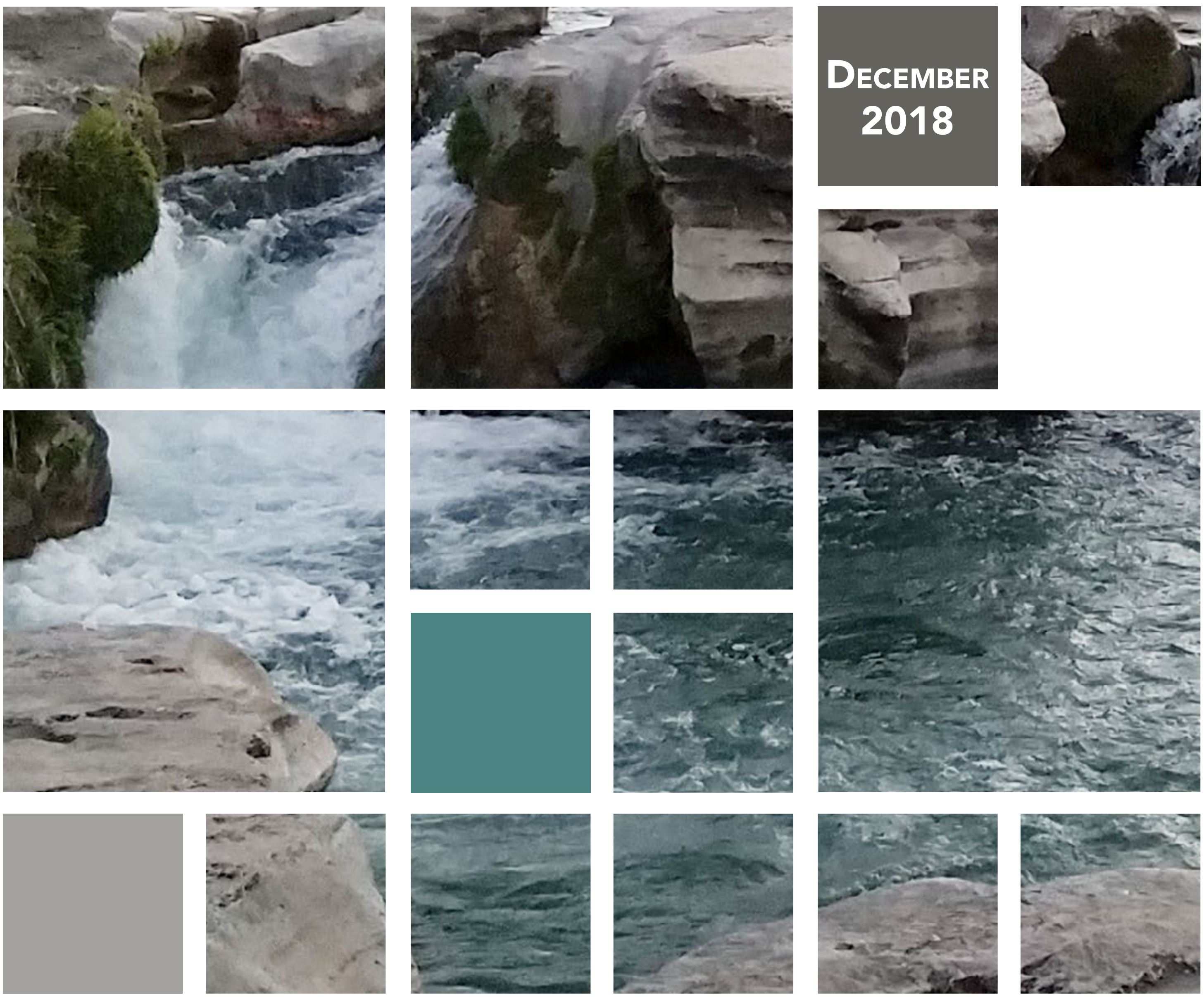
Overview of Groundwater Conditions in Val Verde County, Texas

December 2018



Texas Water Development Board

Prepared by:
Texas Water Development Board
with cooperation of the Texas Commission on Environmental Quality and the Texas Parks and Wildlife Department

Geoscientist Seal

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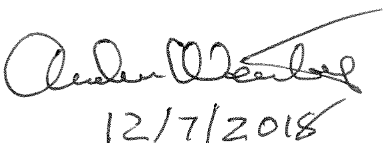

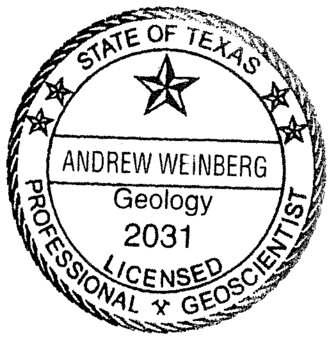

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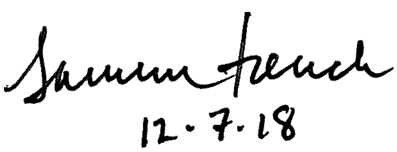

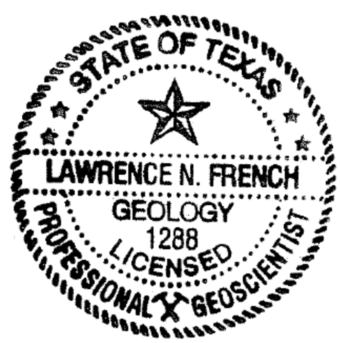

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Mr. Perez was responsible for the GIS efforts associated with preparing illustrations and maps for the project.

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Executive Summary

The Texas Water Development Board (TWDB) has completed an overview of the hydrogeology of Val Verde County, similar to what would be required for a Priority Groundwater Management Area (PGMA) evaluation and assessed the feasibility of employing hydrologic triggers to manage the aquifer. PGMAs are identified and designated by the Texas Commission on Environmental Quality (TCEQ) as those areas of Texas not in any established groundwater conservation district (GCD) that are experiencing or expected to experience critical groundwater problems, including shortages of surface water or groundwater. *Priority Groundwater Management Areas and Groundwater Conservation Districts, Report to the 85th Texas Legislature,* which was prepared jointly by the TCEQ and TWDB, included the following statement:
"Val Verde County and the Devils River were discussed as potential areas of concern and may need follow-up PGMA assessment as more data become available."

Therefore, the scope of this study is tied closely to the purpose and scope of a PGMA study. The scope of PGMA studies is defined in Texas Water Code § 35.007(d). According to the TCEQ:

> *A Priority Groundwater Management Area (PGMA) is an area designated and delineated by TCEQ that is experiencing, or is expected to experience, within 50 years, critical groundwater problems including shortages of surface water or groundwater, land subsidence resulting from groundwater withdrawal, or contamination of groundwater supplies.*
>
> *Since the ultimate purpose of designating a PGMA is to ensure the management of groundwater in areas of the state with critical groundwater problems, a PGMA evaluation will consider the need for creating Groundwater Conservation Districts (GCDs, or "districts") and different options for doing so. Such districts are authorized to adopt policies, plans, and rules that can address critical groundwater problems.*
>
> *If a study area is designated as a PGMA, TCEQ will make a specific recommendation on GCD creation. State law authorizes the citizens in the PGMA two years to establish a GCD. However, if local action is not taken in this time frame, TCEQ is required to establish a GCD that is consistent with the original recommendation. Under either scenario, the resultant GCD would be governed by a locally elected board of directors.*

Among other requirements, a PGMA study must include an appraisal of the hydrogeology of the area and other matters within the TWDB's planning expertise relevant to the area and an evaluation of the potential effects of the designation of a PGMA on an area's natural resources prepared by the Texas Parks and Wildlife Department (TPWD). Accordingly, this report focuses on the hydrogeology and natural resources of Val Verde County, which is located in southwest Texas and borders the Rio Grande.

This report compiles and evaluates available information on groundwater conditions in Val Verde County and discusses the feasibility of using hydrologic triggers to manage the aquifer. The TCEQ and TPWD participated in this study as agency stakeholders and technical contributors. In addition, a broad spectrum of stakeholders and citizens in Val Verde County participated in the review of the scope of work, submitted data and background information on water resources, and provided review comments on the report. The House Committee on Natural Resources held a public hearing in Del Rio on September 13, 2018, in which testimony and comments were received concerning groundwater and surface water issues in Val Verde County.

Groundwater Occurrence, Production, and Usage

The main source of groundwater in Val Verde County is the Edwards-Trinity (Plateau) Aquifer, a major aquifer extending across much of the southwestern part of the state. The water-bearing units are predominantly limestones and dolomites of the Edwards Group, with a few wells screened in the underlying Trinity Group limestone and sands. In the southern part of the county, small normal faults and joints are common, resulting over time in the development of interconnected dissolution cavities and conduits in the limestone rock that have been enlarged by percolating rainwater. The occurrence and movement of groundwater may be strongly influenced by these cavities and conduits.

Groundwater is found at depths ranging from a few feet below ground surface along major watercourses and near springs to several hundred feet below ground surface at higher elevations and between drainage systems. Well yields vary from less than 1 gallon per minute to over 2,000 gallons per minute. Groundwater quality is generally good, but is typically hard because of its mineral contents, and there are local areas where some wells have encountered brackish groundwater. The TWDB is conducting additional work to define brackish groundwater resources in Val Verde County under the Brackish Resources Aquifer Characterization System (BRACS) program. A BRACS study of the Edwards-Trinity (Plateau) Aquifer is scheduled for completion in late 2020.

Based on a comparison of historical groundwater pumping and the current value of modeled available groundwater, Val Verde County does not currently have a groundwater shortage. Groundwater pumping in Val Verde County has historically been less than 5,000 acre-feet per year, not including the amount of surface water originating from San Felipe Springs used for municipal supply by Del Rio. In contrast, the modeled available groundwater totals 50,000 acre-feet per year, which is the amount of pumping that would achieve desired future conditions that are established for the Edwards-Trinity (Plateau) Aquifer in the county.

Public supply wells serving Comstock, several small communities and commercial establishments near Amistad Reservoir, located on the Rio Grande, and state and national park facilities account for most of the groundwater volume used in Val Verde County. Irrigation, mostly along the upper Devils River and near Del Rio, is the second largest groundwater use in Val Verde County. Domestic and livestock use represents less than 10 percent of the total pumping but is the primary use for most of the wells in Val Verde County. Groundwater use by the oil and gas industry represents less than 5 percent of total groundwater use.

Groundwater Flow Conditions

Groundwater in Val Verde County generally flows from north to south and discharges to springs and creeks draining to the Rio Grande. Available data suggest that the groundwater flow system in conduits is poorly connected to the limestone rock matrix. The conduit system is largely recharged separately from the aquifer matrix and there is limited mixing between the two systems. Conduits are primarily recharged by runoff that is concentrated along the surface drainage system and enters the aquifer through large openings, such as sinkholes and solution-enlarged fractures. The matrix is recharged by precipitation percolating through soils and smaller fractures. Because the flow through the rock matrix is much slower than in the conduit system, groundwater originating from the rock matrix represents a small fraction of the overall volume of groundwater discharged from the major springs under normal flow conditions, although the matrix contains a larger fraction of the total groundwater in storage.

Water from Amistad Reservoir has progressively infiltrated the groundwater system. Water level in the reservoir affects groundwater levels, spring discharge, and streamflow in an area extending at least 10 miles from the reservoir in some directions, so that water-level trends after filling of the reservoir are no longer representative of the broader aquifer conditions.

The Trinity aquifer unit of the Edwards-Trinity (Plateau) Aquifer has limited connection to the overlying Edwards aquifer unit. Few wells in Val Verde County are completed in the Trinity Aquifer, and Trinity wells tend to have brackish groundwater. Discharge from major springs at the down-gradient end of the aquifer system shows no evidence of Trinity Aquifer groundwater upwelling and mixing with Edwards water. Isolated areas of brackish groundwater in the Edwards Aquifer suggest that localized communication with the Trinity aquifer unit can occur along fractures and faults. The possibility of increased communication between these aquifer units in the event of increased groundwater pumping in the Edwards has not been evaluated.

The mean residence time of groundwater discharged at Goodenough Springs and San Felipe Springs is estimated to range between 2 and 34 years. Tritium activity and other geochemical indicators were used to estimate groundwater residence time. These isotope-based mean residence times are generally consistent with age estimates based on groundwater velocities in the Edwards-Trinity (Plateau) Aquifer groundwater availability model (GAM) (Anaya and Jones, 2009) and the Devils River Watershed groundwater flow model (Toll and others, 2017).

Baseflow in the upper Devils River, which is entirely from groundwater discharge, has remained essentially the same for at least the last 100 years. Available evidence indicates the starting point of perennial flow has been near Pecan Spring since the early 20th century and has not changed significantly in response to pumping from irrigation wells near Juno, which started in the 1950s.

Surface Water

Perennial surface water resources include the Rio Grande, Amistad Reservoir, Pecos River, Devils River, San Felipe Creek, and Sycamore Creek. These surface water features are regional points of discharge for the groundwater system. Annual flows from Goodenough Springs, the Devils River, and San Felipe Springs are estimated to provide about 23 percent of the flow in the Rio Grande below Amistad Reservoir (Green, 2013). Permitted surface water rights and environmental flow standards for new appropriations (if any) of surface water resources in Val Verde County may have implications for groundwater management.

The intimate connection between groundwater and surface water in Val Verde County has complicated measurements over time. Measured flow in the Devils River at Pafford Crossing increased after Amistad Reservoir filled and may not be a good indicator of conditions in the upper, spring-fed reaches of the river. Also, flow measurements in the Devils River at the Bakers Crossing gage have been inconsistent over time, with measurements by both the U.S. Geological Survey and the International Boundary and Water Commission, complicating interpretation of any long-term trends. On the other hand, periodic low-flow gain-loss studies on the Devils River show nearly identical patterns of spring discharge to the river between 1928 and 2006.

Endangered Species

Threatened or endangered aquatic species in Val Verde County include the Devils River minnow, Proserpine shiner, Rio Grande darter, the Conchos pupfish – Devils River subspecies, the Mexican blindcat, and the recently-listed Texas Hornshell mussel. Evaluation of threatened or endangered species or habitats is an important consideration in the overall understanding of the hydrogeologic system and for groundwater management decisions. Streamflow requirements for these species are linked to spring discharges and are therefore tied to groundwater conditions. Aquatic habitats for these species depend upon groundwater inflows to maintain sufficient, good quality river flows, particularly during droughts and summer low-flows when surface runoff is minimal and water quality begins to deteriorate. Water quality can be compromised during low flow events if water temperatures rise and dissolved oxygen decreases, further impacting these rare aquatic organisms. The TPWD has directly observed mass predation events on Texas Hornshell in the Devils River during a prolonged low spring and streamflow period in 2015. Additionally, there are concerns about elevated water temperatures during periods of low flow that are potentially lethal to larval and adult mussels. The TPWD, The Nature Conservancy (TNC), University of Texas (UT), and Texas A&M University (TAMU) are currently conducting research to determine what these critical lethal temperatures are and under what flows they might occur in Texas Hornshell habitat in the Devils River. The threat of worsening drought, in concert with the potential for groundwater development, could exacerbate the loss of species habitat, thereby increasing the rate of species decline and leading to critical groundwater problems in the future.

The U.S. Fish and Wildlife Service, TPWD, and TNC have conducted extensive research on threatened and endangered species in Val Verde County and maintain active species management programs. Ongoing research by the UT Bureau of Economic Geology is examining the linkages between habitat requirements and the groundwater system.

Groundwater Modeling

Several groundwater flow models have been developed that cover all or part of Val Verde County. The Edwards-Trinity (Plateau) Aquifer groundwater availability model (GAM) is a large regional model developed by the TWDB. Because it has a coarse model grid, annual time steps, and lack of calibration to spring discharges, the GAM is inappropriate for modeling critical flows at possible hydrologic trigger locations. The Val Verde County (Eco-Kai and Hutchison, 2014) groundwater model, which is derived from a TWDB model of Kinney County and surrounding areas (Hutchison, Shi, and Jigmond, 2011), represents the best starting point for a Val Verde County groundwater management model. The Val Verde County model employs a finer spatial grid than the TWDB GAM and has monthly time steps, includes calibration to several major springs, and specifies considerable hydrogeological detail for both the U.S. and Mexican portions of the Edwards-Trinity (Plateau) Aquifer system. The Devils River Watershed Model, a combined surface water-groundwater model developed by Toll and others (2017), has daily time-steps and a much finer grid around critical areas, but covers only the Devils River watershed. In addition, the model specifies considerably more detailed aquifer properties than are supported by available data, making model calibration uncertain and complicating application to the remainder of the county, for which even less data are available. A coupled groundwater-surface water model remains attractive because of the intimate connections between groundwater and surface water in the county but may not be practical at this time.

Improved groundwater flow models would help decision makers with groundwater management issues in Val Verde County. Better models require more groundwater data with the appropriate spatial and temporal coverage. Water level measurements are the fundamental hydrological dataset and current monitoring networks do not provide adequate spatial or temporal coverage. Improved accuracy of groundwater use estimates in Val Verde County would also improve the usefulness of a model. Additional data – whether water levels or groundwater use estimates – requires time to develop and incorporate appropriately into any revisions or updates of groundwater flow models.

Effects of Groundwater Pumping

Groundwater pumping has the potential to affect streamflow and spring discharges in Val Verde County. Due to the strong linkages between surface water and groundwater, reduction in groundwater levels resulting from pumping may decrease surface flows. Pumping is unlikely to affect groundwater recharge over most of Val Verde County. In most areas, the groundwater level is already well below the land surface and the base of the root zone. Lowering the water table further will not induce greater recharge or reduce evapotranspiration. However, concentrated high-volume pumping near Amistad Reservoir or along perennial river reaches could induce capture, or flow, from surface water to groundwater.

Water Usage and Demand Projections

The *2017 State Water Plan* indicates no near-term or long-term water supply shortages under current development scenarios, except for small unmet needs in the mining (oil and gas) sector. The total county water demand is expected to grow 26 percent over 50 years, from 16,777 acre-feet per year in 2020 to 21,127 acre-feet per year in 2070, while the modeled available groundwater is 50,000 acre-feet per year. Not including Del Rio's use of surface water originating from San Felipe Springs, groundwater pumping for all uses in Val Verde County has averaged about 4,700 acre-feet per year since 2001. Total projected demand for groundwater remains less than projected supplies throughout the 50-year planning period. In recent years, several groundwater well fields have been proposed to supply water outside the county. The modeled available groundwater value of 50,000 acre-feet per year was estimated from groundwater flow modeling of three hypothetical well fields north of Del Rio.

Groundwater Management

Val Verde County does not have a groundwater conservation district but is included in groundwater management planning as part of Groundwater Management Area 7 (GMA 7), which includes all or part of 33 counties and 21 groundwater conservation districts in West-Central Texas. Groundwater district representatives voted to adopt new desired future conditions for the county in March 2018, specifying that total net drawdown through 2070 should maintain an average annual flow of 73 to 75 million gallons per day (81,800 to 84,000 acre-feet per year) at San Felipe Springs. There is no current mechanism in place to monitor groundwater conditions or enforce this management goal for the Edwards-Trinity (Plateau) Aquifer.

The Texas Water Code (§36.108(d-1)) allows a groundwater conservation district to consider the specific groundwater conditions in its area and establish separate desired future conditions for subdivisions of aquifers or for different geographic areas of aquifers. Based on review of available groundwater data for the county, variations in the hydrogeological conditions in the county could be the basis for establishing four separate management zones to facilitate groundwater management efforts.

Feasibility of Hydrologic Triggers

Index wells and hydrologic trigger levels are used as groundwater management strategies by groundwater conservation districts in the Edwards Aquifer and elsewhere in Texas. Similar approaches, as well as use of spring flow measurements or streamflow measurements at specific locations, could also be applied to manage groundwater resources in Val Verde County. Index well selection and trigger level determination should be based on specific management objectives and documented correlations between the management objectives and aquifer conditions, such as index well water levels, or related surface water indicators, such as streamflow or spring flow. Demonstrating such correlations, however, is difficult with current data. Many of the wells where water levels have been measured historically are within the area of influence of Amistad Reservoir and may no longer be relevant for tracking aquifer conditions. Discharges at San Felipe Springs and other springs near Amistad Reservoir are likewise influenced by the lake level, and trigger levels based on discharge at these springs are of questionable value for groundwater management purposes. A well-calibrated and validated groundwater model will be essential for establishing defensible index well locations and trigger levels.

1.0 Introduction

Groundwater is the main source of water supply for municipal, domestic, and livestock uses in Val Verde County. Almost all water wells in Val Verde County are completed in the Edwards Group limestones, which form the upper-most portion of the Edwards-Trinity (Plateau) Aquifer, a major aquifer in Texas extending throughout much of Central Texas. Val Verde County is situated at the southwestern edge of the Edwards Plateau, and is an area of regional groundwater discharge. Val Verde County has numerous springs, including several of the largest in Texas. These springs, such as San Felipe Springs, supply surface water for the City of Del Rio, sustain base flow in San Felipe Creek and the Devils River, and contribute to flow in the Lower Rio Grande.

In recent years, there have been a number of hydrogeologic investigations of limited scope covering portions of Val Verde County. However, no comprehensive report on the groundwater resources of the county has been issued in over 45 years, since the U.S. Geological Survey completed the study, *Groundwater Resources of Val Verde County, Texas,* for the Texas Water Development Board (TWDB) (Reeves and Small, 1973). This 2018 study presents an overview of groundwater data collected since that time through routine monitoring, localized investigations, well completions and testing, and groundwater flow modeling efforts.

Background

Groundwater development in Val Verde County has been limited to date; however, the possibility of future groundwater development has raised questions regarding groundwater-surface water relationships, groundwater management, and possible impacts to streams supporting threatened or endangered species. Several numerical groundwater flow models have been developed on behalf of different groups, using a wide range of inputs and assumptions and reaching differing conclusions as to the effects of potential groundwater development. There have been several unsuccessful efforts to establish a groundwater conservation district in the last decade.

