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Supplementary Material for

Issues of Bias in Groundwater Quality Data Sets in an Irrigated Floodplain Aquifer of Variable Salinity

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1. Collation of Historical Data

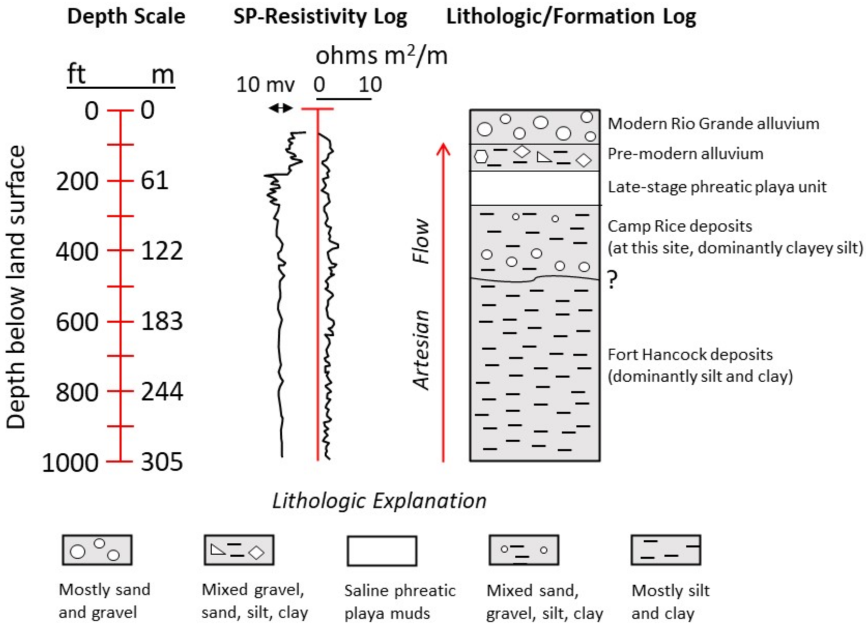
Historical data in the study area were obtained from the public groundwater data base maintained by the Texas Water Development Board (TWDB). This is the most complete data record in the area, and is mostly limited to data collected in the 1950s to 1970s. These data are mostly from the Rio Grande Aquifer and the Hueco Bolson Aquifer, strictly in locations where the bolson fill underlies recent Rio Grande alluvium. The data collected from the data base include early 1960s to early 1970s groundwater quality data. TWDB checks groundwater data using cation-anion balance and flags well records that do not balance within 5%. Data lacking acceptable cation-anion balance were not used. Where incomplete data sets were listed in the TWDB data base, such as reports of anions only, the data were checked against specific conductance measurements as a semi-quantitative way of evaluating reliability. Because groundwater is seldom extracted from the Hueco Bolson Aquifer in the highly saline zone beneath the Rio Grande Aquifer downstream of Socorro, changes over time in the deeper aquifer tend to be negligible. Changes occur in the dynamic shallow aquifer due to widespread application of irrigation water collected from reservoirs in New Mexico. The purpose of our analysis is to determine if these are natural changes, or if well sampling bias accounts for differences we report in this manuscript.

Surface irrigation (project) water data were collected from IBWC Water Bulletins (https://ibwc.gov/Water_Data/water_bulletins.html). Project water samples were collected from the Rio Grande at the gaging station on Courchesne Bridge, 2.7 river kilometers upstream from American Dam, where project water is diverted into American Canal (Figure 1 in main narrative). Irrigation season project water data were identified by comparison with stream discharge records showing release of water from Elephant Butte and Caballo Reservoirs (Figure 1 in main narrative).

