam and post-dam Rio Grande water are equivalent to interpreted activities of pre-dam water found in deeper bolson fill beneath Ciudad Juarez [24] and for post-dam Rio Grande water in the Rio Grande Aquifer [22].

Tritium above 0.5 TU is found in Fabens water supply wells which appear to be mostly pre-dam water (Table 2). Pre-dam water probably mixes with smaller amounts of post-dam water to account for the tritium shows in the Fabens wells (Table 2). Evidence for a mixture of pre- and post-dam water includes higher carbon-14 activities in the Fabens wells with tritium, and slightly heavier stable water isotopes values in the Fabens wells (Table 2). Multiple well screens at different intervals probably accounts for a small amount of post-dam Rio Grande water with tritium in the Fabens wells; the shallowest screens pulling in tritium-laden groundwater. The fact that two deep wells, Fabens CM Well and Fabens GC Well, contain 5.2 and 2.8 TU, respectively, probably indicates the presence of bomb tritium, which would have been very enriched in tritium when recharged.

Three additional wells, Oro-Well 1, Hansen 4T Well, and Aliens 2000-ft Well, show a clearly-defined pre- and post-dam river water mixture based on water isotopes. All contain detectable tritium and carbon-14 signatures reflecting mixtures of pre- and post-dam Rio Grande water (Table 2).
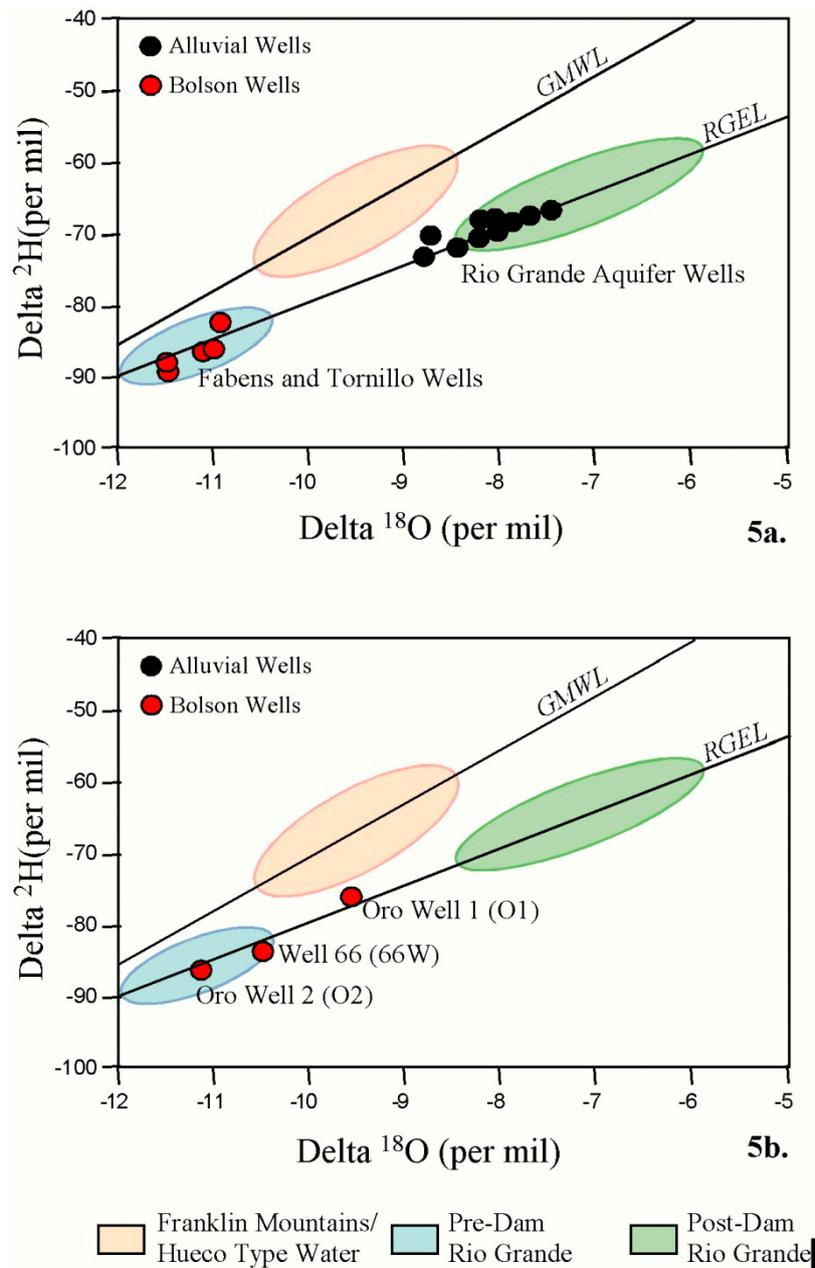
Figure 5. Rio Grande Aquifer samples plot in the post-dam Rio Grande region primarily while deeper bolson wells at the Cities of Fabens and Tornillo plot in the pre-dam Rio Grande range (**a**). Post-audit groundwater sampling for the purposes of hypothesis evaluation confirms additional well control (Well 66 and Oro Well 2) contains pre-dam water while a shallower well (Oro Well 1) near Oro Well 2 contains a mixture of pre-dam and post-dam Rio Grande water (**b**).