This report compiles and evaluates the available information on groundwater resources in Val Verde County, identifies uncertainties and data gaps relevant to groundwater management, and assesses potential groundwater monitoring strategies and hydrological triggers that might be used. The TWDB has solicited input from other state agencies, the public, and other stakeholders in preparing this report. A public meeting was held in Del Rio on January 24, 2018, to kick off the process. We solicited groundwater data from the International Boundary and Water Commission, The Nature Conservancy, and from other interested groups and landowners in the county. The House Committee on Natural Resources held a public hearing in Del Rio on September 13, 2018, in which testimony and comment were received concerning groundwater and surface water issues in Val Verde County. A draft version of this report was provided to the public for review and comment, and this final report incorporates, where appropriate, those public comments.

Scope of Study

Priority Groundwater Management Areas (PGMAs) are identified and designated by the Texas Commission on Environmental Quality (TCEQ) as those areas of Texas not in any established groundwater conservation district (GCD) that are experiencing or expected to experience critical groundwater problems, including shortages of surface water or groundwater. *Priority Groundwater Management Areas and Groundwater Conservation Districts, Report to the 85th Texas Legislature,* which was prepared jointly by the TCEQ and TWDB, included the following statement: "Val Verde County and the Devils River were discussed as potential areas of concern and may need follow-up PGMA assessment as more data become available."

Therefore, the scope of this study is tied closely to the purpose and scope of a PGMA study. The scope of PGMA studies is defined in the Texas Water Code § 35.007(d). Among other requirements, a PGMA study must include an appraisal of the hydrogeology of the area and other matters within the TWDB's planning expertise relevant to the area and an evaluation of the potential effects of the designation of a PGMA on an area's natural resources prepared by the TPWD. Accordingly, this report focuses on the hydrogeology and natural resources of Val Verde County.

This report focuses on compiling and analyzing scientific and technical data on the groundwater and related natural resources of Val Verde County. We also consider the feasibility of potential hydrologic triggers as a groundwater management tool. Ideally, a trigger provides early warning of groundwater conditions that could cause an undesirable result. We examine existing data on pumping, water levels, and streamflow to determine if any current monitoring locations meet these criteria and to define the general types and locations of additional monitoring that might be required to meet potential groundwater management objectives.

Previous studies of the Edwards-Trinity (Plateau) Aquifer have defined the environmental setting, geological framework, and regional groundwater movement (Barker and Ardis, 1996; Kuniansky and Ardis, 2004; Anaya and Jones, 2009). This report includes excerpts of those portions of the regional reports that are relevant to the western Edwards Plateau. This study also has re-examined groundwater data maintained by the TWDB, the International Boundary and Water Commission, and the U.S. Geological Survey, as well as reports commissioned by The Nature Conservancy, the City of Del Rio, and other sources to reflect the most recent information on water levels, water quality, streamflow, and groundwater use in Val Verde and adjacent counties.

This study also evaluated literature on historical spring flows and the effects of land-use changes on groundwater recharge and stream baseflow. The evaluation included a review of well completion and water quality data in the TWDB Groundwater Database, U.S. Geological Survey streamflow records, National Oceanic and Atmospheric Administration (NOAA) weather data, and Landsat satellite imagery to assess the effect of historical landscape changes on the hydrology of Val Verde County.

Public Comments

The TWDB solicited and received public comments on the study and on the draft report following the public hearing conducted by the House Committee on National Resources on September 13, 2018, in Del Rio. The draft report was revised as appropriate to incorporate the public comments. The comments are included in Appendix D.

2.0 Geographic Setting and Natural Resources

Key findings

- Edwards Plateau geography is characterized by limestone outcrops and thin, loose soils.
- On average, evaporation exceeds precipitation in all months.
- Infrequent, extreme precipitation leads to rapid runoff and high flash flood potential.
- Plant communities have changed over time in response to land use, but the effects of these changes on the hydrological cycle are widely debated.
- Several threatened and endangered aquatic species are present in Val Verde County.
- Maintaining streamflow and water quality are important components of wildlife management efforts led by the U.S. Fish and Wildlife Service, the Texas Parks and Wildlife Department, The Nature Conservancy, and cooperating landowners in Val Verde County.
- The prospects of worsening droughts, in concert with the potential for increased groundwater withdrawals, could exacerbate the loss of species habitat, thereby increasing the rate of species decline and leading to critical groundwater problems in the future.

Geography is a major factor in water availability and water use. Topography, climate, soils, vegetation, and land use affect runoff and groundwater recharge, while habitat requirements for sensitive wildlife populations can influence natural resource planning and management.

Val Verde County is in southwestern Texas (Figure 2-1). It covers an area of 3,145 square miles, or 2,085,760 acres, and had a population of 48,879 at the time of the 2010 census. Approximately 75 percent of the county's population lives in the City of Del Rio, located in the southeastern corner of the county. The county's southern boundary is the Rio Grande.

Val Verde County is situated at the southwestern margin of the Edwards Plateau, "a resistant carbonate upland of nearly flat-lying limestone and dolostone, typically veneered with loose, thin soils. Caprock mesas, broad alluvial fans, and dry arroyos are the most prominent features" (Barker, Bush, and Baker 1994). The southwestern corner of the county, west of the Pecos River, is the easternmost part of Trans-Pecos region, while the southeastern corner of the county is the northwestern-most part of the Gulf coastal plain.

Topography

The elevation of Val Verde County ranges from over 2,000 feet above sea level in the north and along the divides between major drainages to about 850 feet along the Rio Grande below the Amistad Reservoir. The topography is relatively flat in the Rio Grande floodplain and along the ridges but is characterized by narrow, steep-walled canyons cut into the carbonate terrain along the Pecos and Devils rivers and their tributaries as the drainages descend from the Edwards Plateau toward the Rio Grande.

Climate

Val Verde County has a semiarid, subtropical climate characterized by dry winters and hot summers. From 1965 to 2018, the daily high temperature averaged 81.3 degrees Fahrenheit and the daily low averaged 58 degrees Fahrenheit at Amistad Dam. The extreme temperatures at

Amistad Dam during this period ranged from 114 degrees on July 29, 1995, to 5 degrees on February 3, 1992 (National Centers for Environmental Information, 2018).

The average annual rainfall at Amistad Dam was 19.4 inches. Of this, 15.2 inches, or about 80 percent, fell during the growing season, from April through October (Figure 2-2). May and September are typically the wettest months, while December and January are the driest (National Centers for Environmental Information, 2018). On average, evaporation exceeds precipitation in every month.

Extreme storm events periodically cause severe flooding. From 1965 to 2018, the maximum monthly precipitation at Amistad Dam was 14.5 inches in July 1976. The maximum daily rainfall over this period was 7.1 inches on August 3, 2014. During the flood of 1954, when Hurricane Alice stalled over Crockett and Val Verde counties, as much as 24 inches of rain was reported for the storm event at Pandale, with 16 inches in a 24-hour period (National Centers for Environmental Information, 2014). Unofficial "bucket surveys" reported as much as 34 inches of rain from this storm (Von Zuben, Hayes, and Anderson, 1957).

The Texas Department of Parks and Wildlife indicates that Val Verde County, included as part of the Southern Great Plains, is projected to have an increased frequency of drought. If this happens, the area will experience an increase of average temperatures and the frequency, duration, and intensity of extreme heat. These conditions would lead to enhanced evapotranspiration and depleted soil moisture.

Soils

There are three broad soil groups in Val Verde County (Figure 2-3) mapped by the U.S. Department of Agriculture Natural Resources Conservation Service (Golden, Gabriel, and Stevens, 1982). Soils derived from the Edwards Plateau limestones cover most of the county. Soils derived from older alluvium deposits in the Rio Grande Plain occur along the river and near Del Rio. Finally, soils derived from recent alluvium, terraces, and valley fills are found along drainages throughout the county.

Soils formed from weathering of the Edwards Plateau limestone cover about 88 percent of Val Verde County. The major components are Ector, Langtry, Lozier, Mariscal, Shumla, Tarrant, and Zorra soils and rock outcrop. The Ector-rock outcrop association covers 48 percent of the county; the Langtry-rock outcrop-Zorra association covers 28 percent; and the Lozier-Mariscal-Shumla association covers 8 percent (Golden, Gabriel, and Stevens, 1982). The Edwards Plateau soils are very shallow, loamy, stony soil and exposed limestone bedrock on uplands. These soils drain easily and typically developed under grass or savanna-type vegetation in sub-humid to semiarid climates. They typically form on the uplands of the Edwards Plateau. The soils are suitable mainly for wildlife habitat and range. Low rainfall, very low available water capacity, and restricted rooting depth limit the amount of range forage produced during most years (Golden, Gabriel, and Stevens, 1982).

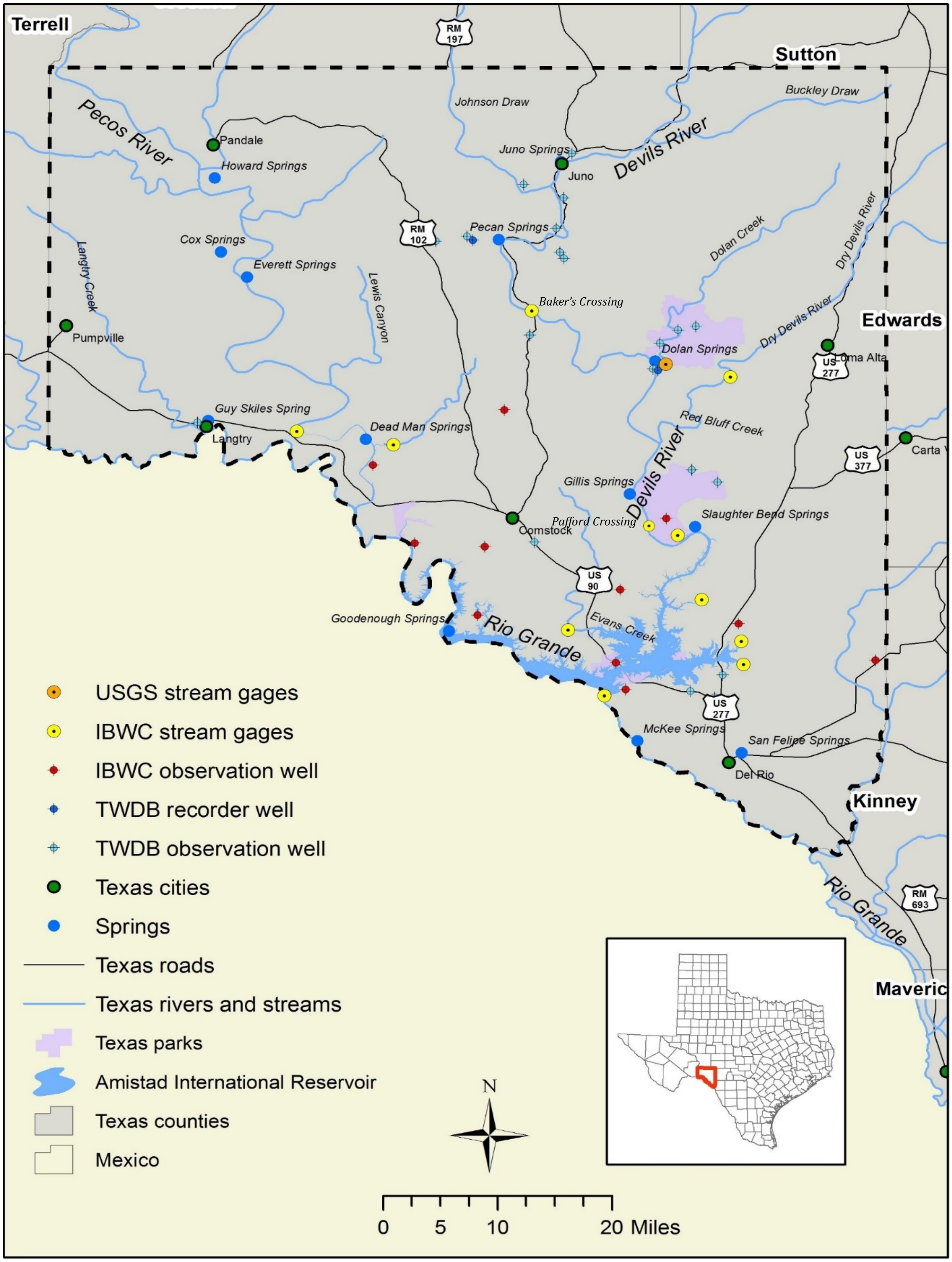

Figure 2-1. Map of Val Verde County, Texas.

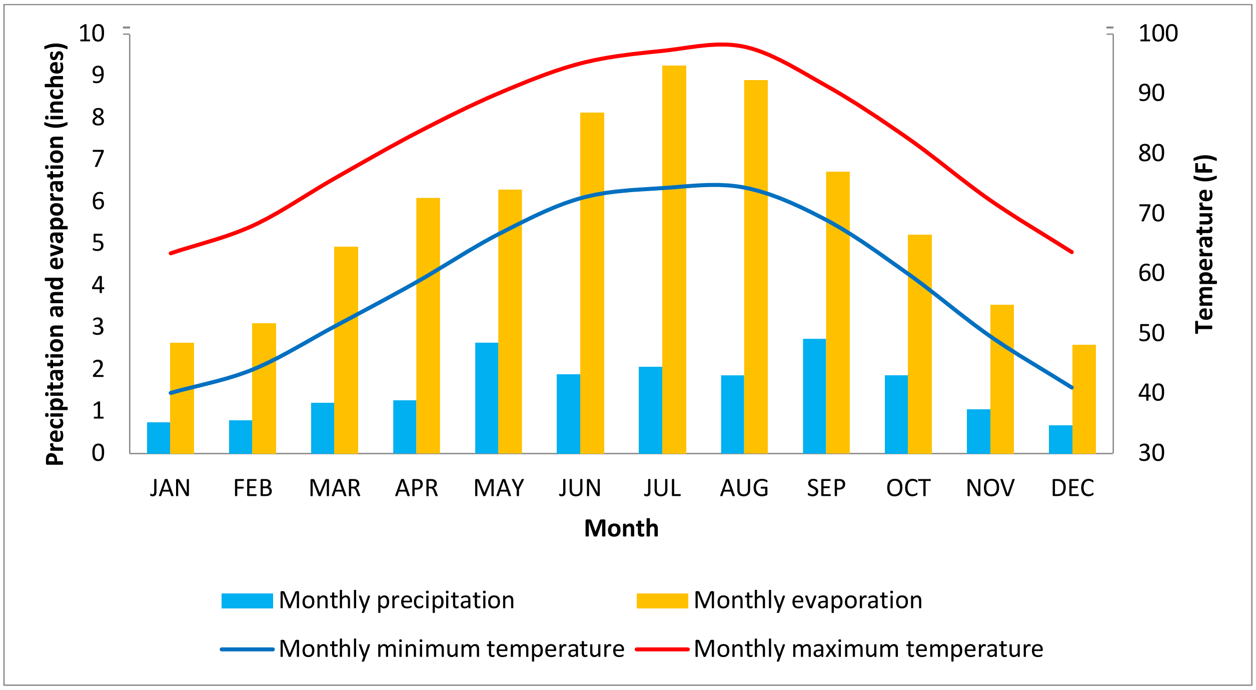

Figure 2-2. Average monthly precipitation, evaporation, and temperature extremes at Amistad Dam, 1965 to 2018. Data from National Centers for Environmental Information, 2018, and TWDB, 2018.

Soils formed from old alluvium overlying caliche cover about 8 percent of the county. The major components are Acuna, Coahuila, Jimenez, Olmos, and Quemado soils. These very shallow to deep, nearly level to sloping soils formed on uplands and terraces of the Rio Grande Plain. These soils are derived from outwash sediment, terrace deposits, and valley fills. These soils are used mainly for wildlife habitat and range. Some soils in this group are moderately well suited to crops and pasture grasses if irrigation water is available (Golden, Gabriel, and Stevens, 1982).

Soils formed in recent alluvium make up about 2 percent of Val Verde County. The major components are Dev, Lagloria, Rio Diablo, Rio Grande, and Reynosa soils. These deep, nearly level to gently sloping and gently undulating soils are on bottomlands and terraces of the Edwards Plateau and Rio Grande Plain. These soils are used mainly for wildlife habitat, range, and pasture. The Rio Grande and Lagioria soils along the river are moderately well suited to cultivated crops, special crops, and pasture plants, such as forage sorghums, wheat, oats, bermudagrass, and kleingrass. These soils are used mostly for pasture (Golden, Gabriel, and Stevens, 1982).

Vegetation and Land Use

Vegetation affects infiltration and runoff, two major components of the hydrological cycle. Plants intercept rainfall and slow runoff, reducing soil erosion and increasing infiltration.

Figure 2-3. Soil map of Val Verde County. Data from Natural Resources Conservation Service, 2018.

Plants transpire water from the soil, increasing evaporative losses, but roots also promote soil structure that facilitates deep percolation; these and other processes create a complex system of feedbacks between plants, soil, and groundwater.

Vegetative cover is generally sparse across the county, except along perennial rivers and streams that support dense woodlands. Val Verde County is situated in a biological transition zone where three major natural regions join: the Trans-Pecos, the Edwards Plateau, and the South Texas plains. The Trans-Pecos, or Chihuahuan Desert, is typically sparsely covered by desert shrubs, scrub, and succulents with denser riparian woods and shrubs. The Edwards Plateau is covered with a patchwork of oaks, Ashe Juniper, and open grassland savannahs, with denser deciduous forests along riparian corridors. The South Texas brush country consists of dense to shallow mesquite, live oak, acacia, blackbrush, and cenizo shrublands (San Felipe Creek Commissioners, 2007; McMahon, Frye, and Brown, 1984). Figure 2-4 shows the distribution of vegetation groups across Val Verde County (Texas Parks and Wildlife, 2018).

The underlying soil type and the extent of grazing pressures largely determine the distribution of vegetation. Golden, Gabriel, and Stevens (1982) describe native range plants as mainly short and mid grasses, with scattered juniper and woody brush. With overgrazing, the range deteriorates, becoming dominated by less desirable short grasses and woody brush.

Historical changes in vegetation on the Edwards Plateau are thought to have increased runoff and reduced infiltration in the aftermath of European settlement in the mid- to late-19th century. Researchers are still debating the more recent effects of ongoing changes in plant communities. Field studies in Central Texas find a modest, short-term decrease in evapotranspiration and runoff and an increase in recharge following brush removal, but areas with thin, karstic soils may not derive significant hydrological benefit from brush removal, and poorly managed or poorly timed intervention can increase erosion and soil loss (Goodwin, 2010, Ball and Taylor, 2003, Afinowicz, Munster and Wilcox, 2005, Banta and Slattery, 2011, Saleh and others, 2009). Other studies have correlated re-growth and spread of woody plants in the Texas Hill Country with increased groundwater recharge and stream baseflow (Wilcox and Huang, 2010), illustrating the complex relationships between plants, soils, and hydrology.

Aquatic Fauna

There are a number of threatened and endangered fish and mollusk species that inhabit springs or spring-fed streams in Val Verde County (Table 2-1). The Devils River supports five listed species, including the Texas Hornshell (*Popenaias Popeii)* (Federal endangered, State-threatened), Devils River minnow *Dionda diaboli* (Federal, State-threatened), Proserpine shiner (*Cyprinella Proserpina)* (State-Threatened), Rio Grande darter (*Etheostoma graham)* (State-threatened), and Conchos pupfish – Devils River subspecies (*Cyprinodon eximius ssp)* (State-threatened) (TCEQ, 2012). The Mexican blindcat (*Prietella phreatophila*) has also been documented in Val Verde County and is being further evaluated by the U.S. National Park Service and the Fish and Wildlife Service.

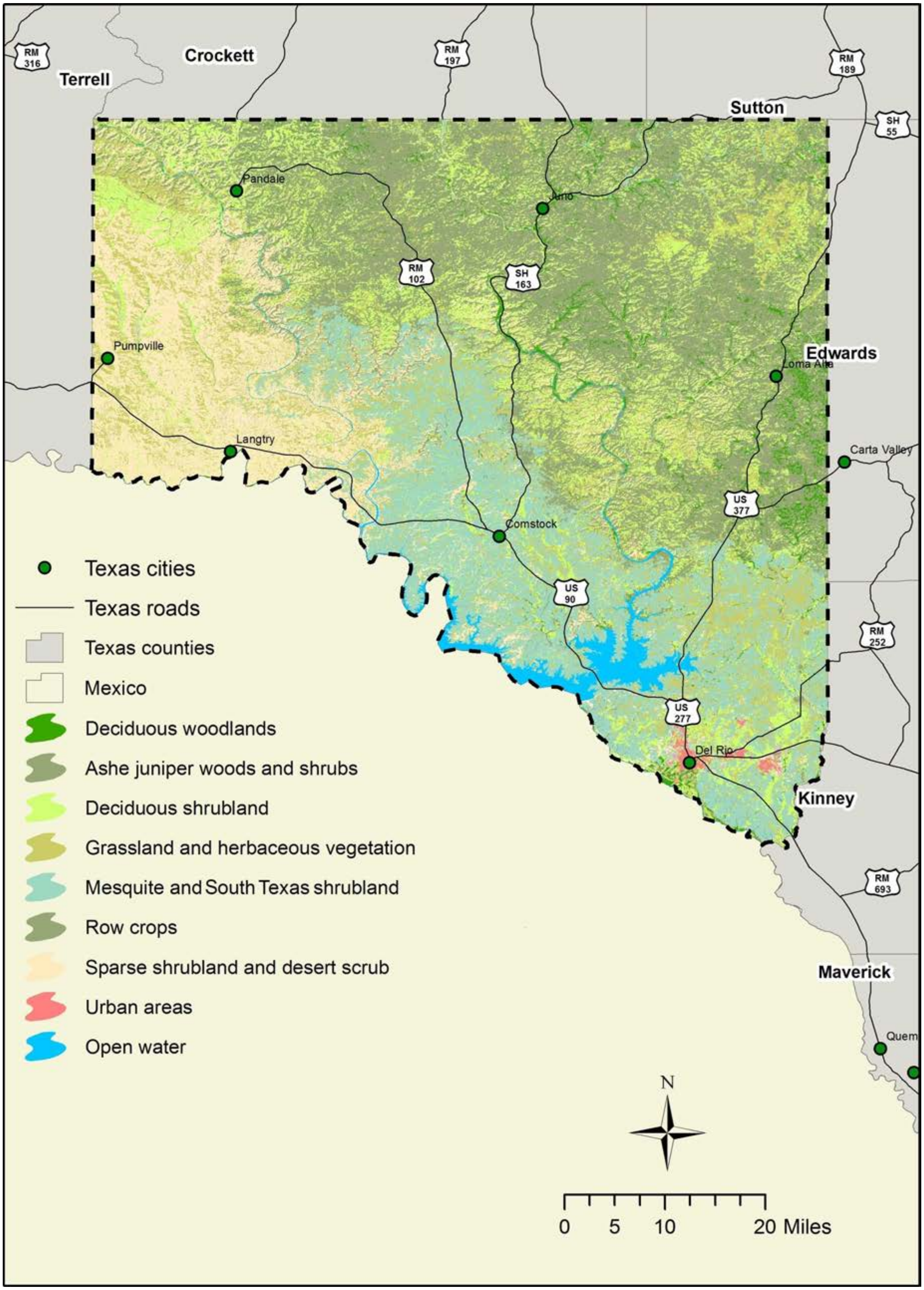

Figure 2-4. Generalized vegetation map of Val Verde County. Modified from TPWD data.