2. Study Area Geology

This section expands on the geology of the study area provided in the narrative. The study area covers the U.S part of the El Paso/Juárez Valley between Socorro and Fort Quitman, Texas, The case study is presented for the part of the Rio Grande Aquifer where the Rio Grande flows across a broad alluvial floodplain, the “El Paso-Juárez Valley”. In this paper, modern Rio Grande floodplain refers to the current floodplain surface across which the Rio Grande flows. 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 in main narrative). Rio Grande alluvium refers to basal-channel floodplain deposits of late Quaternary (~15 ka to modern) age. They average about 65 to 85 feet (19.8 to 25.9 m) in thickness (Hawley, written communication, 2021). Because of the difficulty in distinguishing the Rio Grande alluvium and similar deposits formed by the Ancestral Rio Grande of Early Pleistocene (2.6 to 0.75 Ma) age, the Rio Grande Aquifer has been variably described as 150 to 250 feet (45.7 to 22.9 m) thick (Buckner, 1974; Gates and Stanley, 1976, Hawley, written communication, 2021) and is commonly listed as 200 feet (60.1 m) thick (Alvarez and Buckner, 1980). Mud rotary drilling is the principal means of installing water wells on the floodplain, and it is rarely possible to identify any geologic feature at the contact between older and younger river alluvium, such as a buried paleosol, with mud rotary cuttings. Locally, a cobbly gravel layer is often found at the contact (Hawley, personal communication, 2021) but cobbly layers are found at other depths in the river alluvium. A pertinent feature that sometimes appears at the contact between older and younger river alluvium is a a late-stage buried phreatic playa unit (Supplemental Figure 2), but this evaporite unit occurs only locally. This saline playa unit was identified by Hibbs and Merino (2006) as a thin, <75 ft (15.2 m) thick unit that is syn-depositional with the latest Camp Rice deposits and may be listed as part of the Camp Rice Formation. These buried phreatic playa units, where they occur, are pertinent to arguments about groundwater salinity and sampling bias laid out in our paper. Vadose zone thickness above the Rio Grande Aquifer is usually 5 to 30 feet (1.5 to 9.2 m).

Basin-fill sediments in the Hueco Bolson are usually weakly consolidated, heterogeneous materials that overlie Precambrian through Tertiary rocks (Wilkins, 1986; Hawley et al., 2009) The Camp Rice Formation, lying conformably beneath the Rio Grande alluvium, is in most places the main water-bearing formation of the Hueco Bolson Aquifer. The formation is a Pliocene to early Pleistocene unit including stream-channel and floodplain deposits that are the most prolific in terms of water supply. Camp Rice deposits are juxtaposed against fanglomerates that flank the margin of the basin (Strain, 1966). The Camp Rice Formation consists predominantly of gravels and sands, interbedded with muds, volcanic ash, and caliche that were formed by ancestral channels of the Rio Grande (Supplemental Figure 1). Beneath the Camp Rice Formation is the Fort Hancock Formation of mostly playa-lacustrine origin. The Fort Hancock Formation is of minimal practical importance as a water supply aquifer. Fort Hancock deposits include lacustrine muds, interbedded with layers of bentonitic claystone and siltstone and some discontinuous sand lenses .



FigureS1. Geologic and electrical log collected during drilling of State Well 49-39-207 (Audsley, 1959), located 3215 ft (980 m) east of Hibbs Well Nest (Figure 1 in main narrative). The approximate thicknesses, lithology, and contacts are represented for modern Rio Grande alluvium, intrabasin alluvium deposited before modern Rio Grande established its path, a late stage buried phreatic playa unit, the Camp Rice Formation, and the Fort Hancock Formation. The upper contact of the Fort Hancock Deposit is estimated as accurately as possible with the drilling and electrical log data, but is imprecise. The late stage phreatic playa unit is the source of high-dissolved solids, chloride-dominated groundwater moving up into the Rio Grande alluvium. The lateral extent of the buried phreatic playa complex is patchy, but is clearly identified at this location in the SP log.

3. Broader Details on Water Development, Irrigation, Groundwater Use, and Salinity in the Study Aquifer

The surface water system in the Rio Grande and the associated ditches and drains were engineered for the delivery of "project water" and removal of agricultural drain water return flows. The Rio Grande Aquifer interacts hydraulically with the deeper Hueco Bolson Aquifer (Hibbs, 1998; Hibbs and Boghici, 1998; Hutchison and Hibbs, 2008). Ample fluid exchange has been recorded between the Hueco Bolson Aquifer, Rio Grande Aquifer, Rio Grande, and agricultural drains (Hibbs and Boghici 1998; Hutchison and Hibbs, 2008).