3.2. Post-Audit Isotope Data

These unexpected results indicated the need for more well samples for testing and confirming a pre-dam source of recharge in the study area. Additional groundwater samples were collected strategically; one well (66W) was sampled in an area north of the Fabens municipal wells, and two wells (O1 and O2) were sampled at the midpoint between Fabens and Tornillo (Figure 3). All of these post-audit wells are in the vicinity of San Felipe Arroyo. The wells selected for post-audit sampling and shown in Figure 3 included "Well 66" (66W) and "Oro Wells 1 and 2" (O1 and O2). Well 66, located at the I10 Freeway, is a shallow water supply well, 184 ft (56.1 m) deep that is located 1.5 miles (2.4 km)

north of the northern edge of the Rio Grande floodplain. Oro Wells 1 and 2 are 120 ft (36.6 m) and 160 ft (48.8 m) deep, respectively, and sit at the northern edge of the Rio Grande floodplain. Well 66 was sampled in August 2005 and Oro Wells 1 and 2 were sampled in July 2006. Post-audit sampling was performed 3 to 4 years after initial sampling of Fabens and Tornillo municipal supply wells, after the hypothesis of recharge by pre-dam water at San Felipe Arroyo had already been developed [30].

Stable water isotope results indicate that Well 66 and Oro Well 1 contain mostly pre-dam Rio Grande water (Figure 5; Table 2). The shallower well, Oro Well 2 contains post-dam Rio Grande water with a moderate percentage of pre-dam water (Figure 5). Radioisotopes are not available for Well 66. There is 62.1 pMC and no measurable tritium in Oro Well 1 and 2.9 TU and 97.4 pMC in Oro Well 2 (Table 2). The results of radioisotope and stable water isotope data indicate that groundwater at Oro Well 1 is older river water, consistent with indices determined for other pre-dam Rio Grande waters found in other areas of the Hueco Bolson [24].

When all groundwater samples with corresponding carbon-14 values are plotted against $\delta^{18}O$ in a bivariate scatter plot, a clear relationship is observed between isotopically light and older groundwater defined by carbon-14 (Figure 6). The pre-dam water, having resided in the aquifer for a longer period of time than post-dam water, probably incorporated some dead carbon from dissolution of aquifer cements. This will produce apparent carbon-14 ages that do not reflect the true age of pre-dam groundwater. No attempt is made to provide age-dating corrections to the carbon-14 data. Rather, the radioisotope data are used for semi-quantitative determination of groundwater age via a correlation with water isotope data in the pre-dam and post-dam periods. The isotopically lightest groundwater and the smallest percentages of modern carbon are demonstrably related to pre-dam water with no tritium (Figure 6). Likewise, the isotopically heaviest groundwater has the greatest amount of modern carbon, and always contains tritium (Figure 6).
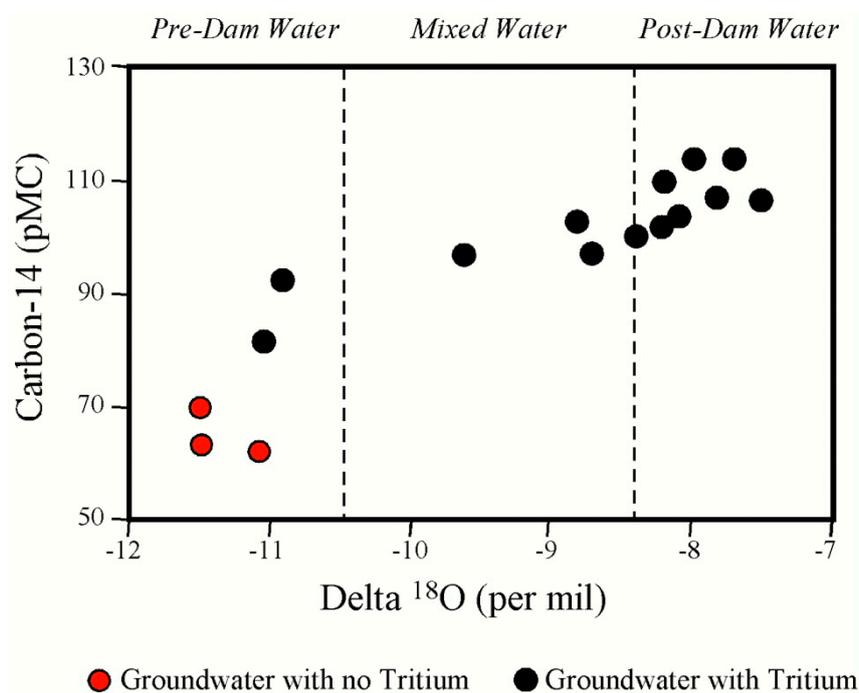

Figure 6. Water isotope and carbon-14 scatter plot using data from Table 2. A clear relationship is observed between isotopically light and older groundwater defined by carbon-14. Stippled vertical lines define dominant water types in the data set.