Table 2-1. Threatened and endangered aquatic species in Val Verde County

Group	Name	Population	Status
Mollusks	Texas Hornshell (*Popenaias popeii*)	Wherever found	Endangered
Fish	Devils River minnow (*Dionda diaboli*)	Wherever found	Threatened
	Rio Grande Silvery Minnow (*Hybognathus amarus*)	Wherever found, except where listed as an experimental population	Endangered
	Proserpine shiner (*Cyprinella proserpina)*	Rio Grande Basin in Texas	State-threatened
	Rio Grande darter (*Etheostoma graham)*	Rio Grande Basin in Texas	State-threatened
	Conchos pupfish – Devils River subspecies (*Cyprinodon eximius ssp*.)	Rio Grande Basin in Texas	State-threatened

Sources: TCEQ, 2012; U.S. Fish and Wildlife Service, 2018.

The Devils River minnow (*Dionda diaboli*) was abundant in the Devils River, San Felipe Creek, and Sycamore Creek as recently as the mid-1970s. It was listed as a threatened species in October 1999 (U.S. Fish and Wildlife Service, 2005). It is currently found in three streams in Val Verde County: Devils River, Dolan Creek, and San Felipe Creek. The status of the species in Sycamore Creek is not known. The Devils River minnow is often associated with emergent aquatic vegetation. The primary threats to the species are habitat loss and invasive non-native species (U.S. Fish and Wildlife Service, 2005).

The Mexican Blindcat (*Prietella phreatophila*), a species of small, cave-dwelling catfish, was recently discovered in caves on the U.S. side of Amistad Reservoir (National Parks Conservation Association, 2017). The Mexican Blindcat is listed as an endangered species in Mexico and is consequently protected as an endangered species wherever it is found under U.S. law (U.S. Fish and Wildlife Service, 2018).

The U.S. Fish and Wildlife Service listed the Texas Hornshell mussel (*Popenaias popeii*) as an endangered species, effective March 12, 2018, because of impaired water quality, habitat loss, sediment accumulation in the stream beds it inhabits, predation, barriers to host-fish movement, and the effects of climate change (U.S. Fish and Wildlife Service, 2018). The Texas Hornshell historically ranged throughout the Rio Grande drainage in New Mexico, Texas, and Mexico. Currently, five known populations of Texas Hornshell remain in the United States, including in the Black River in Eddy County, New Mexico; in the Devils River and Pecos River in Val Verde County; in the lower canyons of the Rio Grande in Brewster and Terrell counties; and in the lower Rio Grande near Laredo.

The Texas Hornshell populations in Texas include a small remnant population in the Pecos River, multiple small, more dispersed populations in the Devils River, and moderate populations in the Rio Grande. The Texas Hornshell were extirpated from the lower reaches of the Pecos River following inundation by Amistad Reservoir, and salinity is frequently too high for mussel survival in the reach from the confluence with the Black River in New Mexico downstream to the confluence with Independence Creek (U.S. Fish and Wildlife Service, 2018). A small population survives in the Pecos River downstream of the confluence with Independence Creek and upstream of Amistad Reservoir near Pandale. Intensive surveys of the Devils River identified Texas Hornshell populations in the lower 29 miles of the river in the Dolan Falls Preserve and the Devils River State Natural Area's Big Satan Unit (U.S. Fish and Wildlife Service, 2018).

Streamflow requirements for these species are linked to spring discharges and therefore are tied to groundwater conditions. Aquatic habitats for these species depend upon groundwater inflows to maintain sufficient, good quality river flows, particularly during droughts and summer low-flows when surface runoff is minimal and water quality begins to deteriorate. Water quality can be compromised during low flow events if water temperatures rise and dissolved oxygen decreases, further impacting these rare aquatic organisms. The Texas Park and Wildlife Department (TPWD) has directly observed mass predation events on Texas Hornshell in the Devils River during a prolonged low spring and streamflow period in 2015. Additionally, there are concerns about elevated water temperatures during periods of low flow that are potentially lethal to larval and adult mussels. The TPWD, The Nature Conservancy (TNC), University of Texas, and Texas A&M University are currently conducting research to determine what these critical lethal temperatures are and under what flows they might occur in Texas Hornshell habitat in the Devils River. The threat of worsening drought in concert with the potential for groundwater development could exacerbate the loss of species habitat, thereby increasing the rate of species decline and leading to critical groundwater problems in the future.

Conservation efforts for these species are being led by the TPWD and TNC. These organizations manage habitat areas in the Devils River State Natural Area and the Dolan Falls Preserve. The TPWD owns and manages the Del Norte Unit and the Dan A. Hughes Unit of the Devils River State Natural Area. Together these units encompass approximately 37,000 acres. In addition, the TPWD cooperates with TNC, which owns or manages the 4,788-acre Dolan Falls Preserve as well as maintaining interest in nearly 130,000 acres in the Devils River basin through conservation easements or fee title ownership. Recent and current research investigations have focused on groundwater levels, spring discharge, river flows, and fish and wildlife habitat suitability. Various collaborative research and monitoring programs between the TPWD, TNC, and UT Bureau of Economic Geology were ongoing or in development as this report was in preparation. These programs and their estimated completion dates include:

- Devils River standardized aquatic monitoring (August 2019)
- Development of fish habitat suitability criteria (August 2019)
- Longitudinal survey of priority species (May 2019)
- Hydraulic habitat model development for the Devils River (2014 – update underway)
- Monitoring the effects of groundwater level on spring and stream discharge, stream temperature, and habitat for Devils River Minnow in the Devils River (August 2018)
- Airborne lidar bathymetry survey and aquatic habitat evaluation for Devils River Minnow and Texas Hornshell Mussel in the Devils River (August 2020)
- Thermal tolerance of Texas Hornshell from the Rio Grande Basin (August 2020).

3.0 Geology

Key findings

- Cretaceous limestone deposits dominate the surface and near surface geology of Val Verde County.
- The geology varies from north to south, reflecting changes in the depositional environment during the Lower Cretaceous period.
- Weathering during periods of low sea level in the Cretaceous period and in more recent times has dissolved channels in the limestone and associated evaporite minerals, creating a karst fabric.
- Areas of subsidence and sinkholes are common, especially in the outcrop of the Devils River Limestone in central Val Verde County.

The surficial geology of Val Verde County consists predominantly of Cretaceous-age carbonate rocks of the Edwards Plateau (Figure 3-1). The Edwards-Trinity (Plateau) Aquifer consists of rocks of the Edwards (Washita and Fredericksburg) Group and the Trinity Group (Figure 3-2). Rocks deposited earlier than the Cretaceous period are not a source of water supply in Val Verde County. The Triassic Dockum Aquifer does not extend as far south as Val Verde County.

The Segovia Member of the Edwards Formation covers most of the northern half of the county, except for the area west of the Pecos River, where the Boquillas Flags and Austin Chalk formations are present at the surface. The Devils River Formation crops out south of the Segovia Formation in a roughly east-west band approximately 8 miles wide. To the west of the Devils River, the Devils River Formation is partially covered by outcrops of the Del Rio Clay, Buda Limestone, and Austin Chalk formations on the higher elevations. The Salmon Peak Formation outcrops in broad areas south of the Devils River Formation. The Salmon Peak Formation is locally covered by the Upper Cretaceous Del Rio Clay, Buda Limestone, and Eagle Ford Group sediments, and Quaternary deposits including the Uvalde Gravel Formation.

Figures 3-3 to 3-5 are generalized geologic cross-sections of Val Verde County. The geometry of the Trinity Group – identified in these sections as the Glen Rose Limestone – is not as well defined as the Edwards Group. Fewer wells are completed in the Trinity Group because adequate water is generally found at shallower depths in the Edwards Aquifer. As a result, well control to define the base of the Trinity Group is relatively sparse.

During the Cretaceous period (145 to 65 million years ago), carbonate sediments were deposited over an eroded surface and accumulated to form southward-dipping and thickening rock layers in Val Verde County (Figure 3-2). The base of the Cretaceous sediments extends from a current elevation of over 1,200 feet in the north to as much as 2,000 feet below sea level in the south near Del Rio (Barker, Bush, and Baker, 1994; Anaya and Jones, 2009).

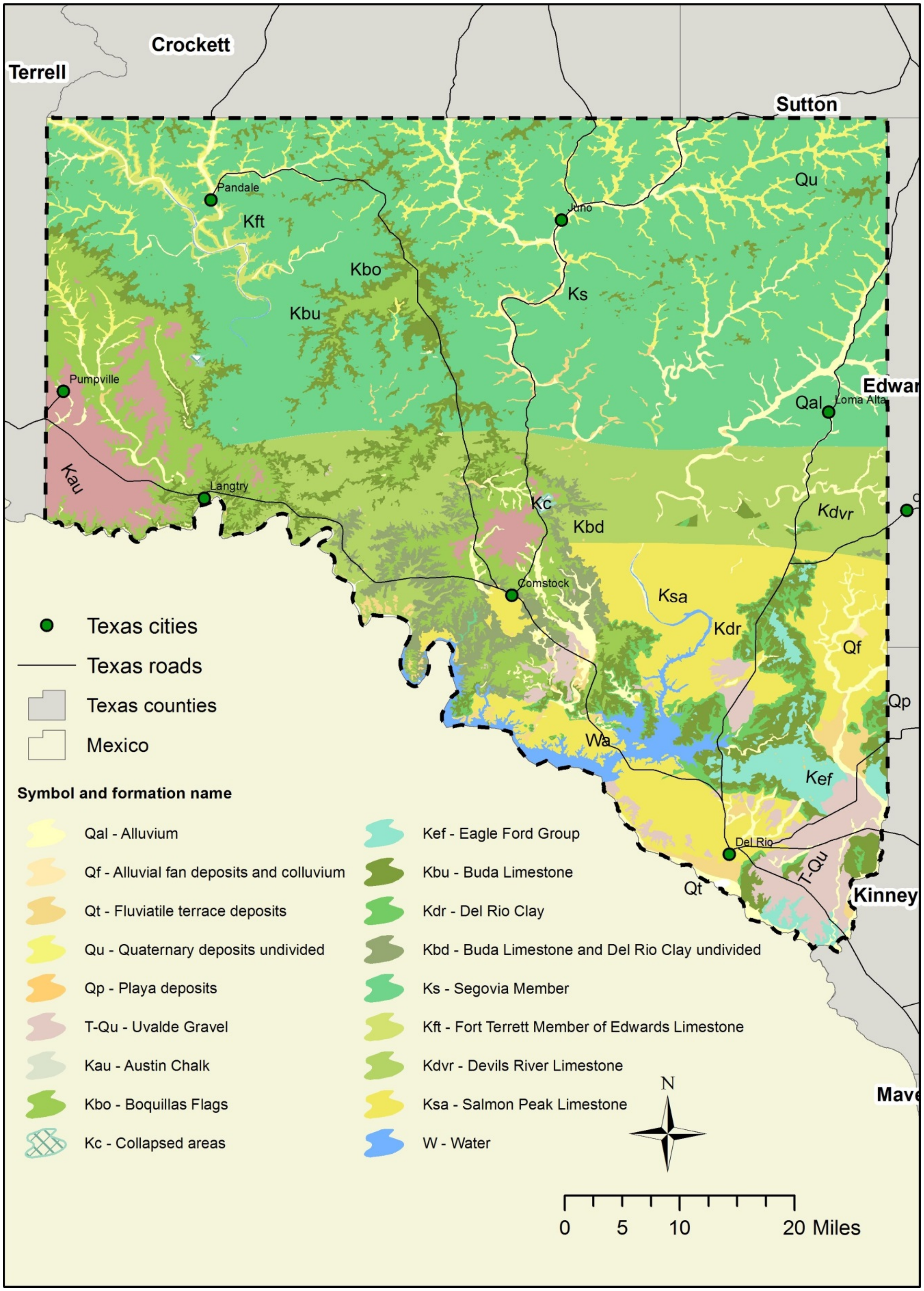

Figure 3-1. Surficial geology of Val Verde County. Modified from the Geologic Atlas of Texas*.*

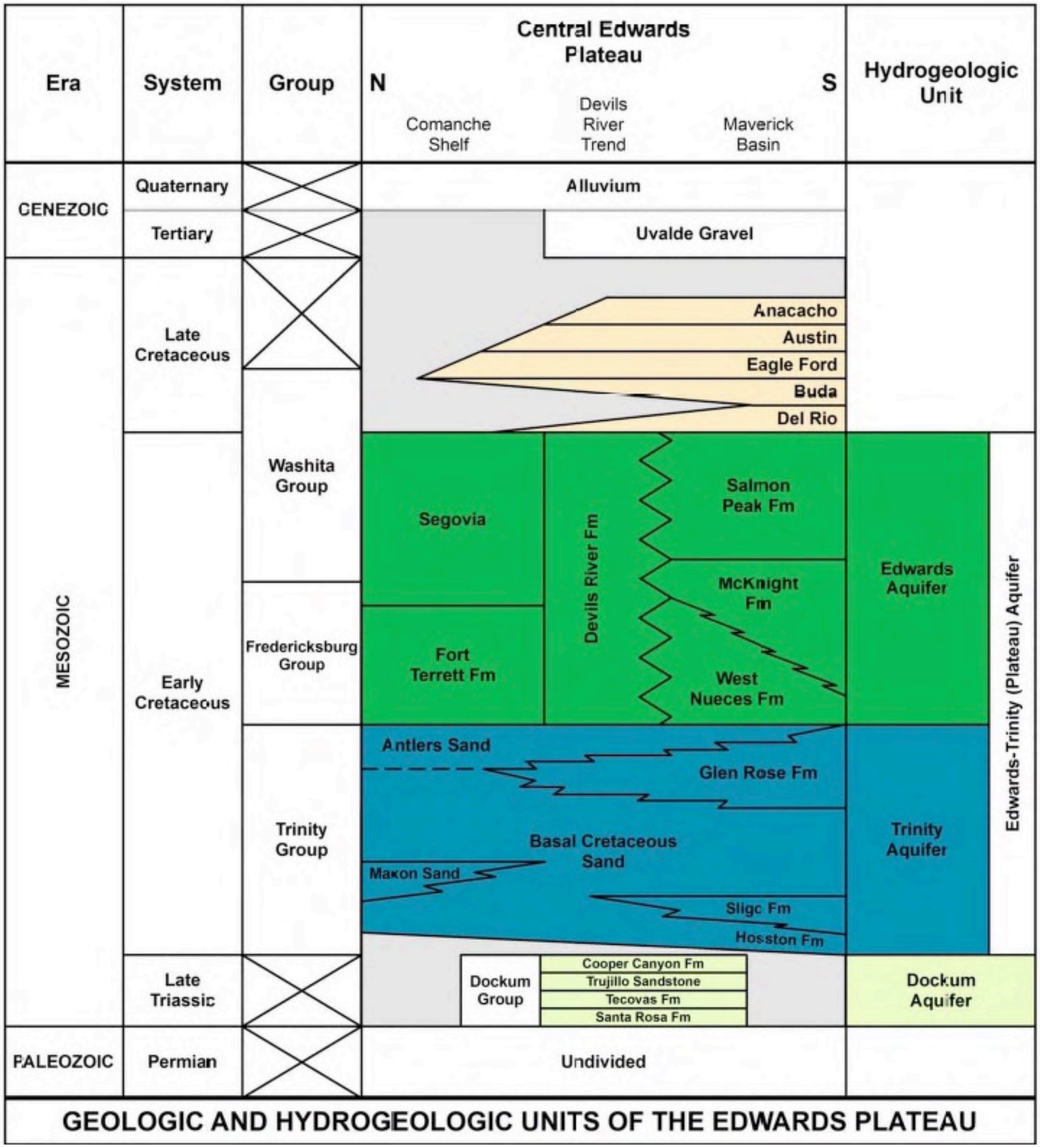

Figure 3-2. Hydrostratigraphic chart of the central Edwards Plateau. Adapted from Anaya and Jones, 2009.

Lower Cretaceous (145 to 100 million years ago) rock units are composed of sandstones and marine carbonates of the Trinity, Fredericksburg, and Washita groups. The basal Cretaceous Sand, an alluvial deposit formed by braided streams draining from the Devils River and Llano uplifts southeast to the Gulf and of Mexico, is the oldest Trinity Group formation ("basement sands" on Figures 3-3 through 3-5). The Glen Rose Limestone was deposited on top of the basal sand in a shallow marine environment as the Gulf continued to subside (Barker, Bush, and Baker, 1994;

Anaya and Jones, 2009). The Fredericksburg Group is a mix of reef, shallow marine, and deep marine sediments deposited along the continental margin (Figure 3-6). The Fredericksburg Group rock units crop out as three east-west bands of roughly time-equivalent formations that reflect different depositional environments.

Subsidence along a tectonic hinge line running through Val Verde County created deeper marine conditions in the Maverick Basin in the southern part of the county. The West Nueces, McKnight, and Salmon Peak formations were successively deposited in the Maverick Basin. The West Nueces Formation consists of re-worked shell fragments, mudstone and grain-stone. It has negligible porosity and permeability in the subsurface but can have large conduit flow associated with dissolution along fractures when exposed near the surface (Stanton, Kress, Teeple, Greenslate, and Clark, 2007). The McKnight Formation is made up of evaporites, lime muds, shale, and organic-rich limestone. It also has negligible permeability except where evaporite dissolution has occurred. The Salmon Peak Formation contains lime muds and limestone (Barker, Bush, and Baker, 1994), and is characterized by extensive karst dissolution.

The Devils River Limestone follows the northern margin of the Maverick Basin along the Devils River Reef Trend. The Devils River Formation developed in an arc along the northern edge of the Maverick Basin as a shallow-marine coral reef on the remnants of Devils River Uplift.

The Segovia and Fort Terrett Formations were deposited in the shallow backreef waters to the north of the Devils River Reef Trend on the Comanche Shelf (Barker, Bush, and Baker, 1994; Anaya and Jones, 2009). Periodic uplift and subaerial exposure during early Washitan time led to extensive leaching, erosion, and karst development in the upper Segovia Formation north of the Maverick Basin, especially in the Kirshburg Evaporite Member at the top of the Fort Terrett Formation. Further dissolution and karstification of the Comanche Shelf sediments took place after deposition of the Segovia Formation, when the majority of the Central Texas Platform was subaerially exposed (Barker, Bush, and Baker, 1994; Anaya and Jones, 2009).

The Upper Cretaceous Del Rio Clay and the Buda Limestone were deposited as a mix of clays and lime muds in late Washitan time. The Del Rio Clay is a calcareous, pyritic, gypsiferous siltstone, up to 69 feet thick, and contains many marine fossils. The Buda is a massive to nodular limestone with an average thickness of 66 feet (Veni, 1994).

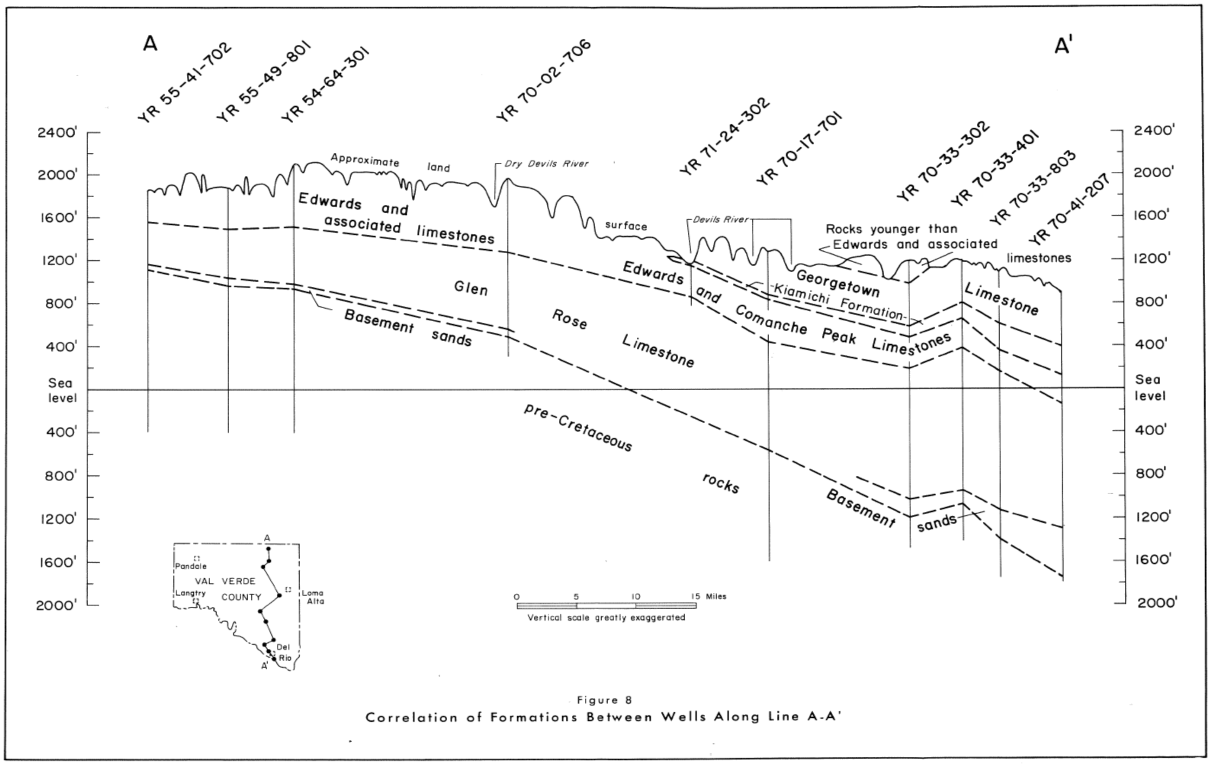

Figure 8
Correlation of Formations Between Wells Along Line A-A'

Figure 3-3. Generalized cross-section (A-A') of Cretaceous deposits in Val Verde County (Reeves and Small, 1973).