International claims on the waters of the Rio Grande Basin and the need for developing and managing irrigable lands led to the promulgation of the Rio Grande Project in 1938 (USBR, 1973). The Rio Grande Project is administered by the United States Bureau of Reclamation (USBR) which provides water from the Rio Grande for irrigating crops in the Rincon and Mesilla Valleys of New Mexico, and the Hueco Bolson in Texas and Mexico. El Paso County Water Improvement District No. 1 serves farms in the lower Mesilla Valley and El Paso Valley, Texas. The Hudspeth County Conservation and Reclamation District No. 1 manages irrigation canals and drainage ditches for farms in the El Paso Valley below the El Paso-Hudspeth County line (USBR, 1973; 1976). Hudspeth County is not entitled to any of the raw delivery water available under the Rio Grande Project, and receives wasteflows and drainwater return flows from the Rio Grande Project (Bluntzer, 1975; USBR, 1976). Groundwater pumping from the Rio Grande Aquifer is common during drought years and augments irrigation water from the Rio Grande (Supplemental Figure 2).

Agriculture is the mainstay of the local economy. The Rio Grande Project provides irrigation water to the water rights holders between Elephant Butte Reservoir, New Mexico and the El Paso-Hudspeth County line (Figure 1 in the main narrative). Downstream of the county line, extending to the confluence of the Rio Grande with the Rio Conchos at Ojinaga, Mexico, the meager flows of the Rio Grande and the well water in the Rio Grande Aquifer are frequently moderately saline, commonly 3000 to 6000 mg/L TDS.

In areas where water of marginal quality is available, funding for groundwater resource assessment is often minimal. Federal and State supported studies of the region under the Rio Grande Regional Environmental Project (RGREP) (USBR, 1976) took place mostly from 1972 to 1982. RGREP performed a comprehensive investigation and inventory of existing and future water resources within the area between Elephant Butte Reservoir and Fort Quitman (Figure 1). The Federal and State agencies involved in RGREP have not been involved in any significant groundwater studies in the Rio Grande Aquifer below El Paso ever since. Evaluation of the Rio Grande Aquifer in the study area by Federal and State agencies is done on a limited basis. Since 1990, the Texas Water Development Board has carried out meager data collection in the study area, limited to a handful of water level measurements and 2 or 3 groundwater quality samples from the Rio Grande Aquifer each year. Agencies such as the Texas Water Development Board and U.S. Geological Survey are more vested in regional groundwater investigations in areas where the economy drives much more extensive groundwater demand

In Hudspeth County, sufficient water for periodic leaching of accumulated salts in soil profiles is rarely available, except during very wet years. Irrigated cropland has been in decline for decades, due to salinization of soils and retirement of farmland. Crop yields have declined since the 1950s (USBR, 1973; McDonald, 2015). In 2014, only a few inches of water per acre was allocated to the farms in the Hudspeth County Conservation and Reclamation District No. 1, when a normal allotment is about 4 feet (1.2 m). This resulted in 85 percent of the fields in the district lying fallow in 2014 (McDonald, 2015). Water in the District's irrigation system canals comes from waste flows and drain flows from the Rio Grande Project, with the addition of some water pumped from the Rio Grande Aquifer from wells belonging to the District. Many of the farms that were planting crops in Hudspeth County in 2014 also used private groundwater wells pumping from the Rio Grande Aquifer to supplement water provided by the district.

Pumping from the Rio Grande Aquifer is highly variable, however. Alvarez and Buckner (1980) stated - "since 1951, and during several years, groundwater has supplied virtually all of the irrigation water requirements of the (El Paso) Valley and has been the survival factor for its agriculture". This was especially true during several drought years during the 1950s through the 1970s when storage in Elephant Butte Reservoir was usually well below capacity (Supplemental Figure 2). Beginning in the 1980's wetter periods settled in and Elephant Butte Reservoir was usually well above half capacity. Plenty of project water was usually available for irrigation (Supplemental Figure 2). As irrigation efficiency improved in the Rio Grande Project area, and as industrial and municipal expansion proceeded down through the El Paso Valley, even more water was available from the Rio Grande Project that was sufficient to meet most of the irrigation demands in El Paso County through 2003. Then a drought struck in the Rio Grande Basin in the early 2000s and intensified in 2003. To prepare for meeting water demands in anticipation of continuing drought, inactive water wells drilled in the 1950s to 1970s were recommissioned and many new water wells were drilled in the Rio Grande Aquifer. Alluvial groundwater has been used extensively since 2004, especially during dry periods in the area between Socorro and Fort Quitman (McDonald, 2015). In 2014, Jesus Reyes, general manager of the El Paso County Water Improvement District No. 1 (EPCWID-1) stated "We are starting to see homes that had wells 50 to 60 feet (15.2 to 18.3 m) deep go dry. We are starting to see the impact of the water table dropping" due to pumping groundwater in the Rio Grande Aquifer (McDonald, 2015). During six field trips to the study area at various times between 2017 and 2022, the main authors observed only a few alluvial aquifer wells pumping. Water well use is now highly variable depending on time of year, weather conditions, agricultural plans and schedules, and project water availability (Supplemental Figure 2).