4. Hydrogeological Framework and Recharge Dynamics

Our data provide a strong case for recharge near San Felipe Arroyo from pre-dam Rio Grande water, and not from local runoff into the arroyo. The geologic and hydrogeologic data lend credible

evidence to a new model of recharge by cross-formational flow and movement downward from Rio Grande alluvium into deeper Hueco Bolson deposits. Surprisingly, the pre-dam water appeared at least as far north as the Interstate 10 Freeway, where Well 66 produces pre-dam water derived from the Rio Grande (Figures 3 and 5).

Overall, radioisotope and stable water isotope data found in deep wells are consistent with pre-dam Rio Grande water in the area near San Felipe Arroyo and extending south and east to Fabens and Tornillo. The results are hydrogeologically intriguing; how does pre-dam water reach depths of at least 350 ft (106.7 m) in the study area? Isotope results in groundwater at Oro Wells 1 and 2 imply there is net downward movement of pre-dam Rio Grande Water due to a natural hydrogeological gradient (Figure 7). The deeper Oro Well 2 contains pre-dam Rio Grande water. The Fabens and Tornillo municipal wells where pre-dam water is found are even deeper than the Oro wells (Table 2).
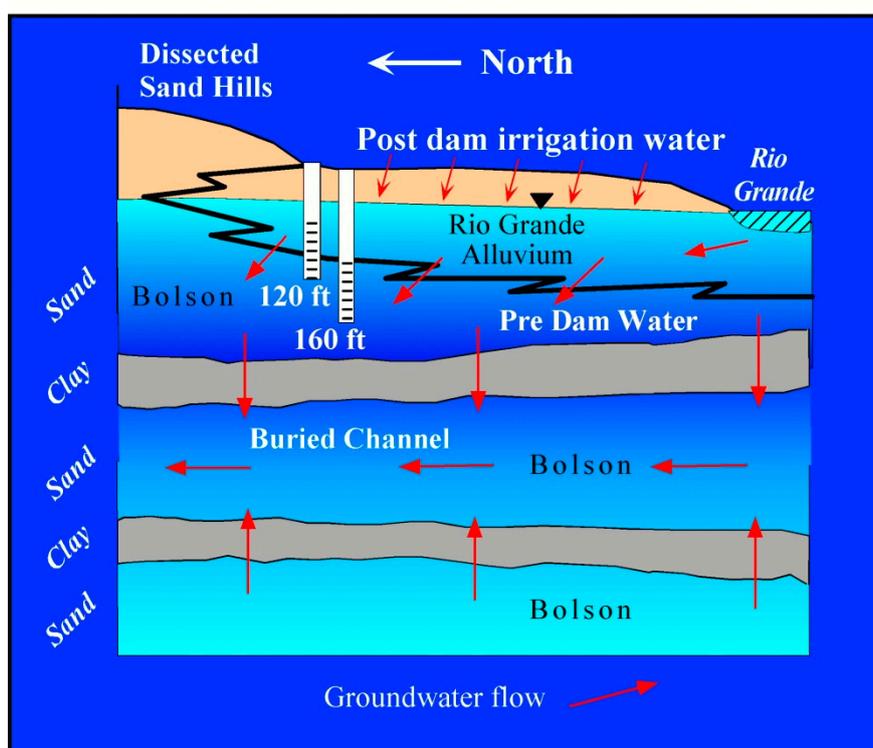

Figure 7. Conceptual model for groundwater flow to a deeper buried channel in the study area. The diagram frames isotope data and hydrogeologic setting at Oro Well 1 (120 ft deep) and Oro Well 2 (160 ft) in the conceptual framework image.

Geological evaluation provides insights on these intriguing results. A conceptual diagram illustrates how pre-dam waters must have recharged deeper strata beneath San Felipe Arroyo at the edge of the Rio Grande floodplain, allowing groundwater to reach depth (Figure 7). A permeable sink must be present at depth in order for groundwater to flow downward. Flow occurred in the pre-dam/predevelopment period before pumping stresses were active in the region.

An examination of the geological and riverine history of the area indicates that there is a buried stream channel north of Fabens that was formed by the ancestral Rio Grande [11]. This buried channel underlies the San Felipe Arroyo (Figure 8). The ancestral channel is a channel branch in the upper part of the Camp Rice deposits of the Hueco Bolson and is between one and two million years old [31]. It may have developed when the ancestral Rio Grande flowed through the Fillmore Pass gap between the Organ and Franklin Mountains [32,33]. The ancestral Rio Grande was diverted away from the Hueco Bolson, due to tectonic uplift between the Franklin and Organ mountains, approximately 1 million years ago [33]. After diversion of the ancestral Rio Grande, the bolson did not receive