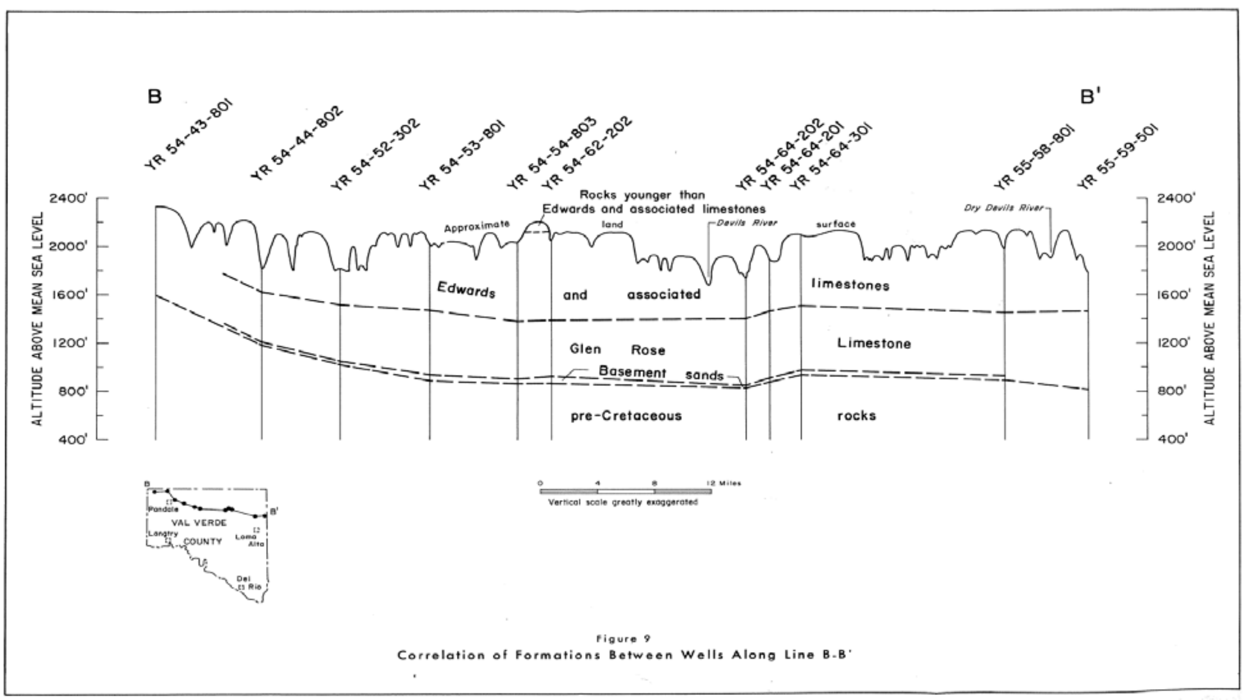

Figure 9
Correlation of Formations Between Wells Along Line B-B'

Figure 3-4. Generalized cross-section (B-B') of Cretaceous deposits in Val Verde County (Reeves and Small, 1973).

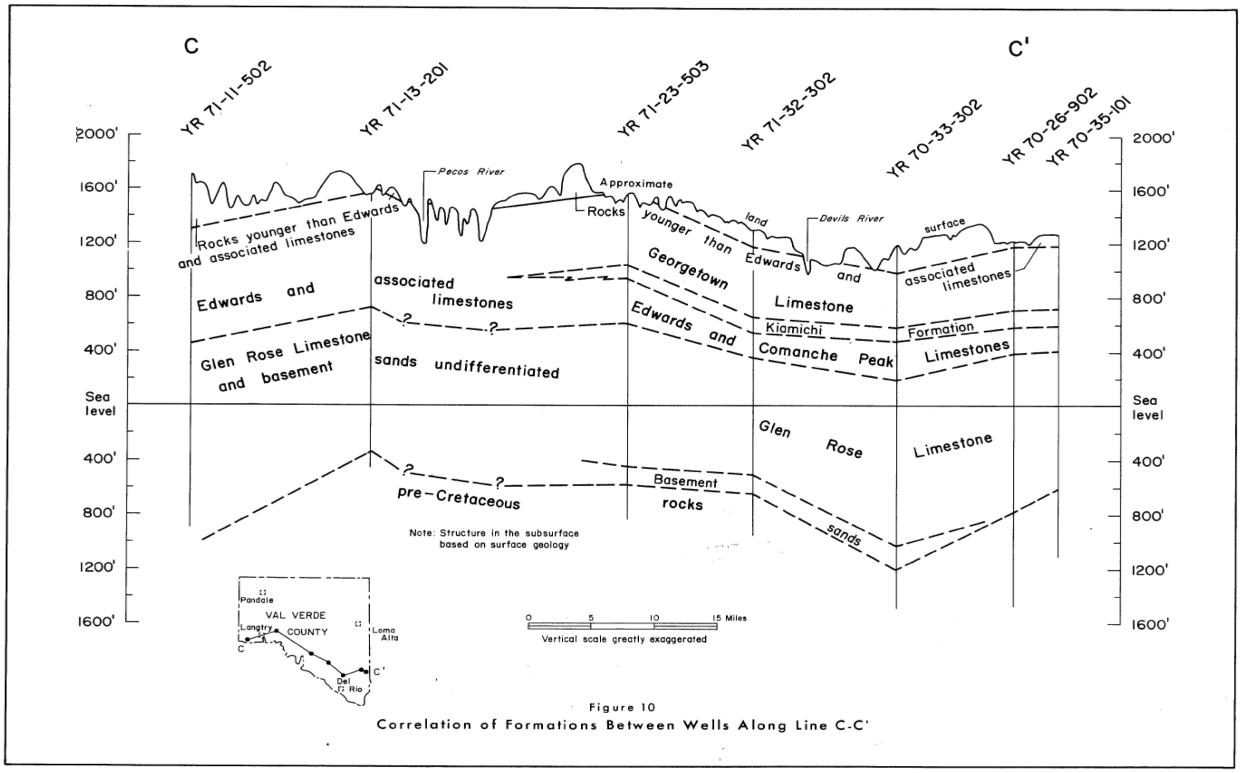

Figure 3-5. Generalized cross-section (C-C') of Cretaceous deposits in Val Verde County (Reeves and Small, 1973).

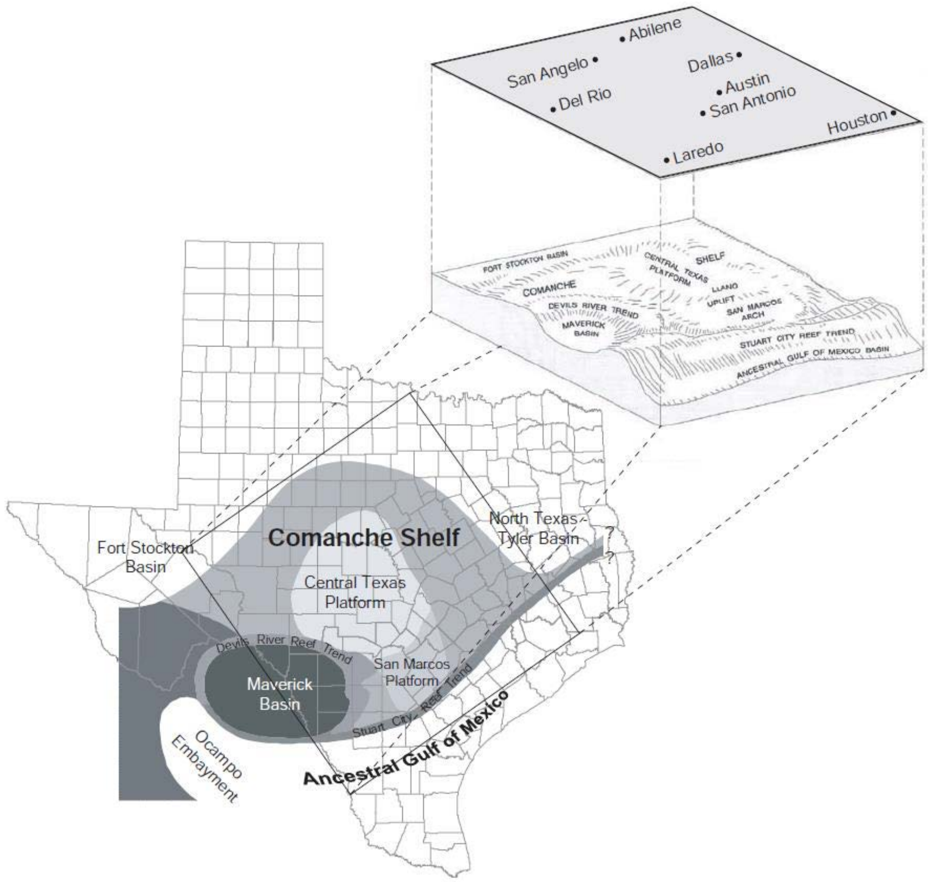

Figure 3-6. Depositional environments in Central Texas during the Lower Cretaceous (Anaya and Jones, 2009).

The late Cretaceous Eagle Ford, Austin Chalk, and Anacacho formations are fine-grained and strongly cemented, with low permeability (Barker, Bush, and Baker, 1994). Regional uplift during the Laramide Orogeny, which created the Rocky Mountains to the west, brought an end to the sediment deposition in the Val Verde County area.

The Cretaceous-age carbonate rocks remain mostly un-deformed by subsequent geological activity, but faulting, dissolution, and collapse features locally disrupt the carbonate rocks (Figure 3-7). Collapse features and faults are concentrated in a west-northwest to east-southeast trend across the county, extending eastward from the outcrop area of the Devils River Trend. Collapse features are most prominent in the Devils River Limestone in the area just to the west of the Carta Valley Fault zone, but smaller areas of collapse are widespread across the southern half of Val Verde County (National Park Service, 2018).

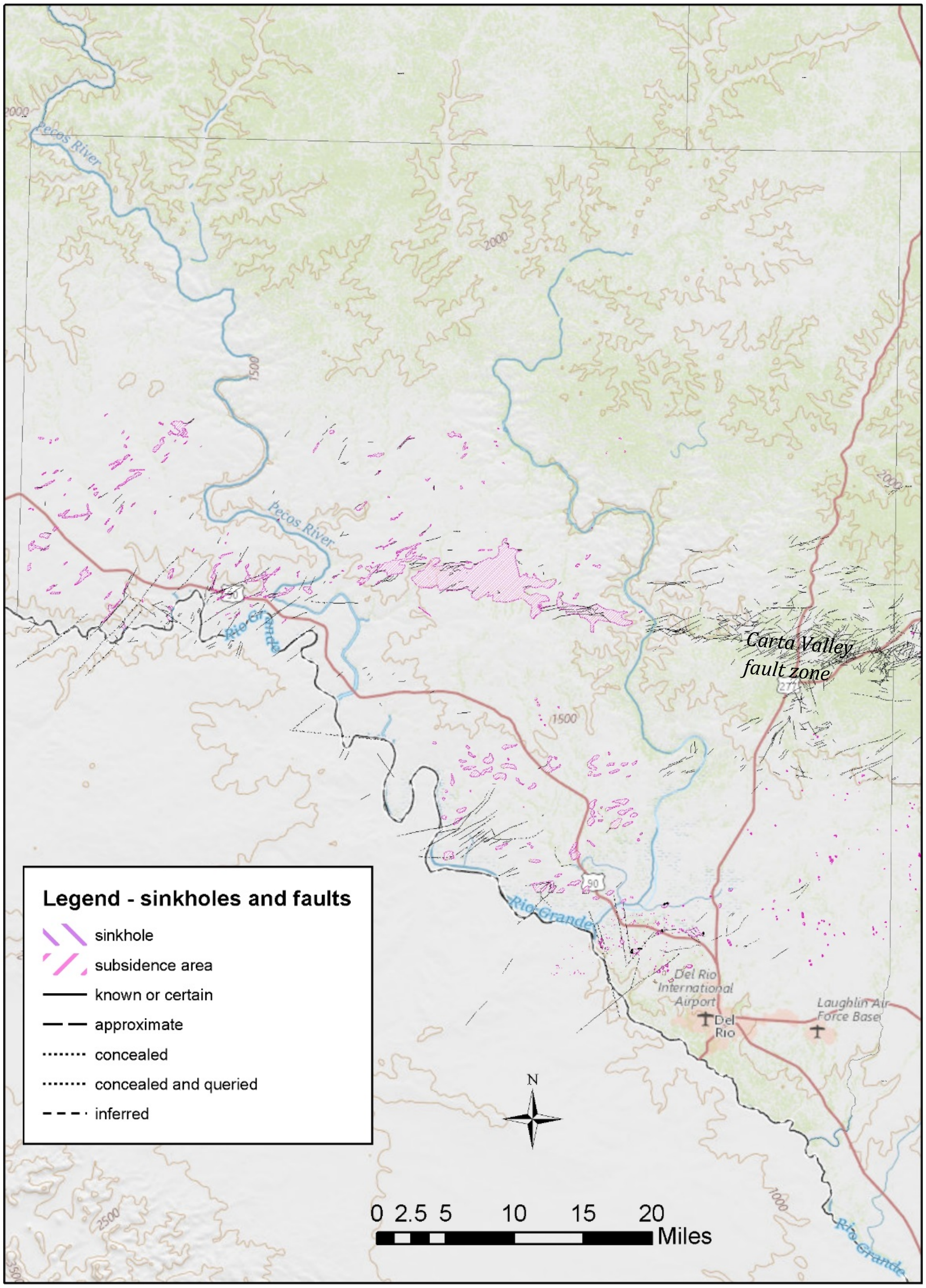

Figure 3-7. Sinkholes, subsidence features, and faults in Val Verde County. Data from National Park Service, 2018.

4.0 Hydrogeology

Key findings

- The Edwards-Trinity (Plateau) Aquifer is the principal aquifer in Val Verde County. Groundwater in the aquifer generally flows from north to south and discharges to springs and streams draining to the Rio Grande.
- Groundwater quality data suggest that most recharge supplying major springs occurs through large fractures and sinkholes, and discharges through a system of conduits with minimal interaction with the aquifer matrix under normal flow conditions.
- Karst conduits associated with stream drainages are important elements of the Val Verde groundwater system, although there remains ambiguity as to the nature of the conduits and their effects on groundwater movement and production at particular locations of interest.
- Widely varying recharge estimates introduce significant uncertainties in the groundwater budget.
- The mean residence time of groundwater discharged from the major springs may range from 2 years to 34 years.
- Resolving the true sources of spring flows are necessary to properly calibrate models and to provide the most accurate estimates of aquifer properties and groundwater volumes available for use.
- Water levels in wells across much of the southern half of the county were affected as Amistad Reservoir filled. Spring flows also increased in this area.
- Water levels in parts of the county outside the area influenced by Amistad Reservoir are very consistent over the period of record and do not exhibit any long-term decline in response to pumping or reduced recharge.
- Well yields are highly variable with the highest yields found along stream channels.
- Available data suggest that the Devils River has had intermittent flow above Pecan Springs over the last 100 years.
- Localized areas of drawdown may be present near some larger capacity wells but cannot be distinguished from background variability given the available network of observation wells.
- Available water level records do not demonstrate any widespread, long-term effects on recharge, streamflow, or groundwater-surface water interaction because of current levels of pumping in Val Verde County.
- Groundwater pumping has the potential to affect the lateral movement of groundwater in Val Verde County. Pumping also has the potential to reduce streamflows and spring discharge.
- More detailed monitoring is needed. The current groundwater monitoring network does not support detailed evaluation of changes in groundwater elevations or flow over time.

The extent and thickness of the different formations comprising the aquifers, and the geological structures developed in those formations, define the physical framework of the groundwater system. Groundwater elevations within the aquifers indicate the directions in which groundwater generally flows. The hydraulic properties of the aquifer affect flow rates and the overall storage capacity of the aquifer. Groundwater recharge and discharge, by pumping, spring flows, and interaction with rivers and lakes, determine how the groundwater system evolves over time. Groundwater quality affects the usability of the resource and can serve as a useful tracer for groundwater movement through the aquifer system.

Hydrostratigraphy

The primary source of groundwater in Val Verde County is the carbonate rocks of the Fredericksburg Group and the lower part of the Washita Group, collectively known as the Edwards Aquifer (Figure 3-2). These include the Fort Terrett and Segovia formations, the Devils River Formation, and the West Nueces, McKnight, and Salmon Peak formations.

Regionally, the hydraulic relationship between the Edwards and the Trinity aquifers is variable and complex. Throughout much of the Edwards Plateau, the Edwards Aquifer is hydraulically connected to the underlying Trinity Aquifer and is mapped as the Edwards-Trinity (Plateau) Aquifer by the TWDB. However, in Val Verde County there appears to be limited communication between the Edwards and the Trinity aquifers, as illustrated by the GAM modeled water budget (Anaya and Jones, 2009), which estimates a net upward flux from the Trinity to the Edwards of about 2,600 acre-feet per year. Veni (1996) considers the Glen Rose Formation as a locally impermeable lower boundary of the Edwards Aquifer in central Val Verde County. Kreitler, Beach, Symank, Uliana, Bassett, Ewing, and Kelly (2013) conclude that there is a small downward flux from the Edwards Aquifer to the Trinity Aquifer, except in a zone of regional discharge near the Rio Grande where there is up-flow of more saline water from the Trinity Aquifer.

The upper zone of the Edwards Aquifer is generally the most prolific source of water. Groundwater flow is predominantly in dissolution channels formed preferentially along bedding planes, joints, and fractures. The contact between the Fort Terrett and Segovia formations has significant porosity due to dissolution of the Kirshburg Evaporite Member of the Fort Terrett Formation (Figure 4-1). Numerous springs discharge along this contact where the Devils River has eroded down to its level near Dolan Springs (Veni, 1996).

The Paleozoic rocks underlying the Trinity aquifer unit provide a relatively impermeable base for the Edwards-Trinity (Plateau) Aquifer on a regional basis (Barker and Ardis, 1992). The Upper Cretaceous Del Rio Clay, Buda Limestone, Boquillas Formation, and Austin Chalk are generally considered confining units on top of the Edwards -Trinity (Plateau) Aquifer.

Figure 4-1. Karstic limestone at the contact between the Fort Terrett and Segovia formations, outcropping in the bed of the Devils River near Finnegan Springs. A. Weinberg photo.

Aquifer geometry

The regional structural framework developed by Anaya and Jones (2009) maps the elevation and thickness of both the Edwards and Trinity aquifers. The base of the Edwards Aquifer slopes to the south and southwest with a gradient from 1 to 50 feet per mile. The elevation of the base of the Edwards Aquifer (Figure 4-2) ranges from over 1,800 feet above sea level along the border with Crockett and Sutton counties in the north to more than 400 feet below sea level near Del Rio in the southeastern part of the county. The thickness of the Edwards Aquifer ranges from less than 100 feet in some parts of the Pecos River canyon to over 1,200 feet near Del Rio (Figure 4-3). The Edwards Aquifer is over 700 feet thick in a large area along the western border with Terrell County. The thickness of the Trinity Aquifer also increases to the south and west; it ranges from less than 100 feet along parts of the northern boundary of Val Verde County to more than 1,700 feet along parts of the southern boundary on the Rio Grande (Figure 4-4).