As part of a NSF "Glue Grant" awarded in 2002, the authors carried out studies of the entire Hueco Bolson and Tularosa Bolson Aquifers in the United States and Mexico. The charge of the NSF grant was to age-date groundwater, to evaluate hydraulic relationships between regional aquifers and the Rio Grande Aquifer, and to determine sources of salinity in all aquifers. Testing in the study was initially limited to 150 water wells with many groundwater samples tested for general minerals, halides, tritium, carbon-14, and stable isotopes of oxygen, hydrogen, carbon, and sulfur. Supplemental funding from NSF and US-EPA Region 6 allowed an additional 70 water wells to be sampled and analyzed. Our study coincided with El Paso Water Utility's extensive exploratory drilling program in which discrete vertical sampling was undertaken in several new wells in and immediately north of East El Paso. Several hundred additional samples were made available for our study from the El Paso exploratory drilling program.

One of our first major efforts in the glue grant was to evaluate salinity and determine source and age of groundwater in the Rio Grande Aquifer. In summer 2003, we collected 30 groundwater samples distributed across the alluvial floodplain between Socorro and Fort Quitman (Figure 3 in the main narrative). Most inactive irrigation wells installed from the 1950s to 1970s had not yet been recommissioned, and many of the new water wells had not been drilled. Believing this number of groundwater samples was enough for an adequate study of an aquifer this size, we thought our task was complete. We had a large number of priority water wells that needed to be sampled in the Hueco Bolson and Tularosa Bolson Aquifers in the U.S. and Mexico as the main focus of our grant. After examining the 2003 data collected from the Rio Grande Aquifer, it was apparent that the samples were much more dilute than found in historical studies. Only 1 of the 10 groundwater samples collected between Fabens and Fort Quitman in 2003 contained greater than 3000 mg/L TDS. In an earlier study, Hibbs et al. (1997) found that 15 of 23 groundwater samples collected between Fabens and Fort Quitman between 1972 and 1979 contained greater than 3000 mg/L TDS. Notably, 7 of those 23 groundwater samples contained greater than 5000 mg/L TDS. Our samples collected from agricultural drains below Fabens in our NSF Glue Grant project had salinity values closer to those shown in the 1972 to 1979 alluvial aquifer data in maps prepared by Hibbs et al. (1997) (their Figures 5.9 and 5.10, 1997). Our drain samples collected during our NSF study were much more saline than found in the 2003 study, when samples were collected from groundwater wells.

Based on these findings, we developed two hypotheses for contrasting salinity in data sets; 1) salinity of the Rio Grande Aquifer changed significantly between the 1970s and 2003; or 2) well sampling produced unrealistically low salinity in the 2003 data set. The difference between historical and 2003 data was so profound we began to speculate that the results came about as a result of limited wells pumping in 2003, with most of the active wells producing some of the best quality groundwater available in the Rio Grande Aquifer. According to this hypothesis, the wells that produce saline groundwater remained inactive. We speculated that the 2003 groundwater samples were biased in a way that is skewed, and demonstrably less saline than the bulk salinity of the Rio Grande Aquifer. It would be most problematic to conclude that the quality of water in the Rio Grande Aquifer had improved considerably by 2003, if the data are biased and follow hypothesis 2.