flows from the Rio Grande for at least another 350,000 years. The Rio Grande was well established in Northern New Mexico to the Gulf of Mexico by around 0.65 m.y. ago and it had entrenched to near present floodplain level by approximately 0.3 m.y. ago [31]. The present El Paso Valley was superimposed on the older Camp Rice deposits [33]. Additional evidence of the existence of the buried channel includes borehole geophysical data, test-hole geological logs, and surface electrical resistivity sounding data [11]. Gates and Stanley [11] suggest that the buried channel reaches depth of at least 570 ft (173.8 m) or greater depth in the Fabens-Tornillo area.
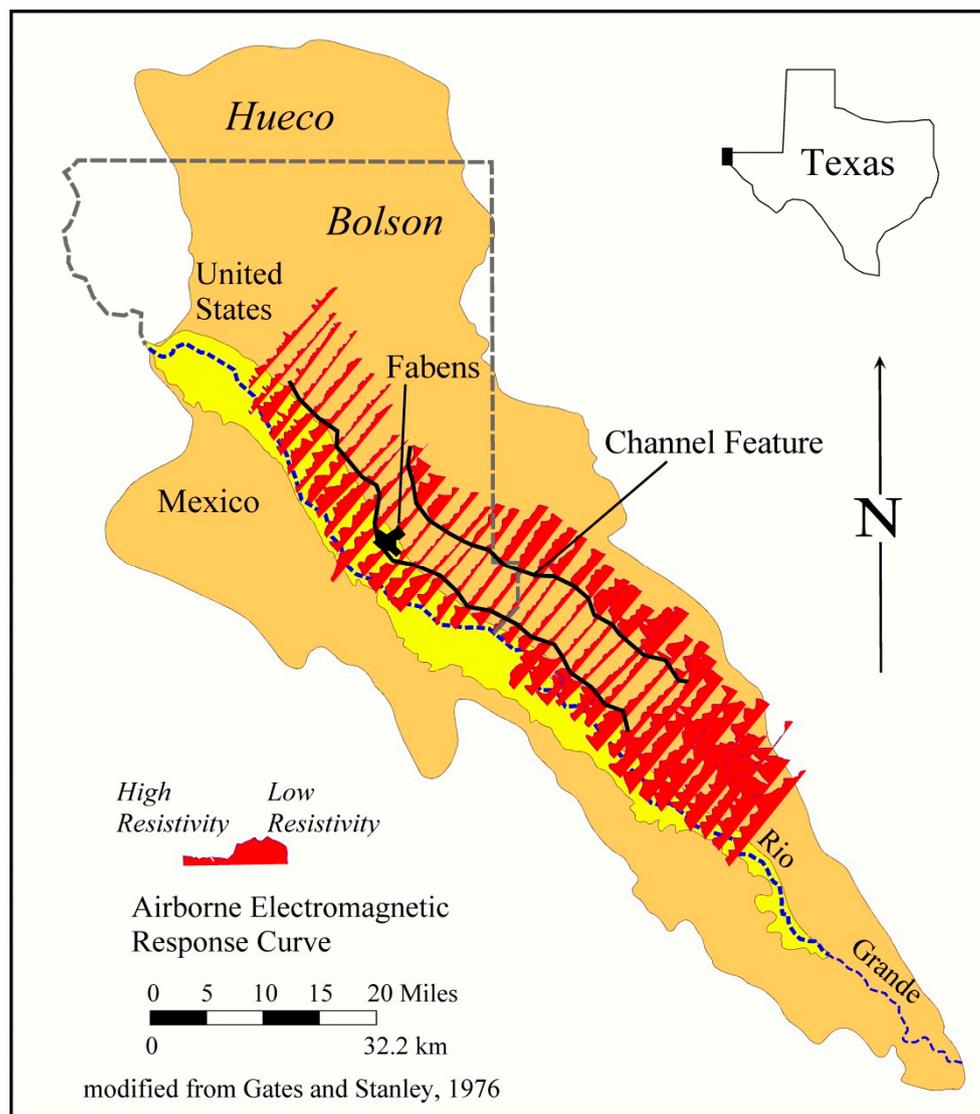

Figure 8. Airborne geophysical mapping by Gates and Stanley [11] identified a buried channel in the vicinity of Fabens. They interpreted this channel as part of the upper Camp Rice Formation formed by the ancestral Rio Grande.

The buried ancestral channel must have a source of pre-dam Rio Grande water in order for recharge of pre-dam water to occur near Fabens and Tornillo. The source of pre-dam water is established by geomorphological lines of evidence. Historic floodplain maps prepared by the International Boundary and Water Commission (1938) establish the pre-dam water source (Figure 9). These maps provide a record of a shift in the Rio Grande that happened in 1857 [34]. This shift placed the active river channel directly south of Fabens. This shift created a region between two alternating active channels of the Rio Grande known as "San Elizario Island". The main Rio Grande Channel remained near Fabens for