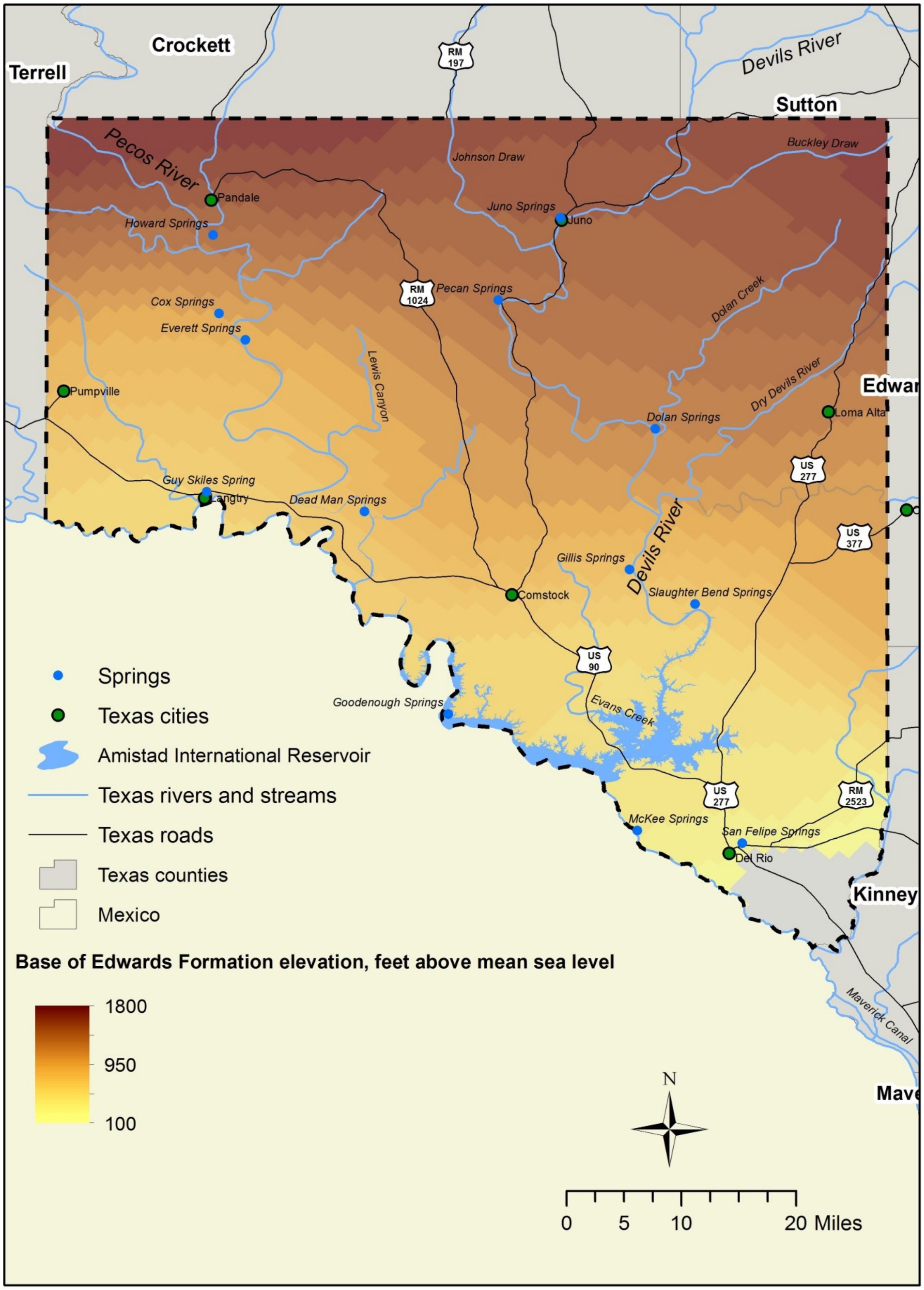

Figure 4-2. Elevation of the base of the Edwards section of the Edwards-Trinity (Plateau) Aquifer in Val Verde County, in feet relative to mean sea level. Data from Anaya and Jones, 2009.

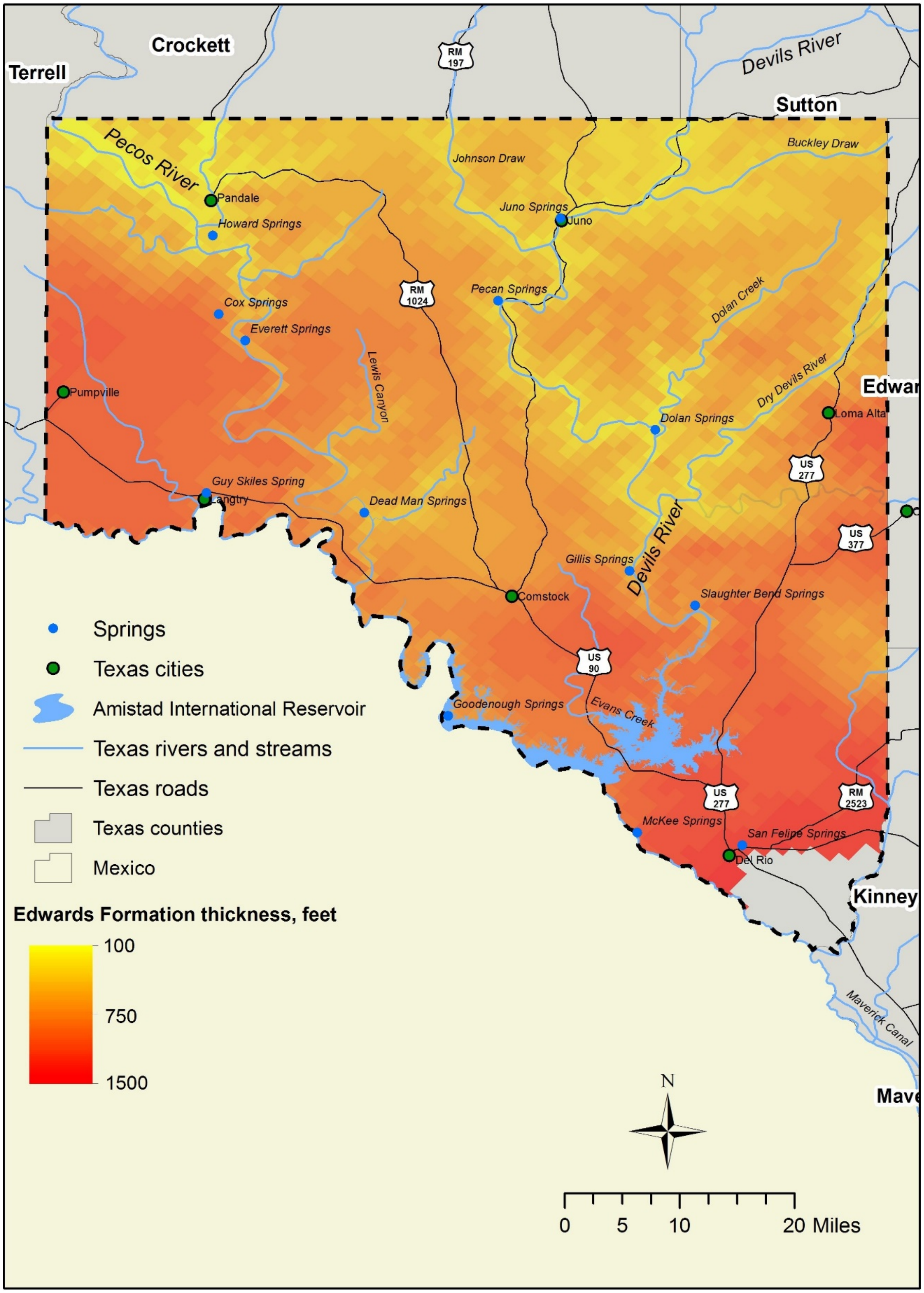

Figure 4-3. Thickness, in feet, of the Edwards section of the Edwards-Trinity (Plateau) Aquifer in Val Verde County. Data from Anaya and Jones, 2009.

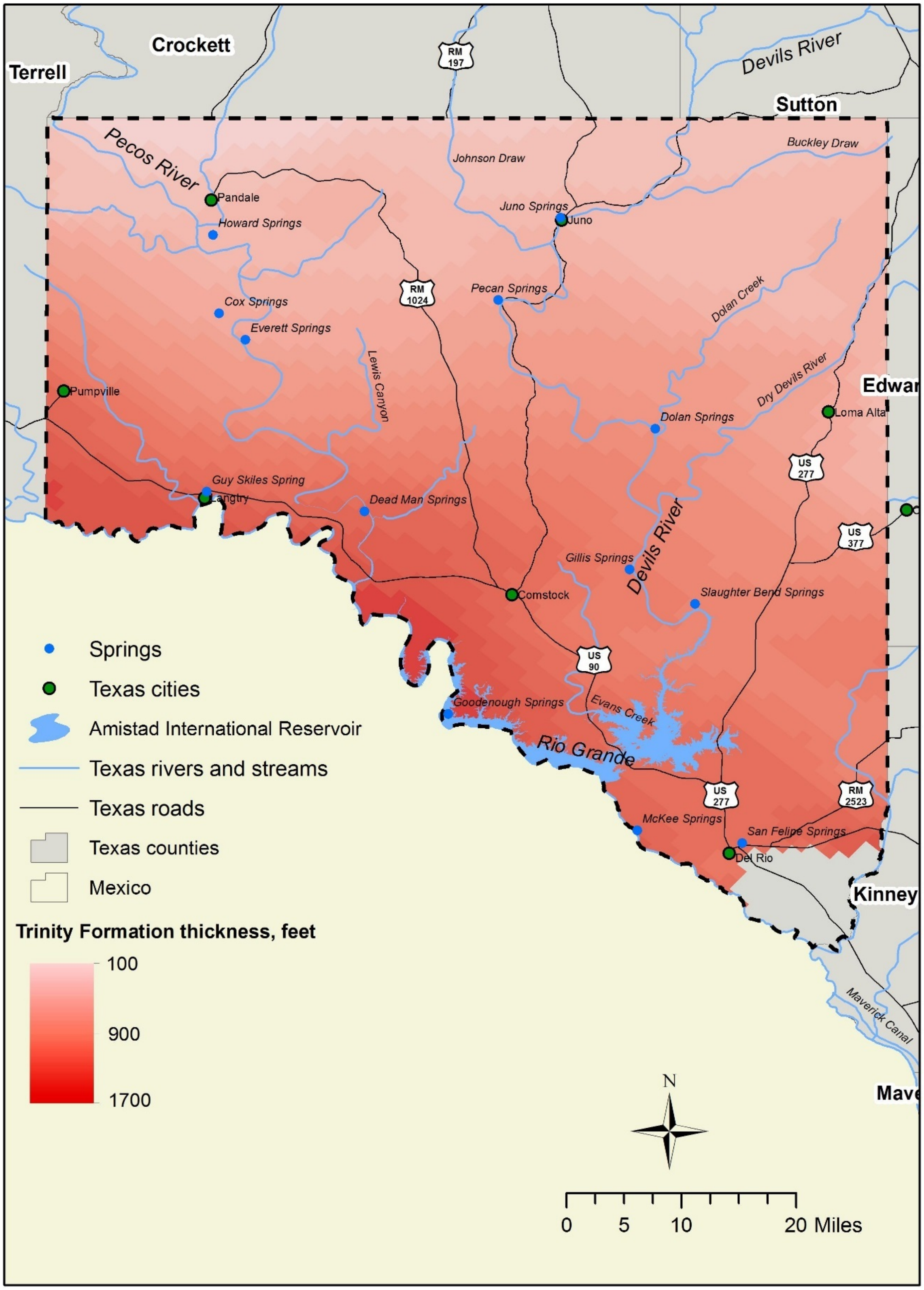

Figure 4-4. Thickness, in feet, of the Trinity section of the Edwards-Trinity (Plateau) Aquifer in Val Verde County. Data from Anaya and Jones, 2009.

Water Levels and Flow

Groundwater elevations in the Edwards-Trinity (Plateau) Aquifer range from over 1,800 feet above sea level in northern parts of Val Verde County to about 900 feet near Del Rio. Groundwater levels in wells near Amistad Reservoir show a strong correlation with the reservoir level. Groundwater flow within the Edwards Aquifer generally follows surface topography and converges on the drainages of the Pecos and Devils rivers and Sycamore Creek.

The TWDB and the International Boundary and Water Commission (IBWC) maintain observation well networks in Val Verde County. Two TWDB recorder wells measure water levels every hour and 20 current observation wells are measured manually by the TWDB once a year. These wells are mostly located along the Devils River and near Amistad Reservoir. In addition, the International Boundary and Water Commission measures water levels in 10 wells in the southern half of the county (Figure 4-5). Wells outside the area of influence of Amistad Reservoir have had generally stable water levels over the period of record. The water level variations of wells within the influence of the reservoir closely track the reservoir surface elevation.

The current groundwater monitoring networks are adequate for defining regional changes in groundwater conditions, but do not provide sufficient spatial or temporal detail to define local groundwater features, such as drainage areas around springs or areas of influence around pumping wells. Some locations (Figure 4-5) listed as TWDB observation wells are no longer accessible or cannot be measured. In addition, monitoring has been discontinued at about half of the IBWC observation wells since 2011; therefore the TWDB has not received any of the IBWC monitoring data since 2011. There are no observation wells in the Pecos River drainage area; there is only one observation well in the Sycamore Creek drainage area; and there is sparse coverage along tributaries to the Devils River such as the Dry Devils River, Dolan Creek, and Johnson Draw.

Water level maps typically show synoptic conditions, reflecting measurements made over a short period of time, and are used to evaluate groundwater flow direction and assess where changes in groundwater level or flow may be occurring. Veni (1996) developed the most detailed map of groundwater levels for the Val Verde County area to date, reporting 172 water level measurements during 1994 and 1995 in the Dolan Springs drainage basin, covering portions of Val Verde, Crockett, Sutton, and Edwards counties. Veni's groundwater elevation map (Figure 4-6) reflects a point-in-time view of the complex groundwater drainage patterns controlled by topography and karst structures but covers only a portion of Val Verde County.

Figure 4-7 shows contours of the interpolated groundwater elevation surface based on the average of winter-time (non-pumping) water level measurements at each of the 261 wells in the TWDB groundwater database listed as completed in the Edwards Group or Edwards and associated limestones. The measurement dates span the interval from 1937 to 2015. The water level contours thus represent long-term average groundwater conditions. To the extent that groundwater levels in Val Verde County have changed over time, these contours may not accurately represent current conditions.

Groundwater elevations in most of Val Verde have been generally stable over the period of record, although there is significant variability because of natural cycles of wetness and drought.

Hydrographs of water level measurements in 33 Edwards Aquifer wells with at least 10 years of data (Figure 4-8) mostly show no increasing or decreasing trends over time. The wells near Amistad Reservoir, shown in the lower panel of Figure 4-8, are an exception. Water levels in these wells rose as much as 100 feet between 1968 and 1977 as the effect of Amistad Reservoir filling propagated through the hydrological system. Several wells in different parts of the county show a decreasing trend since about 2011, including wells 7033508 and 7033302 near Amistad Reservoir and wells 7001402 and 7001404 in the Devils River State Natural Area. These trends could represent the effects of the drought that began in that year or the effects of local increases in pumping in response to the drought.

Figure 4-9 shows the areal extent area affected by the hydraulic pressure of the reservoir based on the geographic distribution of wells where the potentiometric head increased as Amistad Reservoir filled. The pressure effect of the reservoir appears to extend at least 10 miles north of the reservoir, past wells 7123901 and 7114702. It is difficult to distinguish the effects of the rising reservoir level from the effects of the flooding rains and groundwater recharge that caused the reservoir to rise. The groundwater elevation in Well 5456402 (located about two miles north of Juno) increased from 1,692 feet in 1968 to 1,710 feet in 1972. This 18-foot increase in groundwater elevation is within the range of historical variability and is probably related to groundwater recharge from the series of storms that filled the reservoir and not from any pressure effects created by the reservoir itself. Data collection at this well stopped in 1974, so no long-term correlation with reservoir levels can be established. Similar issues apply to interpreting water level records for other wells near potential sources of recharge north of Amistad Reservoir, such as Well 7115501 near Deadman's Canyon and Well 7001404 along Dolan Creek.

More detailed analysis of water level changes over time requires a denser and more stable network of monitoring locations with regular measurements. We developed interpolated maps of groundwater elevation before and after the reservoir filled using the default kriging algorithms in ArcGIS to map the area of hydraulic influence by the reservoir in greater detail. We generated a map of water level change by subtracting the pre-reservoir surface from the post-reservoir surface. The resulting map, which is not included here, showed essentially random variations in groundwater elevation generated by the interpolation process due to differences in the geographical distribution of the measurements.

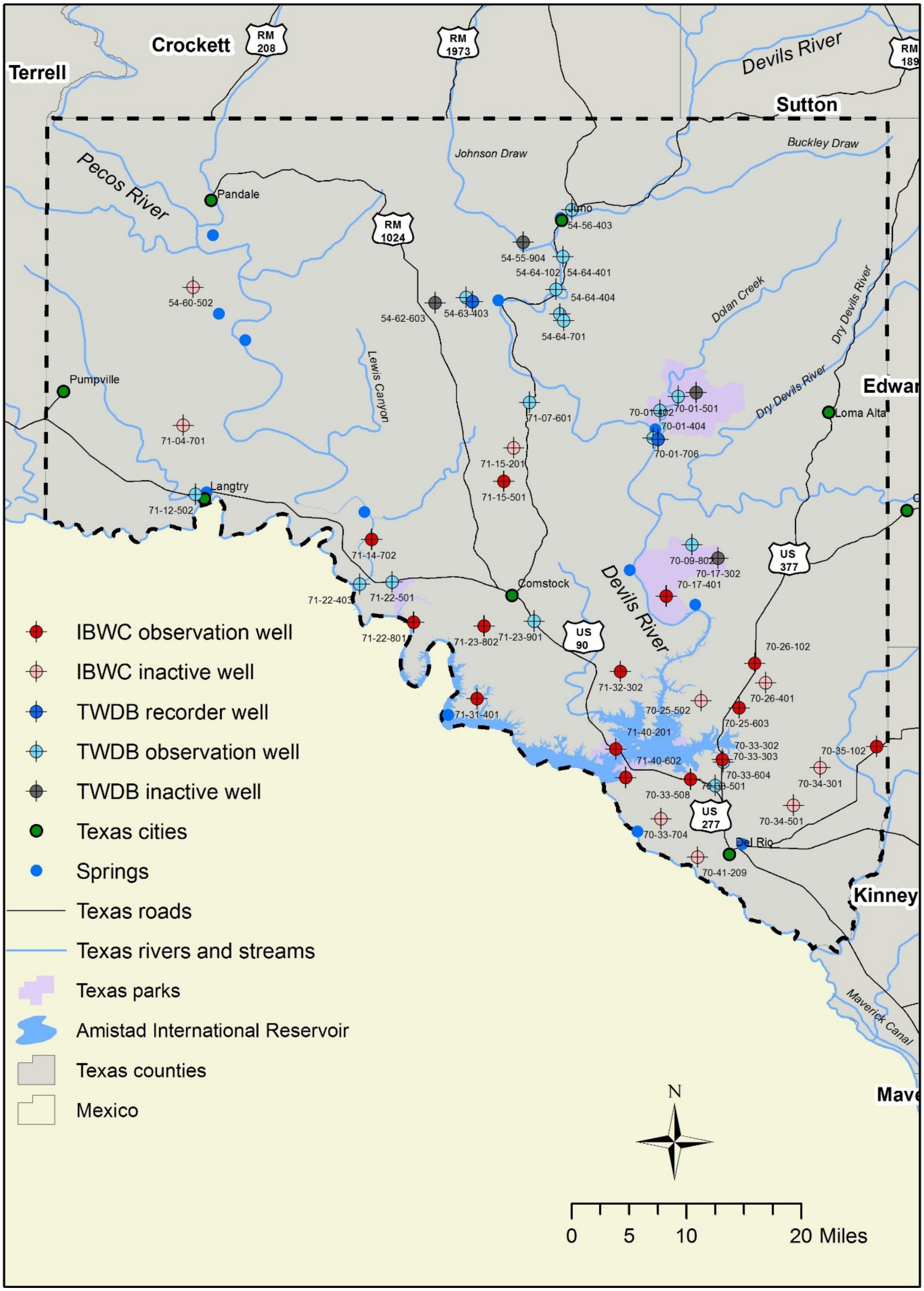

Figure 4-5. Locations of observation wells in Val Verde County.

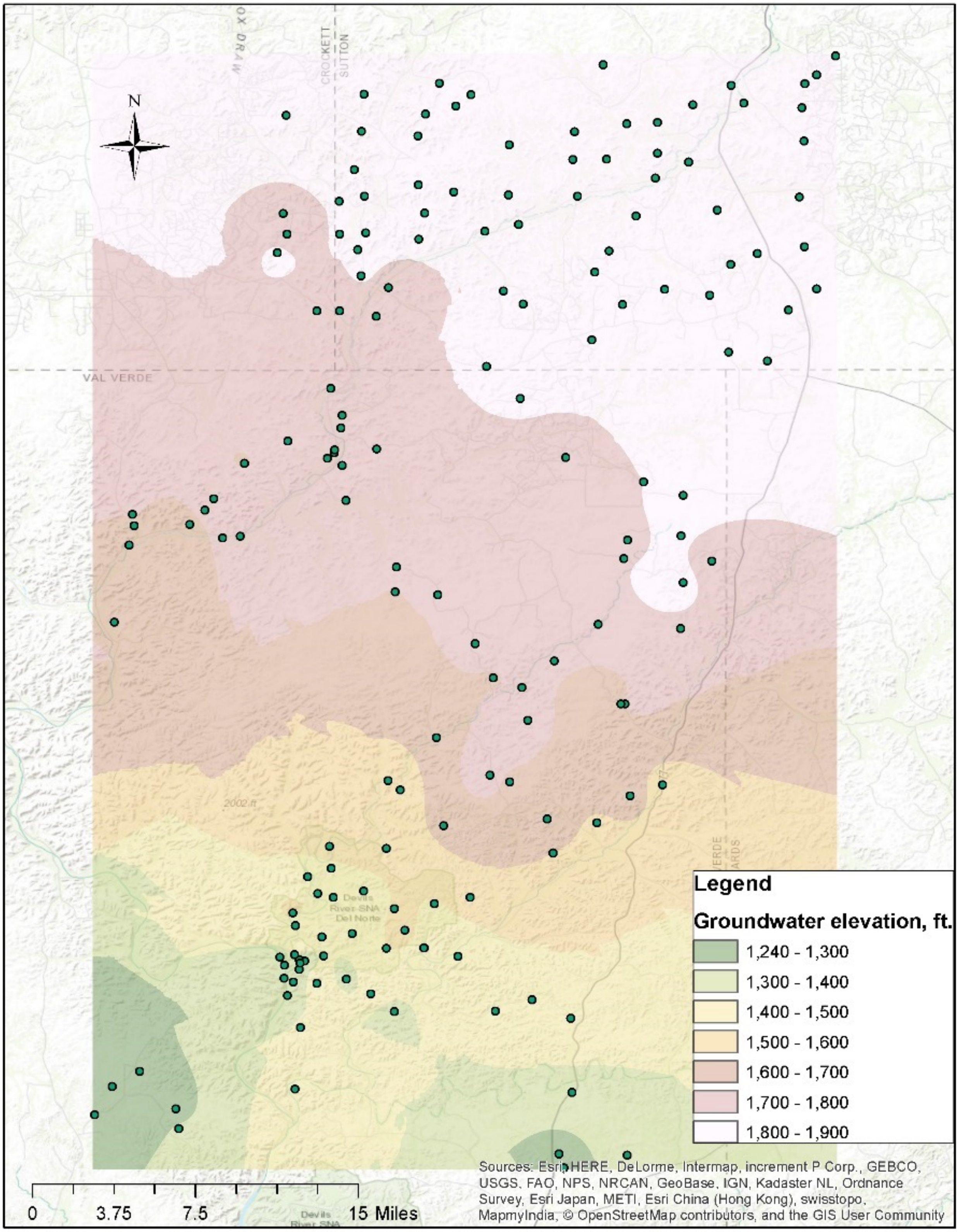

Figure 4-6. 1994 water level contour map of the Dolan Springs drainage basin. Data from Veni, 1996.