After decades of work in the study area, we have seen periods when many water wells are pumping from the Rio Grande Aquifer, and periods where most water wells remain inactive. Inactive wells constructed in the 1950s through the 1970s began to be renovated for use in late 2004, but before 2004, most of the irrigation wells were not active in the study area (Supplemental Figure 2). When most wells are not being used due to supplement project water supply and when there is adequate Rio Grande Project wastage entering Hudspeth County, only the wells producing the highest quality groundwater are likely to be used for agriculture and domestic purposes. If our hypothesis of selective well use is correct, it represents a clear bias in assessing bulk aquifer salinity when only the active wells are tested.

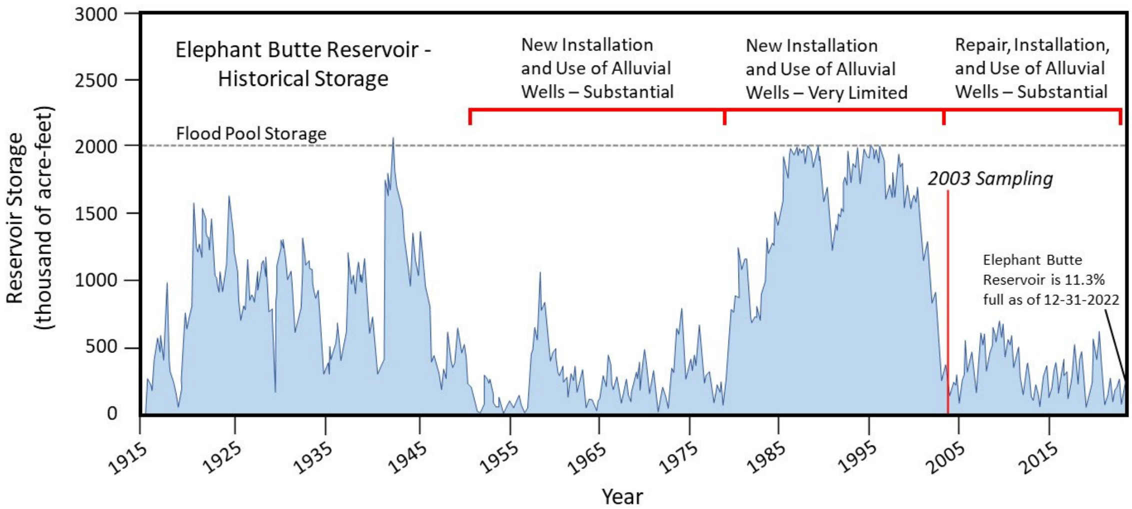


Figure S2. Reservoir storage at Elephant Butte, New Mexico, since construction of Elephant Butte dam, and effects on groundwater use in the Rio Grande floodplain downstream of El Paso (modified from Texas Water Development Board, 2022).

4. Hydrochemical Information from Hibbs Nested Well in the Fabens Artesian Zone

An artesian flow system, with hydraulic head recorded by manometers at 40 feet (12.1 m) above land surface (Alvarez and Buckner, 1980), overcomes density gradients and allows noticeable amounts of very saline groundwater to move upward into the Rio Grande Aquifer near Fabens (Hibbs and Merino, 2006) (Figure 2 in main narrative). Drilling in the upper confining unit of the artesian aquifer system detected very saline groundwater immediately below the modern Rio Grande alluvium, with chloride of about 14,700 mg/L and sulfate about 1100 mg/L (Hibbs and Merino, 2006) (Supplemental Table 1). This artesian system, and the phreatic playa deposits found right below the younger Rio Grande alluvium, account for the shift of numerous Rio Grande Aquifer water samples upward from the RG Enrichment Lines at and downstream from Fabens (red trend line in Figure 2c).

Table S1. Groundwater data collected from the upper confining unit of the artesian aquifer near Fabens, Texas (Hibbs Well Nest location shown in Figures 1 and 3 in main narrative). The uppermost water well is screened in a buried phreatic playa deposit that produces a high chloride input into the Rio Grande Aquifer due to artesian cross-formational flow. All of the wells penetrate semi-pervious confining strata. Two of the wells are true artesian wells and flow freely at land surface.