several decades until at least the early 1930s based upon the map published in Darton [35] (Figure 10). The Rio Grande channel was permanently rectified to its present location by 1938 (Figure 9).
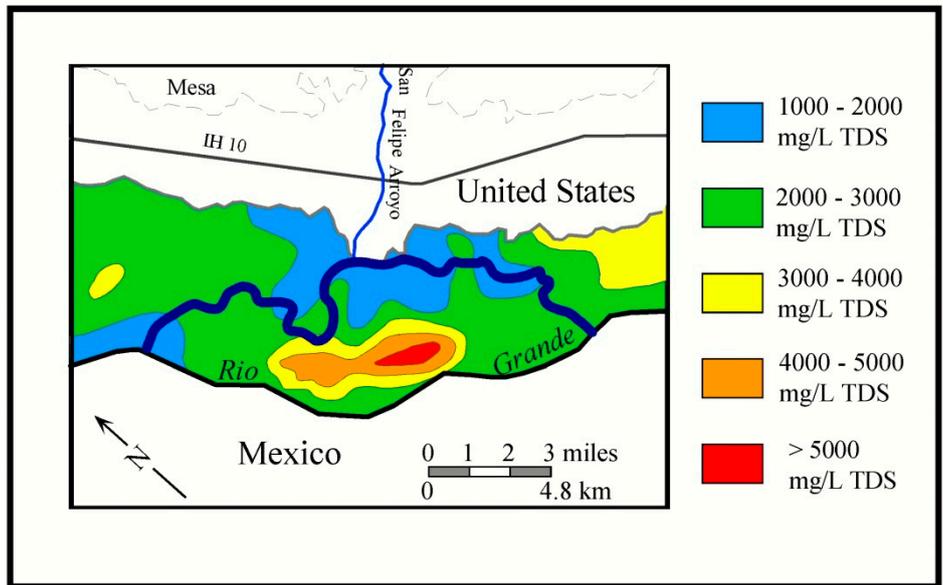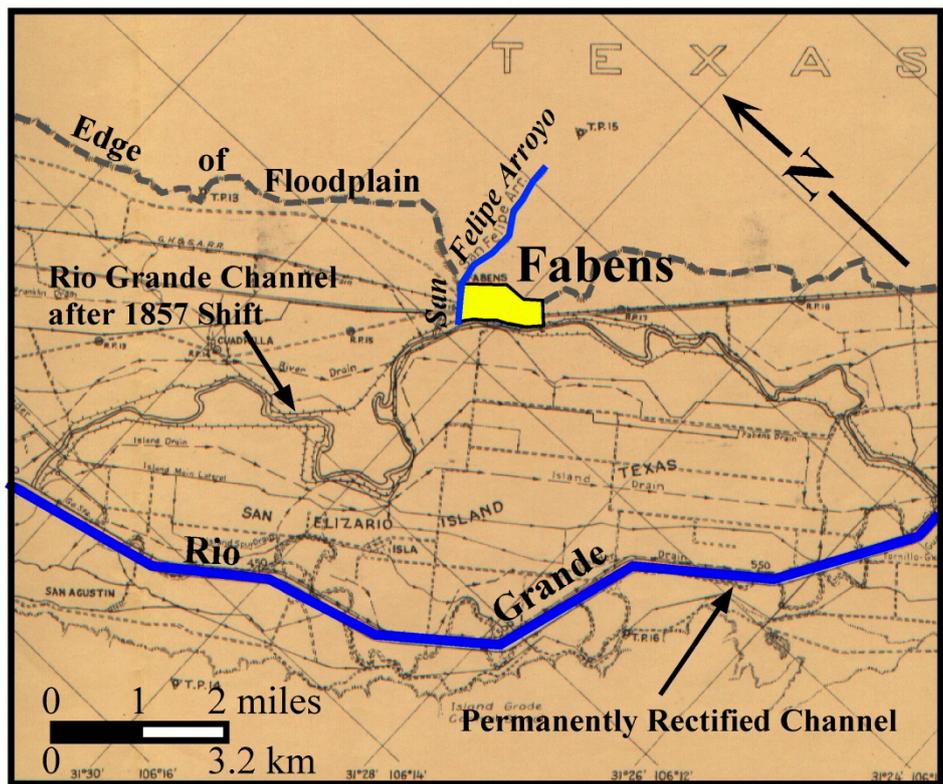
Figure 9. Comparison of the Rio Grande Aquifer salinity map of Alvarez and Buckner [12] with the historic trajectory of the pre-dam Rio Grande, prior to channel rectification completion in 1938. The old channel is shown near Fabens, Texas in the historic map of the irrigation district [36]. The dilute groundwater water presented in Alvarez and Buckner [12], blue color) and the sweet water in deeper wells in the Fabens/Tornillo area appears to have been sourced from the pre-dam Rio Grande and not from San Felipe Arroyo, based on environmental isotopes and geological framework (**a**). The Rio Grande flowed near Fabens for several decades prior to channel rectification (**b**).
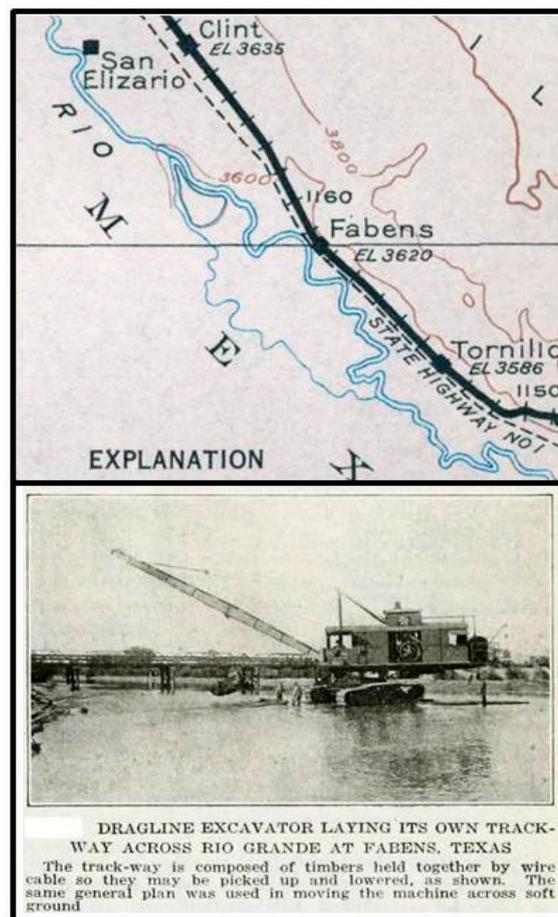
Figure 10. The historic path of the main Rio Grande channel near Fabens in the early 1930s is shown in Sheet 17 in Darton [35]. A photo published in Burkholder [37] depicts excavation works at the main Rio Grande channel near Fabens.