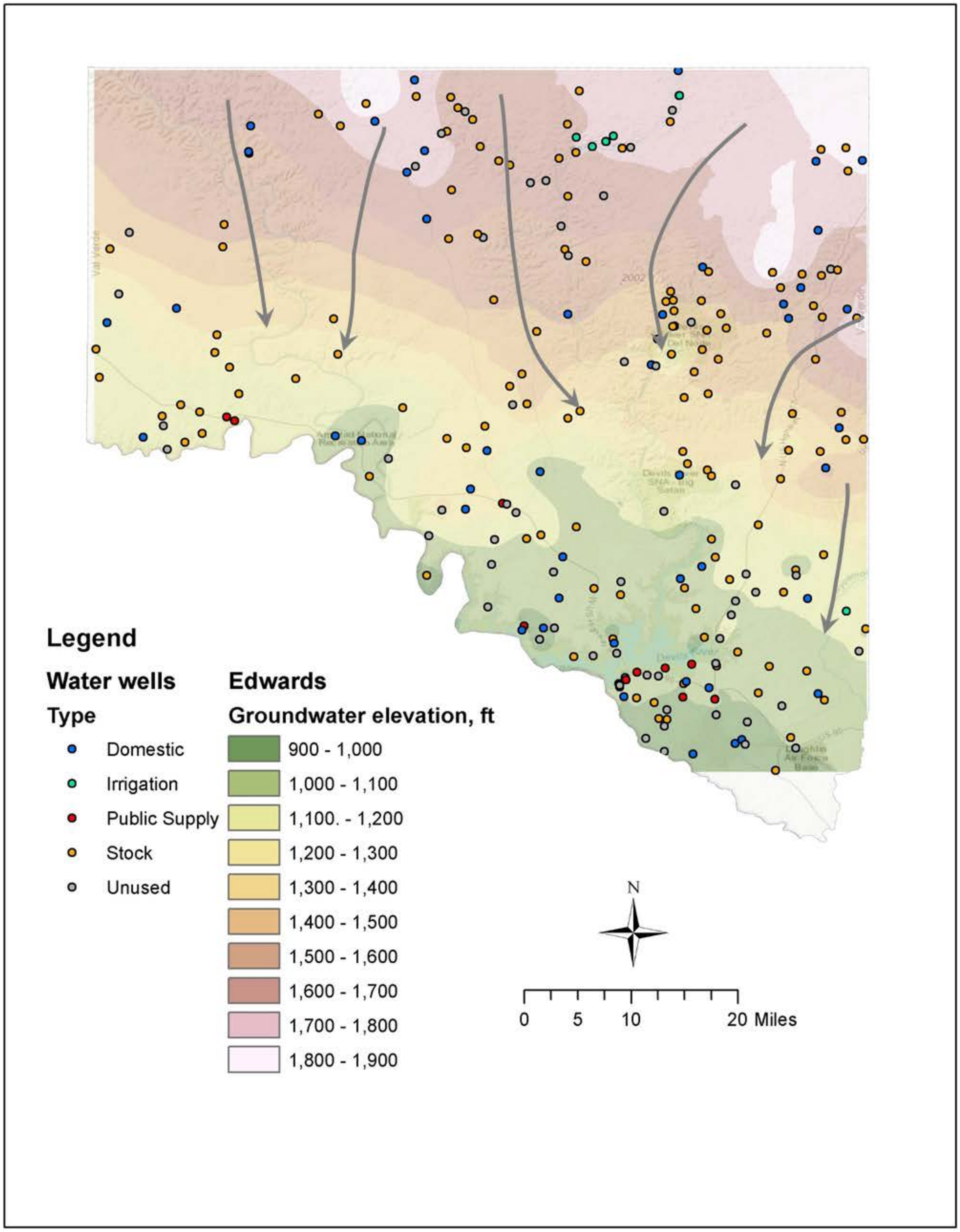

Figure 4-7. Water level contour map constructed from average winter water levels in wells completed in the Edwards Aquifer. Arrows indicate general flow paths. Data from TWDB groundwater database.

Water levels in parts of the county outside the area influenced by Amistad Reservoir are very consistent over the period of record and do not exhibit any long-term decline in response to pumping or reduced recharge. If landscape changes have had any effects on groundwater or spring flows, such changes would have happened prior to the available water level records, the earliest of which are from 1937.

Regional Groundwater Flow Patterns

Groundwater flow patterns in karst aquifers are particularly challenging to determine on regional and local scales. With the larger county-scale context, groundwater flows from generally north to south or southeast along the regional hydraulic gradient, but on smaller basin-level scales groundwater flow directions can deviate significantly from those general patterns. Groundwater flow velocities are often orders-of-magnitude higher in karst aquifers than in porous media aquifers such as the Ogallala Aquifer or the Carrizo-Wilcox Aquifer. Groundwater flow in karst aquifers typically is influenced by the occurrence and development of conduits or channels in limestone rock.

The degree to which preferential groundwater flow patterns are associated with existing river channels is a topic of interest. The Southwest Research Institute (SWRI) has conducted several focused studies to evaluate groundwater flow patterns in Val Verde County in general and in the Devils River basin in particular. The results of much of this work are summarized by Green and others (2014), in which a preferential groundwater flow environment is described in Val Verde County. Based on a review of groundwater wells, well capacities, and well locations, SWRI concluded that there is a high correlation between high capacity wells and proximity to river channels that points to the occurrence of preferential groundwater flowpaths that coincide with river channels. They further conclude that these preferential pathways are the primary means for movement of groundwater from the higher, upgradient portions of the basin to the lower, downgradient areas of the basin where groundwater exits via diffuse discharge in streams or as focused discharge in major springs. This pattern is also incorporated in the Val Verde County model, which assigns higher hydraulic conductivity values in stream channels. However, our review of available well capacity data indicates a possible, but not strong, correlation between well capacity and stream channels (Figure 4-10).

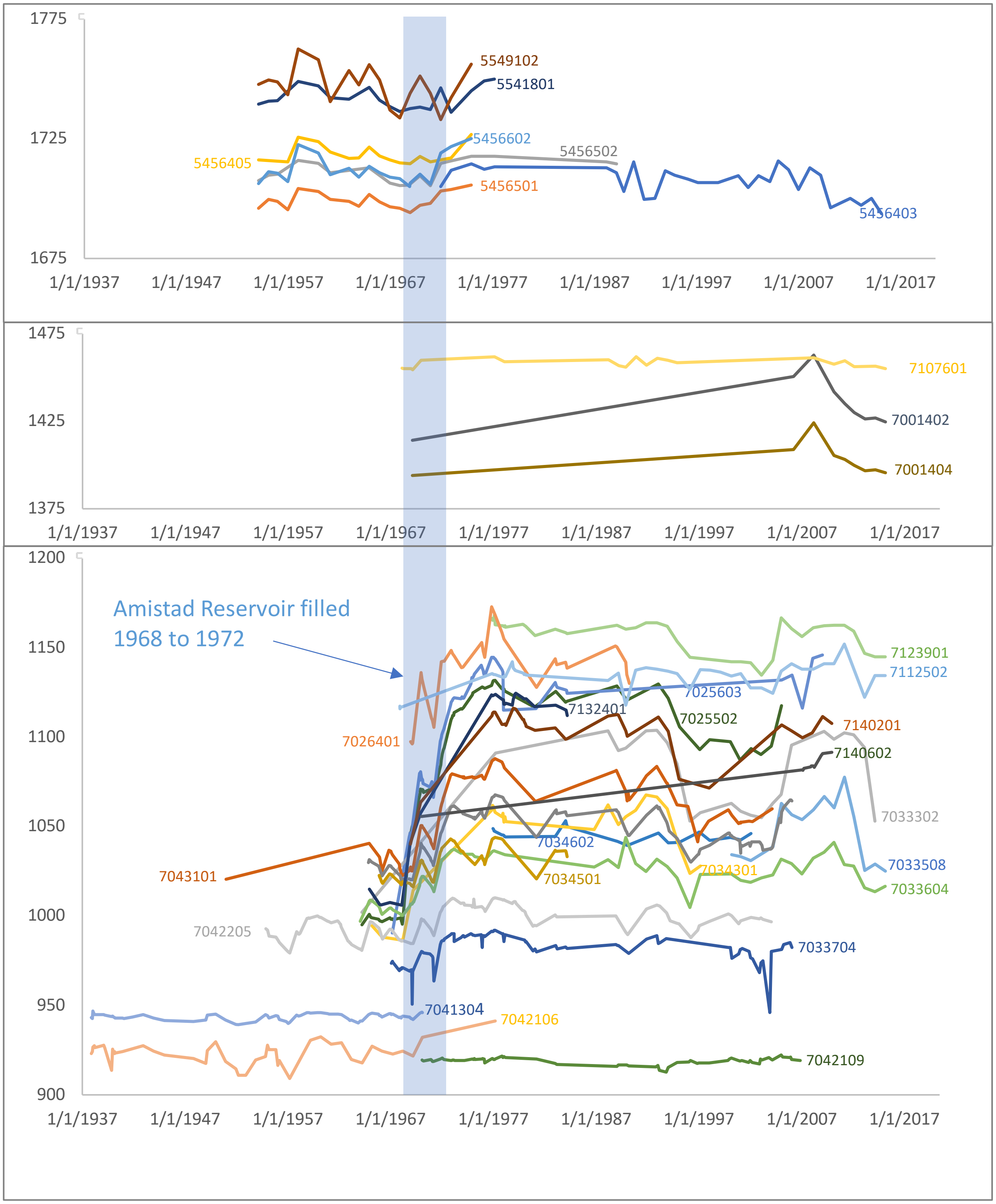

Figure 4-8. Winter water level elevations, in feet above mean sea level, and state well numbers for wells in Val Verde County with at least 10 years of measurements. Data from TWDB groundwater database.

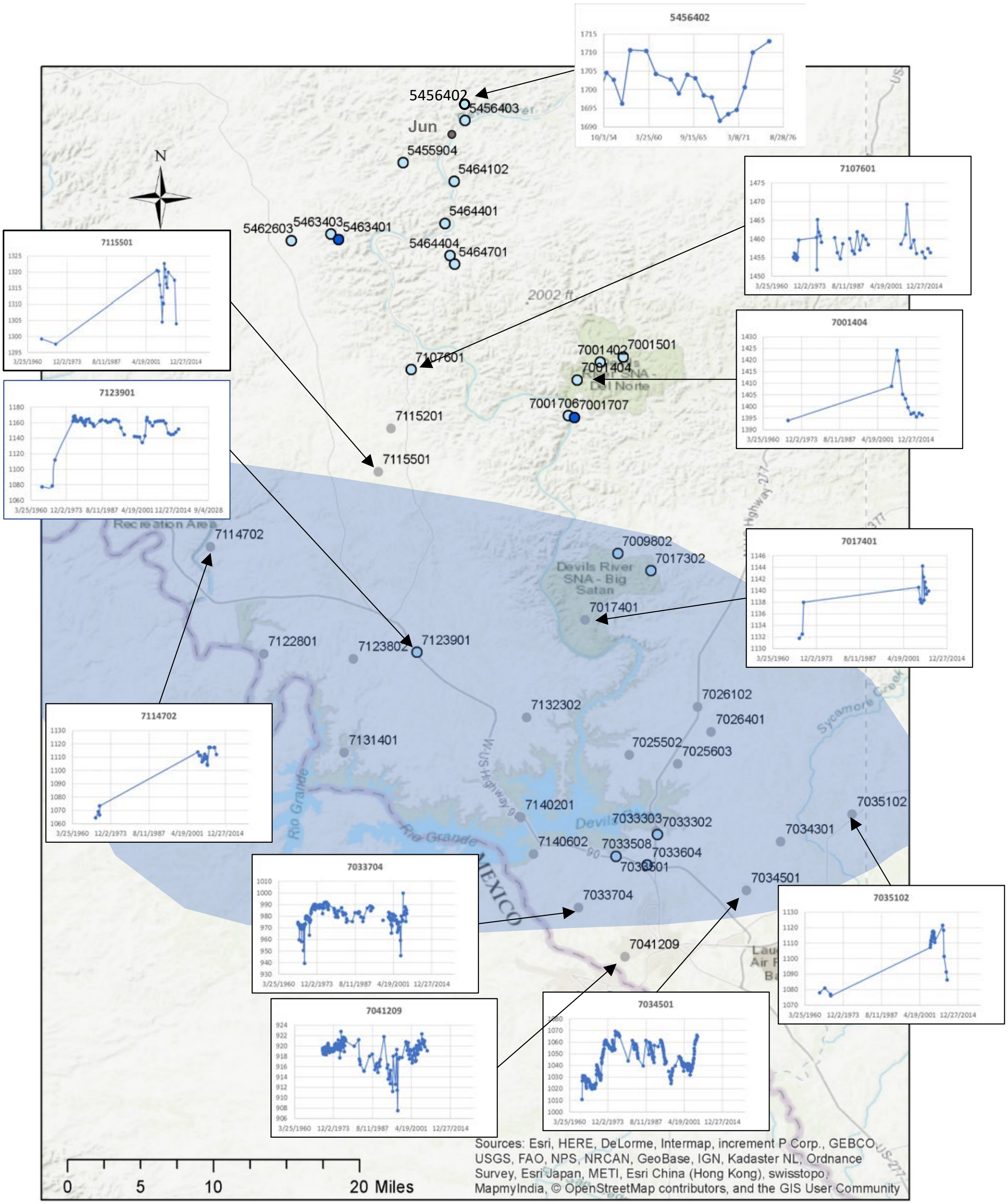

Figure 4-9. Estimated extent of the area influenced by the pressure head in Amistad Reservoir, shaded in blue, with selected hydrographs for observation wells with data covering the period 1968 to 2000. No data for wells in Mexico are available. Data from TWDB groundwater database.

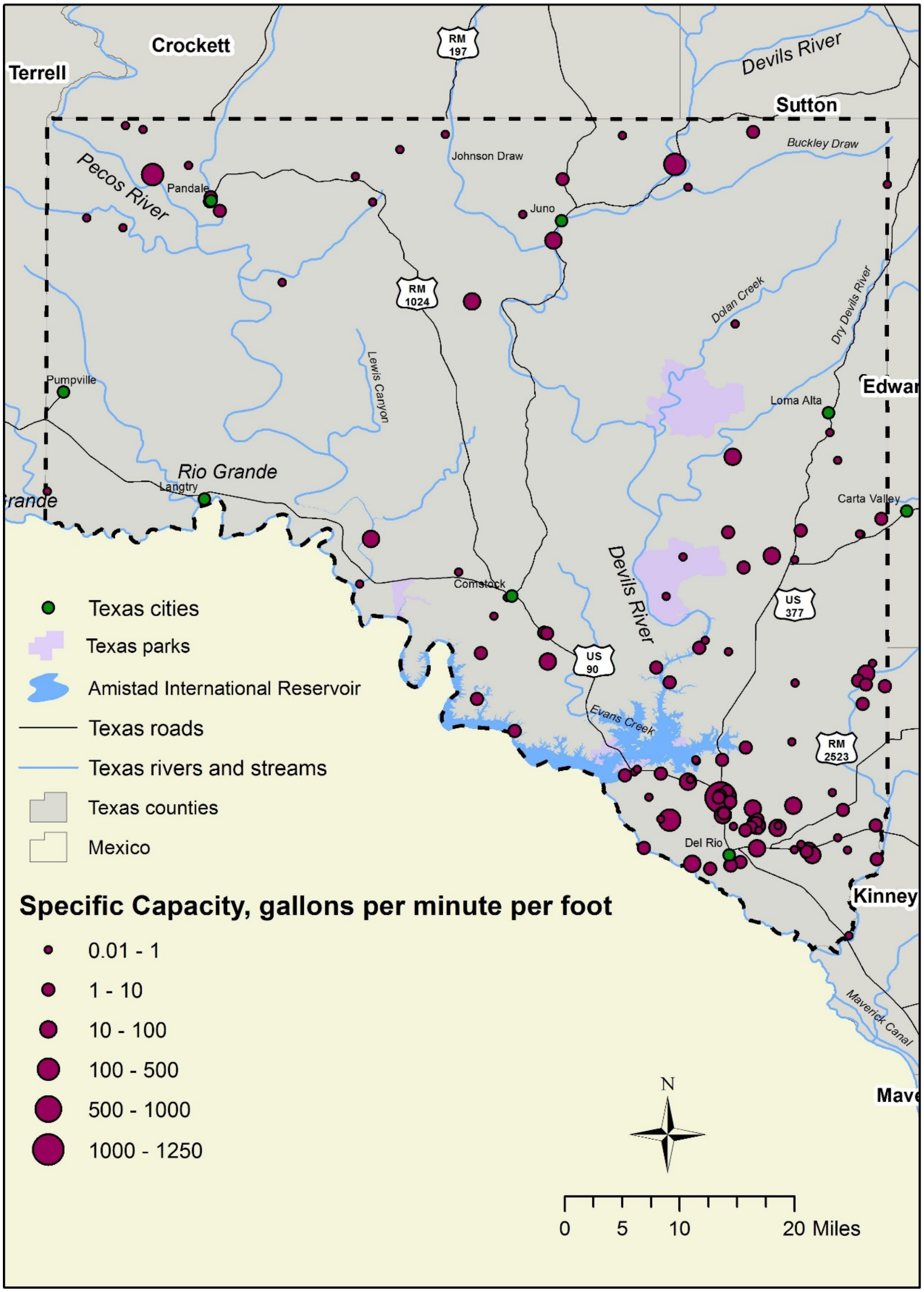

Figure 4-10. Estimated specific capacity of wells in Val Verde County, from drillers' reports and the TWDB groundwater database.

Well yields and aquifer properties

Well yields in Val Verde County vary widely, from a few gallons per minute to over 2,000 gallons per minute. High well yields are typically found when a well intersects karstic features of the aquifer, where large open channels allow high flow rates. Also, well yield generally increases with increasing aquifer thickness from the north to the south across the county.

Hydrogeological models often express aquifer properties in terms of specific capacity, specific yield, and specific storage. Specific capacity is calculated by dividing the pumping rate by the drawdown of the water level in a well during sustained pumping. The specific yield is a dimensionless number representing the drainable porosity of an unconfined aquifer. Specific storage is the amount of water released from storage in a unit volume of a confined aquifer for a unit drop in head. Specific storage is related to the compressibility of water and the aquifer materials and is generally a quantity much smaller than the specific yield.

The GAM model (Anaya and Jones, 2009) calibrated aquifer properties to observed water level changes by varying specific yield and specific storage. Two measured specific yield values were available for the model, 4×10^{-3} in Terrell County, and 5×10^{-3} in Sutton County, but none in Val Verde County. Specific yield can be as high as 0.15 in sand aquifers but is typically much smaller in fractured rock and karst systems. The calibrated specific yield for the Edwards was 5×10^{-3} in the northwestern third of Val Verde County and 5×10^{-4} in the rest of the county, broadly reflecting facies changes in the aquifer matrix. The specific yield of the Trinity portion of the aquifer was calibrated at 0.003 for all of Val Verde County. Anaya and Jones (2009) calibrated specific storage in the Edwards at 5×10^{-7} in the northwestern third of the county and 5×10^{-6} per foot in the remainder of the county. Specific storage in the Trinity portion of the aquifer was calibrated at 1×10^{-6} per foot for the entire county. The hydraulic conductivity of the Edwards in Val Verde was calibrated at 6.65 feet per day and the Trinity at 2.5 feet per day.

Two sets of pumping tests conducted since 2000 provide some additional Edwards Aquifer properties near Del Rio. Test results are summarized in Table 4-1. Wet Rock Environmental conducted pumping tests on three wells on the Weston Ranch property, in southeastern Val Verde County. The wells on the Weston Ranch property are completed in the confined portion of the Edwards-Trinity (Plateau) Aquifer. The tests included pumping at three irrigation wells and water level observation at three non-pumping wells.

Well 1 was pumped at an average rate of 660 gallons per minute for 36 hours, followed by a 36-hour recovery period. Wet Rock Environmental observed 219.5 feet of drawdown in Well 1, for a specific capacity of 3.01 gallons per minute per foot, and a drawdown of 4.32 feet at Well 2, located 2,603 feet from the pumping well. They calculated an average transmissivity of 2,760 feet squared per day and an average hydraulic conductivity of 4.60 feet per day from pumping and recovery data. Storativity was estimated as 2.53×10^{-5}, for a specific storage of 4.2×10^{-8} per foot, based on the stated 600-foot aquifer thickness.