Hibbs Well Nest – Screen Settings	Chloride (mg/L)	Sulfate (mg/L)	Cl/Br (wt. ratio)
150 to 250 ft BGS (below ground surface)	14,657	1123	5881
350 to 450 ft BGS (true artesian well)	239	878	293

650 to 750 ft BGS (true artesian well)	176	5234	568

References

1. Alvarez, H.; Buckner, A. Ground-water development in the El Paso region, Texas, with emphasis on the resources of the lower El Paso Valley, Texas Department of Water Resources Report 246. 1980, 346 p.
2. Audsley, G. Records of wells and results of exploratory drilling in the El Paso Valley and Hueco Bolson southeast of El Paso, Texas, U.S. Geol. Survey open-file report. 1959, 144 p.
3. Bluntzer, R. Water supply problems in the El Paso Area, Texas, American Society of Civil Engineers Irrigation and Drainage Specialty Conference, Logan Utah. 1975, 29 p.
4. Buckner, A. Results of exploratory drilling by the Texas Water Development Board in the vicinity of San Elizario, Texas, Texas Water Development Board open-file report. 1974.
5. Gates, J; Stanley, W. Hydrologic interpretations of geophysical data from the southeastern Hueco Bolson, El Paso and Hudspeth Counties, Texas. U.S. Geological Survey Open-File Report 76-650. 1976, 137 p.
6. Hawley, J., oral communication by telephone, retired geoscientist of the New Mexico Bureau of Mines and Mineral Resources, September 22. 2021.
7. Hawley, J., written email communication, retired geoscientist of the New Mexico Bureau of Mines and Mineral Resources, September 21. 2021.
8. Hawley, J.; Kennedy, J.; Granados-Olivas, A.; Ortiz, M.A. Hydrogeologic framework of the binational western Hueco Bolson-Paso del Norte area, Texas, New Mexico, and Chihuahua, overview and progress report on digital model development, New Mexico Water Resources Research Institute Technical Completion Report 349. 2009, 45 p.
9. Hibbs, B. Water quality and hydrogeologic issues along the City of El Paso-Ciudad Juárez corridor, international case study, Environmental & Engineering Geoscience. 1998, v.5., no.1, p 27-39.
10. Hibbs, B.; Merino, M., A geologic source of salinity in the Rio Grande Aquifer, New Mexico Journal of Science. 2006, v.44, p. 165-181.
11. Hibbs, B.; Boghici, R.; Hayes, M.; Ashworth, J.; Hanson, A.; Samani, Z.; Kennedy, J.; Creel, B. Transboundary aquifers of the El Paso/Ciudad Juarez/Las Cruces region, Texas Water Development Board and New Mexico Water Resources Research Institute, Technical contract report prepared for the U.S. Environmental Protection Agency. 1997, 148 p.
12. Hibbs, B.J.; Boghici, R. On the Rio Grande Aquifer; flow relationships, salinization, and environmental problems from El Paso to Fort Quitman, Texas. Env. and Eng. Geos. 1998, 5, 51-59.
13. Hutchison, B.; Hibbs, B. Groundwater budget and isotopic analysis of cross formational flow in an arid basin. Ground Water J. 2008, 46, 384-395.
14. McDonald, C. Disappearing Rio Grande, why follow the Rio Grande, The Texas Tribune. 2015, https://riogrande.texastribune.org/blog/2014/10/2/
15. Strain, W.S. Blancan mammalian fauna and Pleistocene formations, Hudspeth County, Texas. University of Texas at Austin, Memorial Museum Bulletin 10. 1966, 55 p.
16. Texas Water Development Board. Water data for Texas, Elephant Butte lake, https://waterdatafortexas.org/reservoirs/individual/elephant-butte. 2022, accessed 12-2022.
17. U.S. Bureau of Reclamation (USBR). Water resources of El Paso County, Texas, Rio Grande Project, New Mexico-Texas Project Office, El Paso, Texas. 1973, 97 p.
18. U.S. Bureau of Reclamation (USBR). Status report, Elephant Butte Reservoir, Fort Quitman Project, New Mexico-Texas, Rio Grande Regional Environmental Project, 1976, 25 p.
19. Wilkins, D.W. Geohydrology of the southwest alluvial basins regional aquifer-systems analysis, parts of Colorado, New Mexico, and Texas. U.S. Geological Survey Water-Resources Investigations Report 84-4224. 1986, 61 p.