Stream avulsion placed the Rio Grande on the south side of Fabens for many decades and provided an ample source of pre-dam water near the buried stream channel identified by Gates and Stanley [11]. A map overlay shows a clear relationship between the Rio Grande channel near Fabens, and dilute water in the Rio Grande Aquifer mapped by Alvarez and Buckner [12] (Figure 9). The dilute groundwater is demonstrably shown by environmental isotopes to be pre-dam water, sourced from the pre-rectification channel that defined the active Rio Grande channel for many decades. The main Rio Grande channel that existed near Fabens from 1857 to the early 1930s was the most recent channel avulsion prior to permanent channel rectification.

Hall and Peterson [38] mapped an earlier channel avulsion that placed the active Rio Grande channel near Fabens for several decades prior to 1829. They called the channel the Rio Viejo del Bracito (Figure 11). The Rio Grande Channel close to its present rectified location was reoccupied in 1829 before the Fabens avulsion occurred in 1857 (Figure 11). This places pre-dam water near Fabens for an extended period of time prior to permanent channel rectification. In earlier studies, pre-dam water was found in the Rio Grande Aquifer at a few additional locations in El Paso and Hudspeth County [22,39]. Frequent channel avulsion and other hydrogeologic factors account for pre-dam water still residing at a few places in the Rio Grande Aquifer. In other areas, most pre-dam water has been flushed out and diluted by application of copious quantities of post-dam irrigation water.
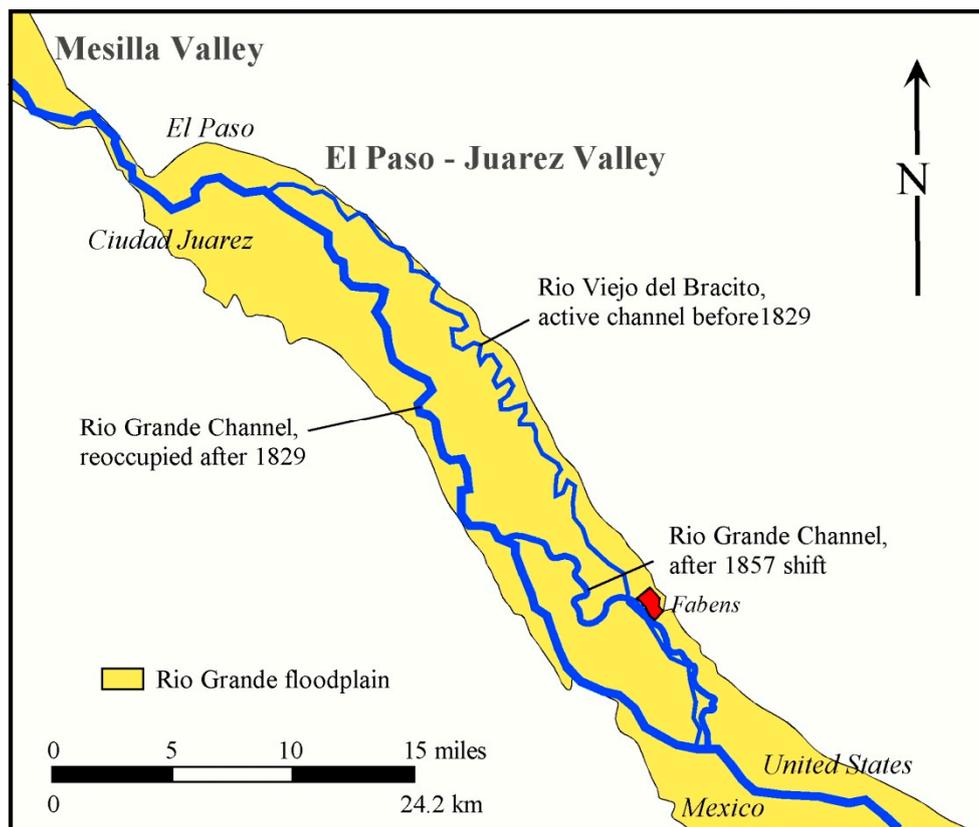
Figure 11. A channel avulsion places the active Rio Grande channel near Fabens prior to 1829. Hall and Peterson [38] called the channel the Rio Viejo del Bracito. The Rio Grande channel, close to its present day location, was reoccupied in 1829 before the subsequent Fabens channel avulsion occurred in 1857. This places pre-dam water near Fabens for extended periods of time prior to permanent channel rectification. Figure modified from Hall and Peterson [38]. Pre- and-post 1829 channel delineation from Hall and Peterson [38] and 1857 channel delineation from IBWC [36].