Well 2 was pumped at an average of 1,200 gallons per minute for 36 hours, followed by a 36-hour recovery period. The observed drawdown in Well 2 was 191.62 feet, for a specific capacity of 6.26 gallons per minute per foot. No drawdown was observed in Well 1, located 2,603 feet from the pumping well, or in Well A, located 5,221 feet from the pumping well. The calculated average transmissivity from pumping and recovery data was 4,170 feet squared per day and the average hydraulic conductivity was 6.96 feet per day. Storativity was estimated at 1.25 x 10^{-4}, for a specific storage of 2.1 x 10^{-7} per foot, based on the stated 600-foot aquifer thickness.

Table 4-1. Summary of pump test results

Pumping well	Pumping rate, gpm	Pumping duration, hours	Draw down, feet	Specific capacity	Trans-missivity[1], ft²/day	Hydraulic conductivity, feet/day	Specific storage, per foot [1]
Well 1	660	36	219.5	3.01	2,760	4.60	4.2 x 10^{-8}
Well 2	1200	36	191.6	6.26	4,170	6.96	2.1 x 10^{-7}
Well 3	2700	168	73.11	36.7	22,300	37.1	1.0 x 10^{-8}
Agarita	716	27.5	14.5	49	25,094	NA	NA
Hackberry	286	24	230	1.3	1,936	NA	NA
"Y" well, Salmon Peak	246	23.5	1.5	166	54,265*	NA	NA
"Y" well, West Nueces	35	1	3	11.5	3,080	NA	NA

1: Transmissivity values based on stated aquifer thickness of 600 feet
gpm= gallons per minute

Well 3 was pumped for seven days at an average rate of 2,700 gallons per minute, followed by a seven-day recovery period. The observed drawdown in Well 3 was 73.11 feet, for a specific capacity of 36.70 gallons per minute per foot. A maximum of 35.11 feet of drawdown was observed in Well B, located 1,811 feet from Well 1. The calculated average transmissivity for Well 3 was 22,300 feet squared per day and the average hydraulic conductivity from pumping and recovery data was 37.1 feet per day. The storativity is estimated at 6.05 x 10^{-6}, giving a specific storage of 1.0 x 10^{-8} for the 600-foot aquifer thickness.

The pump test storage values are somewhat lower than the calibrated model values used in the GAM model (Anaya and Jones, 2009).

LBG-Guyton (2001) conducted pump tests on three wells but did not collect data from non-pumping wells and thus did not obtain hydraulic conductivity or storage estimates. LBG-Guyton did collect geophysical and downhole video logs to define formation depths and identify productive zones. They classify the lower Edwards McKnight and West Nueces formations as confining beds with little permeability. Pump test results for the upper part of the West Nueces showed a transmissivity of 3,080 feet squared per day, or more than one order of magnitude lower than the upper portion of the Edwards. LBG-Guyton (2001) also lists the Trinity Glen Rose Formation as a confining bed with low permeability and probably containing saline water, based on geophysical logs showing decreasing resistivity near the top of the Glen Rose.

The TWDB Record of Wells report for Val Verde County was used to evaluate the specific capacity of wells as a proxy for other, less direct measurements of aquifer properties such as specific yield and specific storage. The county well report (TWDB, 2018a) lists 59 wells with reported well yield and drawdown values. The median specific capacity for these wells was 2 gallons per minute per foot, with an average of 39.5 gallons per minute per foot, and a range of 0.01 to 1,256 gallons per minute per foot. We derived specific capacity estimates for an additional 60 wells in Val Verde County from the TWDB Submitted Drillers Reports database (TWDB, 2018b) and the Wet Rock pump tests. Specific capacity for these wells ranged from 0.01 gallons per minute per foot to 100 gallons per minute per foot, with an average of 5 and a median of 1.7 gallons per minute per foot.

The highest specific capacity wells are located near stream drainages (Figure 4-10), consistent with the pattern in well yields noted by Green and others (2014) and Toll and others (2017). Several high-capacity wells are located along the upper Devils River, above Juno, and along the Rio Grande in the Del Rio area. Several moderate-capacity wells are located near the Pecos River in the northwestern part of the county. The well yield data used by Green and others (2014), which includes more locations over a larger area, found a statistically significant correlation between well yield and distance to third-order or higher stream segments. However, well yields alone can be a poor measure of aquifer properties because of widely varying test duration, drawdown, and aquifer thickness between locations.

Toll and others (2017) mention additional data collected to help define conduit locations, their sizes, and orientation, including geophysics and geochemistry, but do not include detailed analysis of these results in their model report. Geochemical data presented by Nunu, Bertetti and Green (2017) are discussed in Appendix B. In summary, Karst conduits associated with stream drainages are important elements of the Val Verde groundwater system, although there remains ambiguity as to the nature of the conduits and their effects on groundwater movement and production at particular locations of interest.

Groundwater Recharge

Natural recharge to the Edwards-Trinity (Plateau) Aquifer occurs as diffuse recharge from precipitation over the aquifer outcrop, direct recharge from surface runoff into sinkholes, and direct recharge from losses along intermittent streams and normally dry draws. Since evaporation losses significantly exceed average precipitation, recharge tends to occur only where fractures and joints allow water to rapidly percolate down past the root zone or where surface runoff collects in drainages.

Recharge is difficult to measure directly, so it is usually estimated indirectly. Most estimates for Val Verde County area are derived from river baseflow or spring discharge data and records of precipitation over the contributing area. The baseflow method is applicable under steady-state conditions where discharge is assumed to approximately equal recharge. The total annual discharge volume is simply divided by the recharge area (generally assumed to equal the surface watershed area), to obtain a recharge value in terms of depth of water per year. There is some evidence that the groundwater drainage basins for major springs in Val Verde County are significantly larger than the corresponding surface watersheds (URS, 2004), leading to various correction factors.

Estimates of recharge to the Edwards Trinity (Plateau) Aquifer vary widely, reflecting geographic trends in rainfall across the Edwards Plateau and differences in the methods and assumptions used to estimate recharge. Published recharge estimates for Val Verde County and adjacent areas vary by more than a factor of 10 (Table 4-2).

Reeves and Small (1973) estimated recharge of 1.5 inches per year, or 9 percent of precipitation, from the 500,000 acre-feet average baseflow from 1961 to 1967 for the rivers and springs that discharge in Val Verde County, and assuming a 6,500-square-mile contributing zone encompassing the drainage area of the Pecos River from its confluence with Independence Creek, the Devils River, and Sycamore Creek.

Veni (1996) estimated a 3.4 inch per year recharge rate from the 452,000 acre-feet total discharge between 1966 and 1983 of the group of springs near the confluence of Dolan Creek and the Devils River and a total 2.66 million acre-feet estimated precipitation on the drainage basin area of 129 square miles over the same interval. Veni (1996) attributes the difference between this recharge rate and the 1.5 inches per year obtained by Reeves and Small to upstream capture of streamflow amounting to approximately 50 percent of the total spring discharge.

HDR (2001) used the baseflow index program developed by the U.S. Geological Survey and the U.S. Bureau of Reclamation to estimate recharge from streamflow data for eight watersheds draining the Edwards Plateau, deriving average annual values of 1.4 inches per year for Sycamore Creek and 0.41 inches per year for the Devils River above Juno. Streamflow gain-loss study data are discussed in Section 6.

Table 4-2. Comparison of recharge rate estimates from various publications.

Area	Recharge, inches per year	Reference
Real County	2.0	Long, 1958
Crockett County	0.3	Inglehart, 1967
Kerr County	1.0	Reeves, 1969
Val Verde County drainage area	1.5	Reeves and Small, 1973
Trans-Pecos	0.3 to 0.4	Rees and Buckner, 1980
Eastern Edwards Plateau	0.1 to 2.2	Kuniansky, 1989
Dolan Springs watershed	3.4[1]	Veni, 1996
Hill Country	1.5	Mace and others, 2000
Sycamore Creek watershed	1.4	HDR, 2001
Devils River above Juno	0.41	HDR, 2001
West Nueces basin	2.5	Mace and Anaya, 2004
Devils River watershed	0.41	Anaya and Jones, 2009
Val Verde County	2.1	Wet Rock (2010)
Devils River watershed	0.95 to 0.63	Green and Bertetti (2012)
Val Verde County	0.17	Hutchison/Eco Kai (2014)

[1] Includes captured streamflow

Anaya and Jones (2009) delineated recharge zones based on surficial geology, varying recharge as a percentage of annual precipitation for each type of outcrop during model calibration. Calibrated recharge values for Val Verde County include 1 percent of precipitation for Buda/Del Rio Formation outcrop; 2 percent for Edwards outcrop; 5 percent for Devils River Formation outcrop; and 10.9 percent for Edwards outcrop within the Maverick Basin in the southern part of the county (Figure 4-11). The spatially averaged recharge over the Devils River basin was 0.41 inches per year. The calibrated average annual recharge values for other zones of the regional model closely matched previously published estimates, including 0.3 inches per year for Crockett County and 2.6 inches per year for Kinney County (Anaya and Jones, 2009).

Wet Rock Groundwater Services (2010) evaluated groundwater resources in Val Verde County for Grass Valley Water L.P., estimating an average annual recharge of 2.1 inches per year, or 10.2 percent of precipitation, based on the work of Mace and Anaya (2004). Mace and Anaya (2004) developed their recharge estimate for the West Nueces basin, building on an approach previously used by Bennet and Sayre (1962) using river baseflow data.

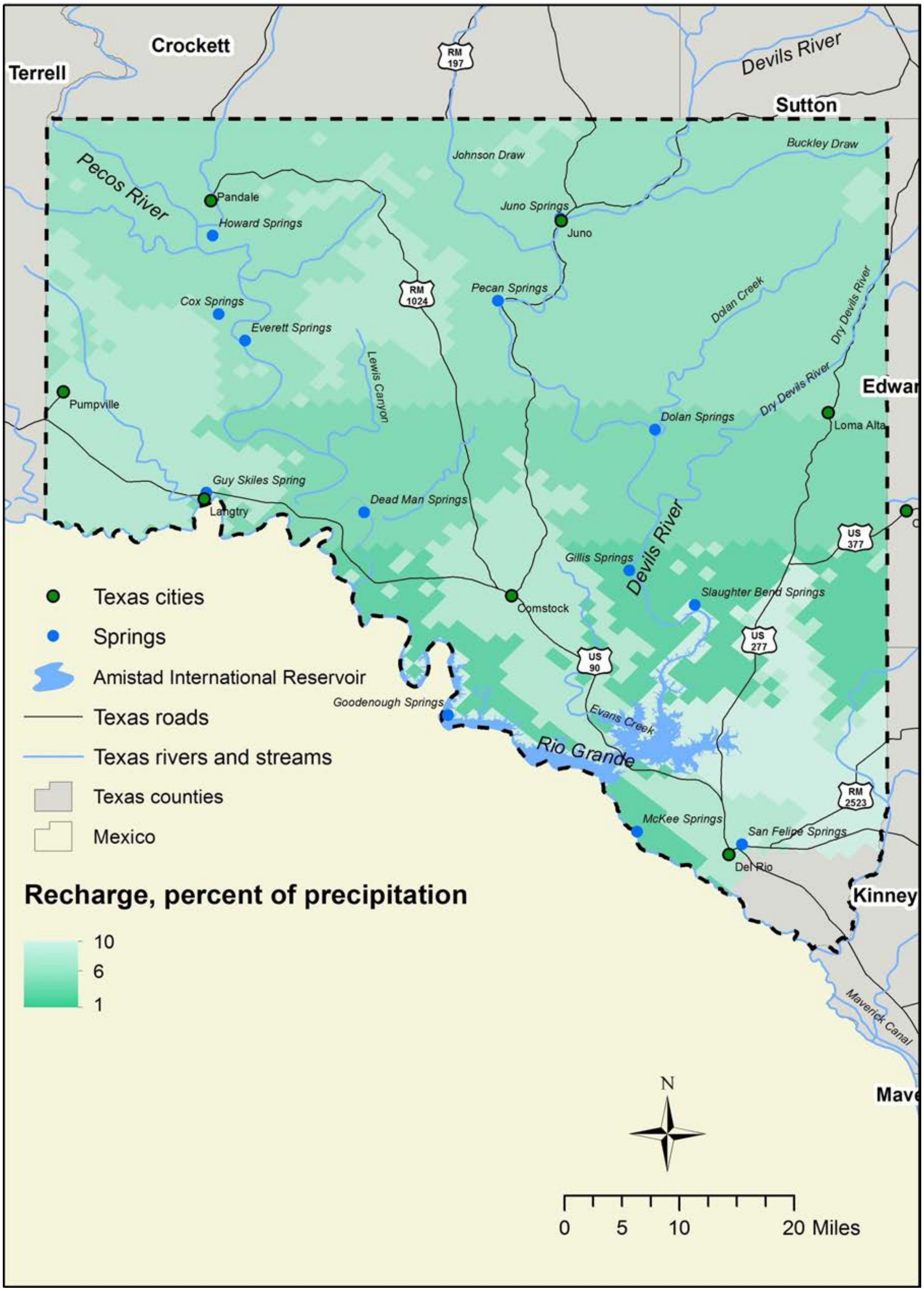

Figure 4-11. GAM model distribution of recharge across Val Verde County (Anaya and Jones, 2009).

Mace and Anaya (2004) separate total recharge into two components, direct recharge where stream courses intersect the faults and fractures of the Balcones Fault Zone, and diffuse recharge on the Edwards Plateau. Wet Rock expresses the West Nueces diffuse recharge value as a percentage of total precipitation and, noting similarities in the surface geology between Kinney and Val Verde counties, multiplies the average Val Verde precipitation by the West Nueces recharge percentage to derive a recharge value for Val Verde County. Wet Rock notes: "This is likely a conservative estimate of total inflow to the aquifer in Val Verde County as it does not account for direct recharge that occurs along stream channels in the county or underflow into Val Verde County from neighboring counties."

Green and Bertetti (2012) also used average river baseflow to estimate recharge, deriving a value of 0.95 inches per year for Val Verde County. They stated that this value seemed excessive and made a correction assuming the groundwater catchment area for the Devils River was 50 percent greater than the surface catchment, arriving at an average annual recharge rate of 0.63 inches per year, or about 3 percent of precipitation, for the Devils River watershed and Val Verde County as a whole. Green and Bertetti (2012) also proposed calculating annual recharge as 15 percent of annual precipitation over 16.5 inches per year, giving the following relationship between recharge (R) and precipitation (P):

$$R = 0.15(P - 16.5) \text{ for } P > 16.5, \; R = 0 \text{ for } P \leq 16.5$$

Hutchison and Eco Kai (2014) calculated monthly recharge rates as a function of precipitation and evaporation. They divided monthly rainfall by monthly evaporation, if the rainfall was above a threshold value, and then raised the resulting value by an assigned exponent. The time constant, threshold value, and the exponent were adjusted during calibration. They also adjusted recharge locally to account for focused recharge along drainages. The average model-calibrated recharge rate for Val Verde County was 0.17 inches per year, and annual values ranged from approximately zero to 0.55 inches per year. While estimated recharge for one year was near zero, in general the Val Verde County model (Hutchison and Eco-Kai, 2014) model produced some recharge even in dry years, as the monthly time-step and focused recharge features account for local and short-term periods where precipitation exceeds evaporation.

The amount of recharge entering the aquifer system plays a major role in long-term groundwater availability. Anaya and Jones (2009) found that their regional groundwater availability model was more sensitive to recharge than any other parameter. They also found that recharge is the primary source of inflow to the groundwater system, accounting for up to 85 percent of the Edwards aquifer unit water budget under steady state conditions, far outweighing lateral flows or inflows from other aquifers. Consequently, recharge has a major effect on predicted water levels, flow rates, and groundwater availability. Their sensitivity analysis suggested that a plus-or-minus 25 percent change in recharge would result in an average change in predicted water level of about 100 feet under steady-state conditions if other model inputs remained the same (Anaya and Jones, 2009). The wide range of recharge values used in recent models developed to assess the effects of potential pumping in Val Verde County imply that even larger differences in other model parameters are needed to achieve calibration with respect to measured water levels.

Springs

Springs are natural outlets for groundwater discharge. Most springs in Val Verde County are located at points where streams have eroded down to intersect conduits in the saturated portion of the aquifer. A 2005 study prepared for the Plateau Regional Water Planning Group identified 45 mapped springs in Val Verde County (Table 4-3 and Figure 4-12), while noting that numerous additional wet weather springs likely exist (Ashworth and Stein, 2005).

Springs in Val Verde County represent regional points of discharge from the Edwards-Trinity (Plateau) Aquifer and an accurate representation of spring discharges is essential for groundwater models of the area. Goodenough Springs, now located under about 150 feet of water in Amistad Reservoir, was historically the third largest in Texas, discharging an average flow of about 101,000 acre-feet per year. In 2005 it was still discharging 52,000 acre-feet per year beneath the reservoir (Kamps, Tatum, Gault, and Groeger, 2009). San Felipe Springs, a collection of about 10 springs along San Felipe Creek, collectively represents the fourth largest spring flow in Texas, with an average discharge of about 80,000 acre-feet per year since Amistad Dam was completed in 1969 (Ashworth and Stein, 2005). Spring-fed baseflow in the Devils River totals approximately 197,000 acre-feet per year between 1972 and 2017. Together these spring flows total almost 330,000 acre-feet per year, a rate that is substantially greater than discharge from pumping wells, which totals about 5,000 acre-feet per year.

While there is anecdotal evidence that spring flows along the Devils River have declined significantly since the mid-19th century, other lines of evidence indicate that hydrological conditions in Val Verde County have been relatively stable since the early 20th century. Many springs in Texas have ceased to flow because of groundwater development and landscape alterations since the late 19th century. Groundwater development can reduce the water level or pressure head in the aquifer around springs, which reduces spring flow or stops it entirely if the water level falls below the level of the spring orifice. Recorded water level measurements in Val Verde County generally do not document long-term declines in groundwater levels that would adversely affect spring flows since the early 20th century. Analysis of more recent data, from a variety of sources, suggest that observed variations in groundwater levels, spring flows, and streamflow are primarily a response to natural variability in rainfall and not an artifact of groundwater development. San Felipe Springs may be an exception to this pattern, reflecting more intensive groundwater use in the Del Rio area than in other parts of Val Verde County.

Table 4-3. Locations of mapped springs in Val Verde County.

State well number	Name	Latitude	Longitude	Elevation, feet
	Big Norris Spring	30.0141	100.968	1,959
7001704	Blue Spring	29.8936	100.9938	1,480
	Camp Spring	29.8869	100.8755	1,667
7033801	Cantu Springs	29.3875	100.9322	979
	Carlos Camp Spring	29.8016	100.9583	1,373
	Cienegas Creek Spring	29.3662	100.9379	938
5460804	Cox Springs	30.0416	101.5416	1,763
	Dead Man Springs	29.7916	101.3583	1,378
7001702	Dolan Springs	29.8969	100.9836	1,340
	Everett Springs	30.0083	101.5083	1,683
7108901	Finegan Springs	29.9083	101.0083	1,607
7124301	Gillis Springs	29.752	101.0416	1,180
	Glenn Spring	29.8116	100.8886	1,449
7130901	Goodenough Springs	29.5363	101.2531	1,122
	Grass Patch Springs	29.8736	100.9922	1,331
7112504	Guy Skiles Springs	29.8166	101.5579	1,320
5452801	Howard Springs	30.1583	101.5417	1,661
5463801	Hudspeth Springs	30.025	101.175	1,618
7107603	Huffstutler Springs	29.9583	101.1416	1,506
	Indian Springs	29.665	101.9263	1,220
	Jose Maria Spring	29.9283	100.9872	1,451
5455905	Juno Springs	30.1583	101.1254	2,007
	Leon Spring	29.8811	100.9725	1,492
	Little Norris Spring	30.0091	100.9683	2,010
	Lowry Springs	29.6269	100.9208	1,196
7140903	McKee Springs	29.425	101.0416	970
	Pecan Springs *	30.0626	101.1869	1,600
7041301	San Felipe Spring E	29.3725	100.883	975
7041302	San Felipe Spring W	29.3728	100.8847	960
7041303	San Felipe Spring S	29.373	100.8825	975
	San Felipe Creek Spring	29.3981	100.8666	1,015
	Scott Spring	30.0166	101.5189	1,447
	Seep Springs	29.8233	101.5116	1,422
7017501	Slaughter Bend Springs	29.6751	100.9416	1,345
	Snake Springs	29.8961	100.9808	1,385
	Spotted Oak Spring	29.8802	100.8775	1,671
	Tardy Spring	30.1239	101.5378	1,563
7140905	U.S. No. 3 Spring	29.4122	101.0365	921

7042601	Yoas Springs	29.3083	100.7751	980
7112501	Unnamed	29.8099	101.5732	1,260
5460301	Unnamed	30.1233	101.534	1,537
5460302	Unnamed	30.1235	101.5335	1,537
7108801	Unnamed	29.8952	101.0582	1,472
7001703	Unnamed	29.8913	100.9923	1,520
7001701	Unnamed	29.8955	100.9829	1,360

Source: Ashworth and Stein, 2005. Note: Locations may be approximate because of differing methods of location and map projections for historical data.

In general, spring flow measurements in Val Verde County are sparse. Brune (1975) describes Juno Springs as the headwaters of the Devils River. He states that:

> *"The Devil's River at this point was described in 1916 as a beautiful stream with large live oaks. The springs, Beaver Lake upstream, and the perennial flow of the Devil's River in this area have all disappeared. In May 1971, the first headwater springs were 15 miles downstream, at Pecan Springs."*

Toll and others (2017) have followed Brune's description of the upper Devils River in modeling the pre-development steady-state condition of the Devils River Watershed Model. One of the major findings of their model is that a relatively modest volume of groundwater pumping is responsible for moving the starting point of "live water" downstream from Juno Springs to Pecan Springs, suggesting a highly sensitive groundwater system. In contrast, our review of historical accounts and satellite data suggests that Pecan Springs has been the start of perennial flow in the Devils River for at least the last 100 years. These two perspectives are not necessarily contradictory, but together imply that any hydrological changes associated with development must have happened in the late 19th or early 20th century, before widespread groundwater pumping, suggesting an association with vegetation and land-use changes rather than groundwater abstraction.