4.1. Historical and Modern Hydraulic Head Data in Relation to the New Conceptual Model

Conditions allowing the unique recharge phenomena include a buried channel underneath San Felipe Arroyo formed by the ancestral Rio Grande, and channel avulsion of the modern Rio Grande providing a ready source of pre-dam water near Fabens and Tornillo. The buried alluvial channel appears to be a vertical sink for groundwater recharge (Figure 8). Avulsion of the modern Rio Grande prior to completion of permanent channel rectification in 1938 led to the source of pre-dam Rio Grande water at the dilute groundwater lens in predevelopment times. A natural hydrogeologic condition must allow postulated downward flow. Hydraulic head conditions in predevelopment times must be considered because pumping-stresses did not exist in Fabens or Tornillo when pre-dam Rio Grande water was, according to postulated conceptual model, being recharged to depth.

The Fabens and Tornillo wells extract water from semi-confined strata in bolson fill [11,12]. Sustained pumping in the semi-artesian systems has produced small cones of depression extending across the Fabens and Tornillo area where the environmental isotope data were collected. Contemporary hydraulic head data cannot be used to establish a natural hydraulic sink for downward vertical flow in the predevelopment period because the drawdown cones have changed predevelopment hydraulic head gradients. Earlier hydraulic data are preferable to help establish whether a natural vertical hydraulic head gradient might have existed in the pre-dam period, allowing groundwater to move vertically downward into deeper bolson strata.

The best available hydraulic head providing possible evidence for downward vertical flow is from test-hole drilling carried out by the USGS in 1957 [40]. At a nested test-hole site near Fabens, a drilling procedure was developed where the drill bit was advanced to a permeable zone of interest to test for water production and suitable water quality (Figure 3). This test hole is identified as Texas State Well #49-31-901. As the test hole was being drilled, inflatable packers were set up in the borehole to isolate a permeable zone for water quality sampling. After the packer zone was developed to free drilling mud from the formation and to collect water quality samples, a period of time elapsed before hydraulic head was measured during recovery of the packer zone (Table 3). Unfortunately the packer slipped in the shallowest 324–344 ft (98.8–104.9 m) depth zone (Table 3) and no hydraulic head data are available at that depth. Two Rio Grande Aquifer wells, Texas State Well #49-31-801 and #49-31-806 had been installed very close to the test-hole years before test-hole drilling commenced. Static water level data for these wells were collected a few years before test-hole drilling at Well #49-31-901 (Table 3). The two shallow water level measurements in nearby wells are used as proxy hydraulic head data for shallow strata near the nested test hole.

Table 3. Hydraulic head data derived from vertical packer testing of a bore-hole at Texas State #49-31-901 and hydraulic head data from two shallow water wells adjacent to the test hole (Figure 3 shows year 1957 test-hole location).

Well ID/Year Measured	Depth Tested (ft Below Ground Surface)	Time Since Pumping Interval Stopped (Minutes)	Water Level in Well/Test-Hole Interval (ft bgs)	Land Surface Elevation (ft)	Hydraulic Head (ft)
** 49-31-801 (1950)	70	Static	20	3625	3605
** 49-31-806 (1951)	100	Static	16	3630	3614
Upper data are derived from shallow Rio Grande Aquifer wells very close to test hole 49-31-901					
* 49-31-901 (1957)	324–344	Packer Slipped		3632	–
* 49-31-901 (1957)	793–813	12 20	72.8 69.3	3632	[1] 3559.2 [1] 3562.7
* 49-31-901 (1957)	1325–1345	75	1.5	3632	3630.5
* 49-31-901 (1957)	1596–1636	50	15.0	3632	3617

[1] lowest hydraulic head is recorded at this depth interval. * test-hole data from Audsley, 1959; ** shallow well data from Alvarez and Buckner, 1980.

When proxy hydraulic head data in the nearby shallow wells are compared to test-hole head data, results indicate that the zone that was packer tested at 793–813 ft (241.8–247.8 m) beneath land surface had hydraulic head that was approximately 50 ft (15.2 m) lower than the measured zones above and below this depth zone. If these data represent natural hydraulic head conditions, the head relationships support the conceptual model of a water-bearing zone at depth with hydraulic head lower than head in water-bearing zones above and below (Table 3).

These data must be interpreted conservatively due to the method of pumping within a discrete packer zone, allowing recovery for only 20 to 75 min after pumping stopped. The data lend support to the existence of a groundwater sink where hydraulic head is lower than vertically adjacent water-bearing strata. No wells are known in the Fabens-Tornillo area that extract water at the packer depth of 793–813 ft (241.8–247.8 m). As a result, the extent to which aquifer development had occurred in 1957 probably could not account for lower hydraulic head in this depth zone.

The assumption of almost full head recovery after 20 min in the 793–813 ft (241.8–247.8 m) deep packer test zone is a limiting factor in this analysis (Table 3). The packers were set in permeable sand zones encountered during drilling. The purpose of test-hole drilling was to find water-bearing strata of sufficient chemical quality to produce water in copious quantities. It is possible that the short recovery period was sufficient for hydraulic head to approach static water level. The fact that water-level

measurements were made during these tests implies the USGS may have considered water-bearing zones to be almost recovered after packer zone evacuation. The reliability of the data is limiting and the question of almost full recover of packer test zones will never be known because the report by Audsley [40] does not provide further details. What is certain is that pre-dam Rio Grande water is found at depth in the study area, and older Rio Grande water could not have percolated to these depths unless a vertical hydraulic head gradient was directed downward during predevelopment times.

4.2. Groundwater Discharge Area

There are questions on the area of discharge of the pre-dam water that was recharged in pre-development times near Fabens and Tornillo. Fluid mass balance prescribes that groundwater flows from recharge to discharge areas. We did not find evidence of traceable pre-dam water discharge at any area located down-valley of Tornillo. Paucity of well control, particularly in the Hueco Bolson deposits southeast of Tornillo, precludes tracking the movement of the pre-dam water beyond the vicinity of Fabens and Tornillo. The most likely area of discharge is to the southeast of Tornillo along the axis of the Rio Grande floodplain, where groundwater probably moves upward from Hueco Bolson deposits into the Rio Grande alluvium. Dilution of pre-dam water by copious amounts of modern Rio Grande water in irrigable tracks of land may mask the isotopic signature of pre-dam water where it ultimately follows trajectories to areas of discharge.

It is interesting to note that the channel feature identified by Gates and Stanley (1976) reaches its terminal point approximately 25 miles (40.3 km) southeast of Fabens (Figure 8). Gates and Stanley [11] postulated that the channel either terminated in a paleo-lake, or possibly turned south to a position now occupied by the modern Rio Grande. In the latter scenario, the modern Rio Grande may have eroded the remnants of the buried channel formed by the ancestral Rio Grande, creating an abrupt and artificial termination of the buried channel [11].

4.3. Summary Model of Historical Recharge and Implications for Modern Recharge

The aquifer beneath Fabens and Tornillo does not appear to be recharged to any degree by San Felipe Arroyo; the aquifer in this area was replenished by a pre-dam source. The pre-dam Rio Grande water was historically of relatively good quality entering the El Paso Narrows, except during periods of very low flow [41]. Stream rectification in 1938 shifted this source of good quality water several miles south of Fabens and Tornillo (Figure 9). The Rio Grande Aquifer in the study area has been noted for its elevated salinity [12,16,22,42]. Any alluvial groundwater flowing toward the Fabens and Tornillo wellfields today will likely result in diminished water quality at their municipal wells.

The unlined Fabens Waste Channel now occupies the abandoned river channel that once flowed near Fabens from the mid-1800s until channel rectification in 1938 (Figure 9). The Fabens Waste Channel collects drain flows and occasional overflows from the Rio Grande Project. Its water is of much poorer quality than Rio Grande flows entering the El Paso Narrows. Controlled flows in the waste channel have eliminated cycles of erosional scour. The bed of the old Rio Grande channel/Fabens Waste Channel has silted up with channel fines. This has created a low-permeability skin in the channel bed, restricting movement of water between aquifer and channel. Consequently, any limited recharge that occurs through the Fabens Waste Channel will be of diminished quality and may perpetually impact potability of Fabens and Tornillo municipal wells.

5. Conclusions

Although the hydrogeological system near San Felipe Arroyo is unique, the results found in this study demonstrate that anecdotal models of slope-front recharge should be viewed with skepticism unless ground truth confirms their accuracy. A workup of the geologic history of an area and acquisition of isotopic and hydrochemical tracers should be completed before anecdotal models of slope-front recharge are accepted as a paradigm. Regional heterogeneity in aquifers can create circuitous and three-dimensional groundwater flow, challenging the hydrogeological interpreter to look

past conventional models of groundwater flow and recharge. Once the geologic and hydrogeologic framework is understood, the task of deciphering processes of recharge, or any aspect of a hydrogeologic flow system, is more manageable [1,43].

Further work is needed in several areas. A digital model could be developed to test under what conditions downward vertical flow is plausible. Factors that could be evaluated in the model might include high horizontal to vertical anisotropy ratios commonly found in basin and alluvial fill, and variable hydraulic head boundary conditions. Should more well control or investigative resources become available later, areas of discharge of the pre-dam Rio Grande water found near San Felipe Arroyo might be detected by further analyzing the channel feature described by Gates and Stanley (1976). Resources could be devoted to evaluate the reason for the apparent termination of the buried channel, as depicted in Figure 8. It is plausible that the pre-dam water detected in the Fabens-Tornillo area discharges, at least partly, where the buried channel ends abruptly in the electromagnetic image of Gates and Stanley [11].

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