Early descriptions of the Devils River suggest an intermittent flow in the upper reaches. In 1881, William Peery Hoover watered 200 head of cattle at Beaver Lake, just above the town of Juno. Weinger (1984) quotes James G. Bell, who in 1854 described the flow in the Devils River as "the water sinking and when up running over the dry beds," suggesting low or intermittent flow. Bell reports that his group crossed the Devils River six times, with two dry crossings, before reaching Camp Hudson, just below Bakers Crossing and 19 miles by road south of Juno. Roberts and Nash (1918) provide the first recorded observations of the upper Devils River by professional geoscientists, noting that many springs discharge waters from the Edwards into the Devils River, and that "the most prominent of these springs are the Pecan Springs, which supply the main water for dry season flow of the Devils River."

Byron Hodge (2018), whose family has owned the property surrounding Beaver Lake since about 1932, states that three major floods – in 1932, 1948, and 1954 – filled Beaver Lake with gravel, after which it ceased to hold water.

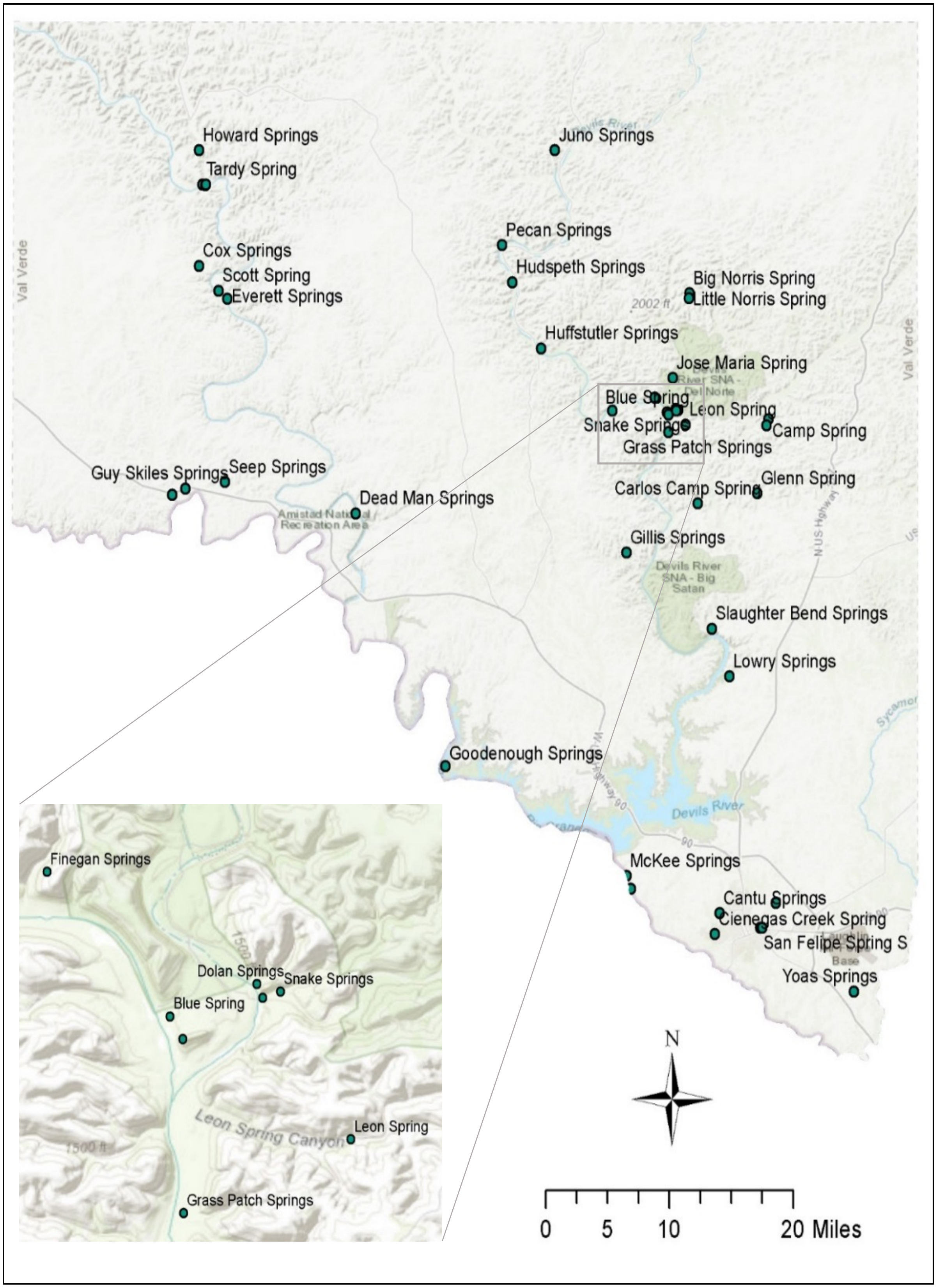

Figure 4-12. Locations of springs in Val Verde County (adapted from Ashworth and Stein, 2005).

Satellite imagery gives us a much clearer record of regular observations over the last 35 years. Landsat imagery from 1983 through 2018 shows continuous perennial flow in the Devils River downstream of Pecan Springs, while flow between Beaver Lake and Pecan Springs is discontinuous and restricted to periods following above-normal rainfall.

We used rainfall data for Brackettville and Ozona weather stations to select image dates following peaks in 365-day cumulative rainfall during the period of available Landsat coverage from 1983 to 2017 (Figure 4-13). Images were selected for analysis based on peaks in accumulated rainfall over the previous 90- and 365-day intervals (the Brackettville station was inactive from 2002 to 2006). Water is present in isolated pools between Juno and Pecan Springs in at least nine images. Only one image, from September 22, 2007 (Figure 4-14), shows nearly continuous flow between Juno and Pecan Springs, following over 8 inches of rainfall in the upper watershed on August 18, 2007.

Consistent flow downstream of Pecan Springs is observed in all images regardless of antecedent rainfall. Images acquired following localized heavy rainfall and runoff in the watershed above Juno (Figure 4-15) show evidence for stream bed infiltration instead of groundwater discharge in this reach. Images acquired under drought conditions (Figure 4-16) show flow originating at Pecan Springs and dry stream bed above that point. U.S. Fish and Wildlife Service wetlands mapping (Figure 4-17) also indicates that perennial flow in the Devils River begins at Pecan Springs.

While these records do not resolve the issue of how early European settlement changed the Edwards Plateau landscape in the mid-19th century, they do indicate that intermittent flow above Pecan Springs has been the norm for the last 100 years and is not likely the result of more recent irrigation development along the upper reaches of the Devils River.

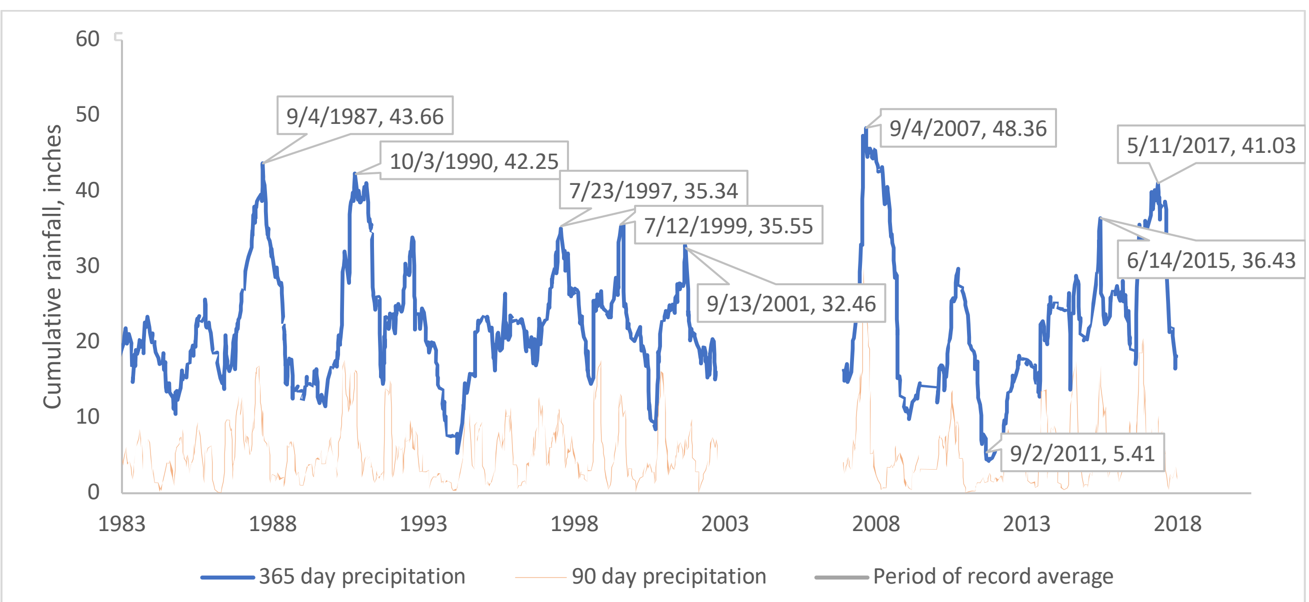

Figure 4-13. Precipitation data for Brackettville used to guide Landsat image analysis. Data from National Centers for Environmental Information, 2018b.

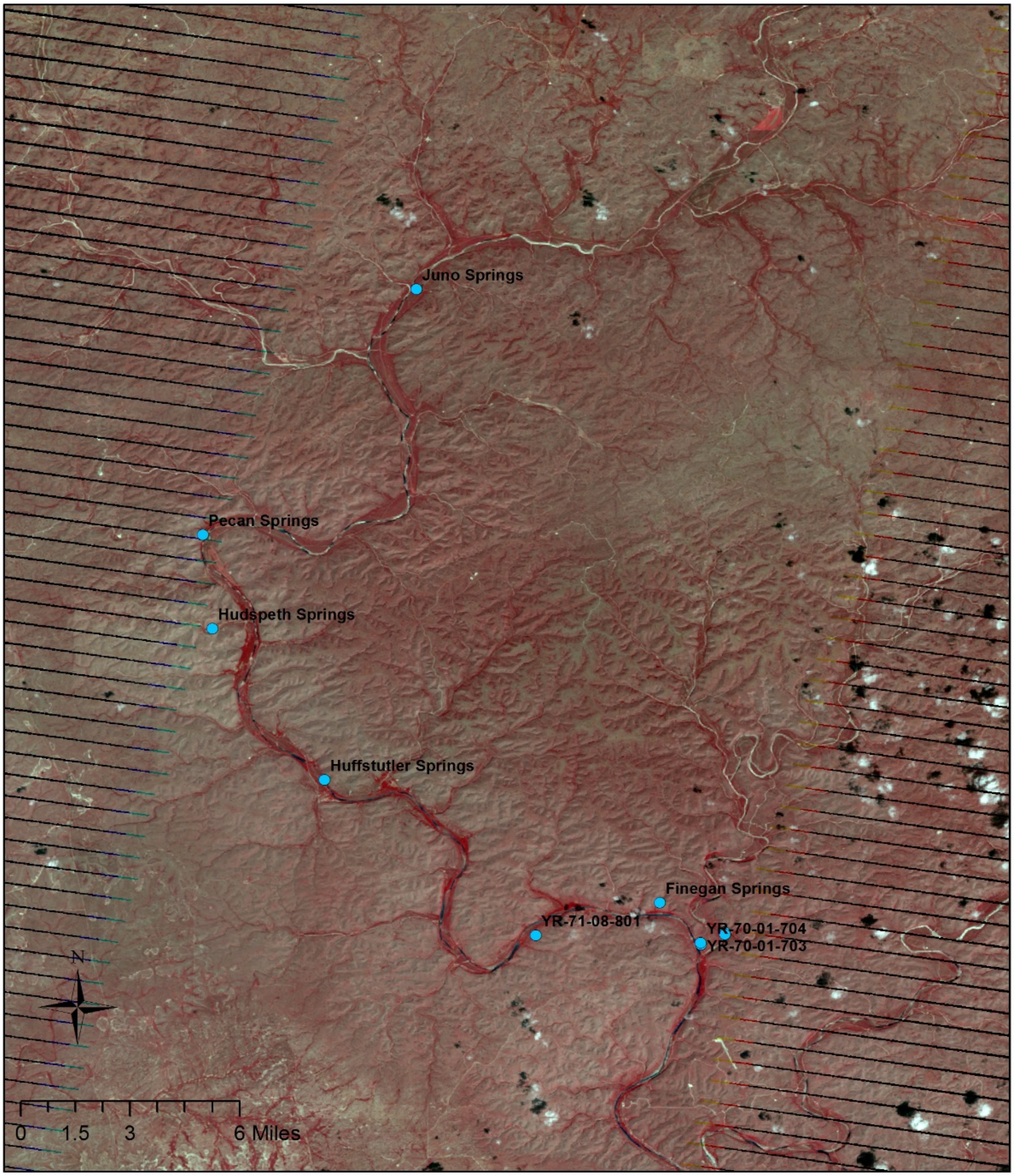

Figure 4-14. Landsat 7 false-color near-infrared color composite image for September 22, 2007, representing wet weather conditions. Rainfall in the upper Devils River watershed at the Ozona 22 SE weather station totaled 18 inches in the preceding 90 days and over 40 inches for the preceding year. Water (dark areas) is present between Juno and Pecan Springs, and actively growing vegetation (red) is widespread along the Devils River and tributary streams. Dark lines are an artifact of satellite scan line correction malfunction. Imagery from U.S. Geological Survey Earth Explorer.

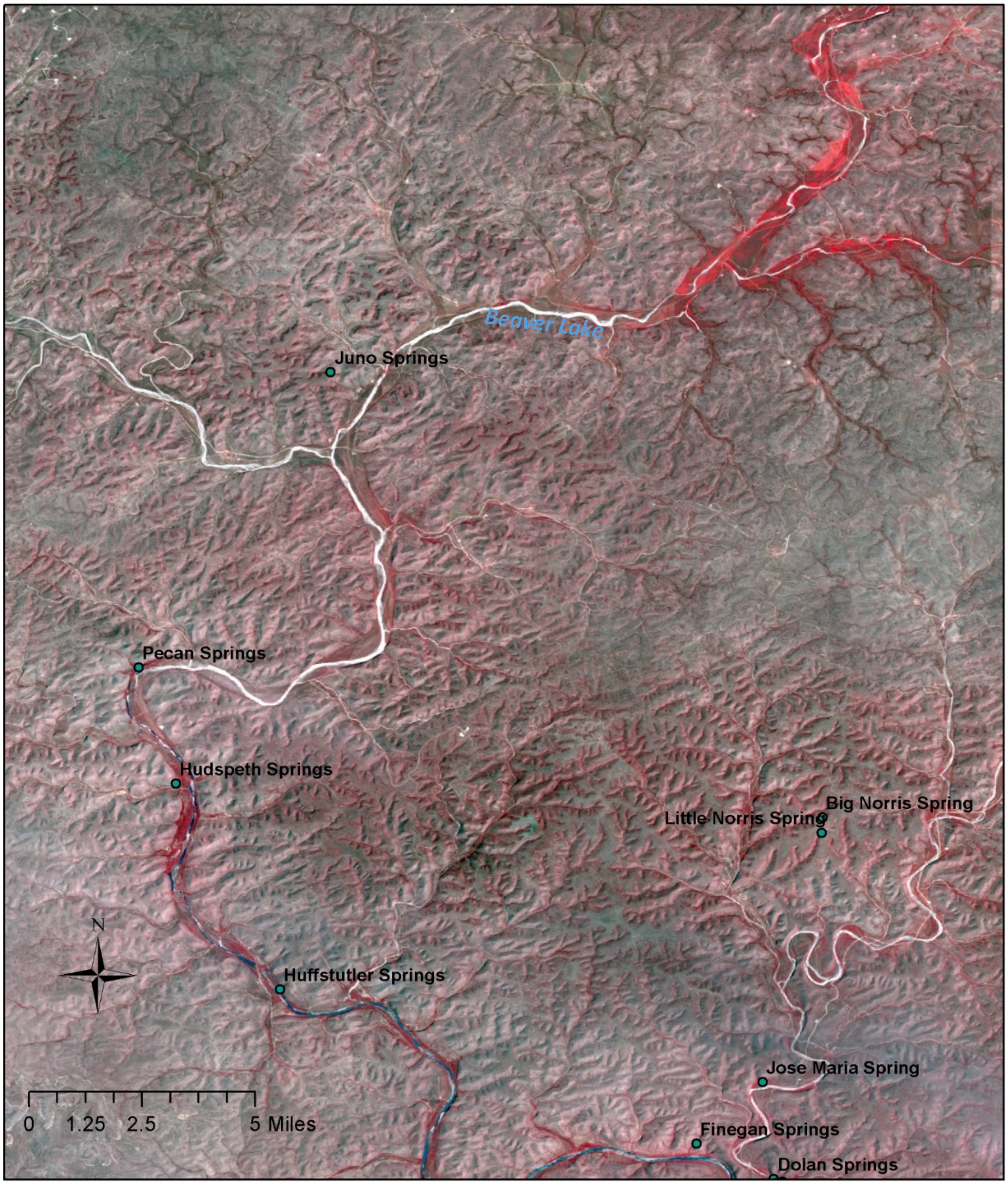

Figure 4-15. Landsat 5 false color near-infrared image for April 6, 1995. Regional records indicate near normal precipitation, with less than 1.5 inches of rain in the preceding 90 days and 22 inches of rain in the preceding year. Active vegetation (bright red) upstream of Juno indicates runoff from a localized storm that infiltrated the stream bed before reaching Beaver Lake. No flow is present between Juno and Pecan Springs; downstream of Pecan Springs there is continuous flow. Imagery from U.S. Geological Survey Earth Explorer.

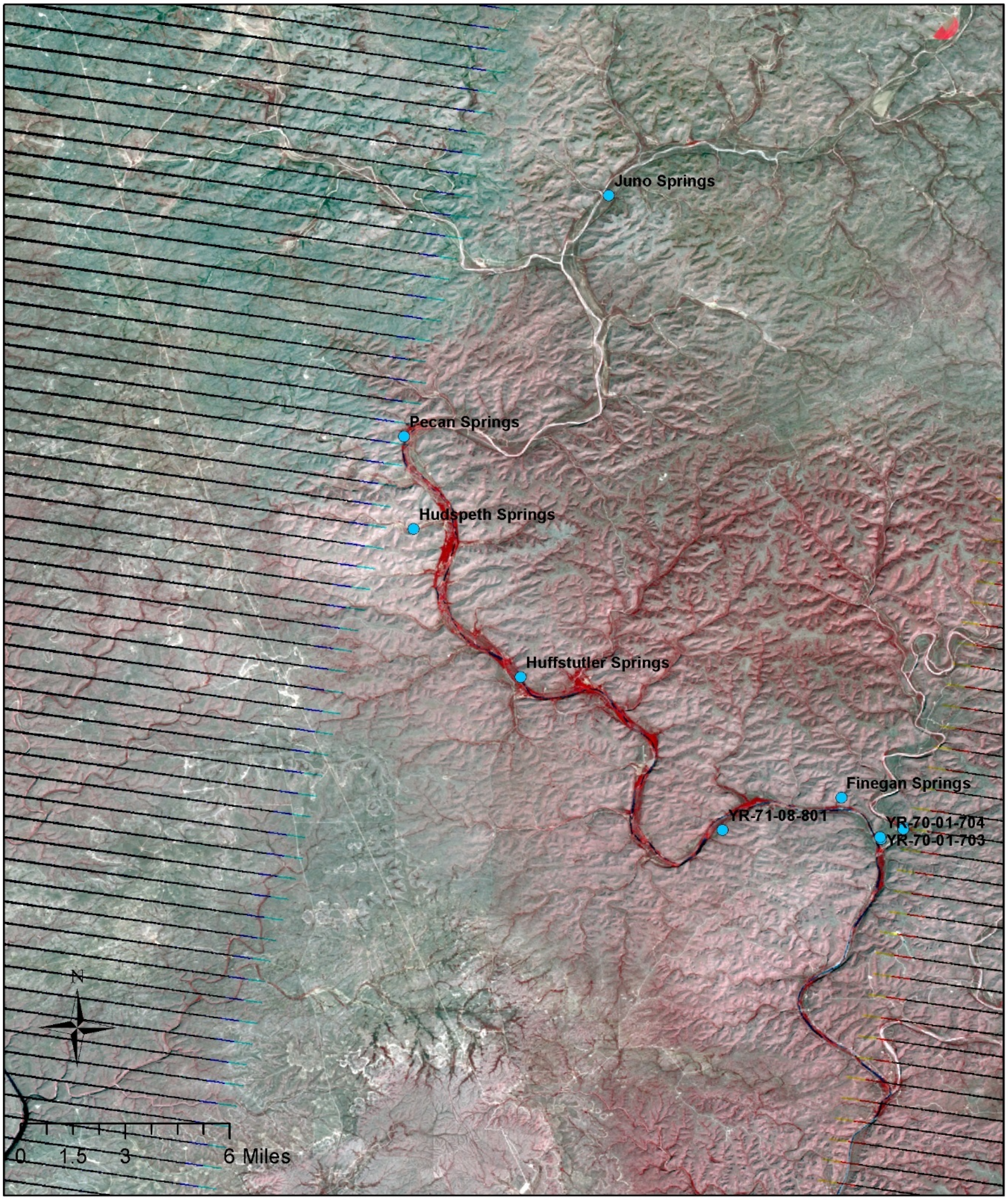

Figure 4-16. Landsat 7 false-color near-infrared image for October 3, 2011, showing flow below Pecan Springs under drought conditions; rainfall in the preceding 90 days totaled 2.15 inches and 4.06 inches for the preceding year. Imagery from U.S. Geological Survey Earth Explorer.

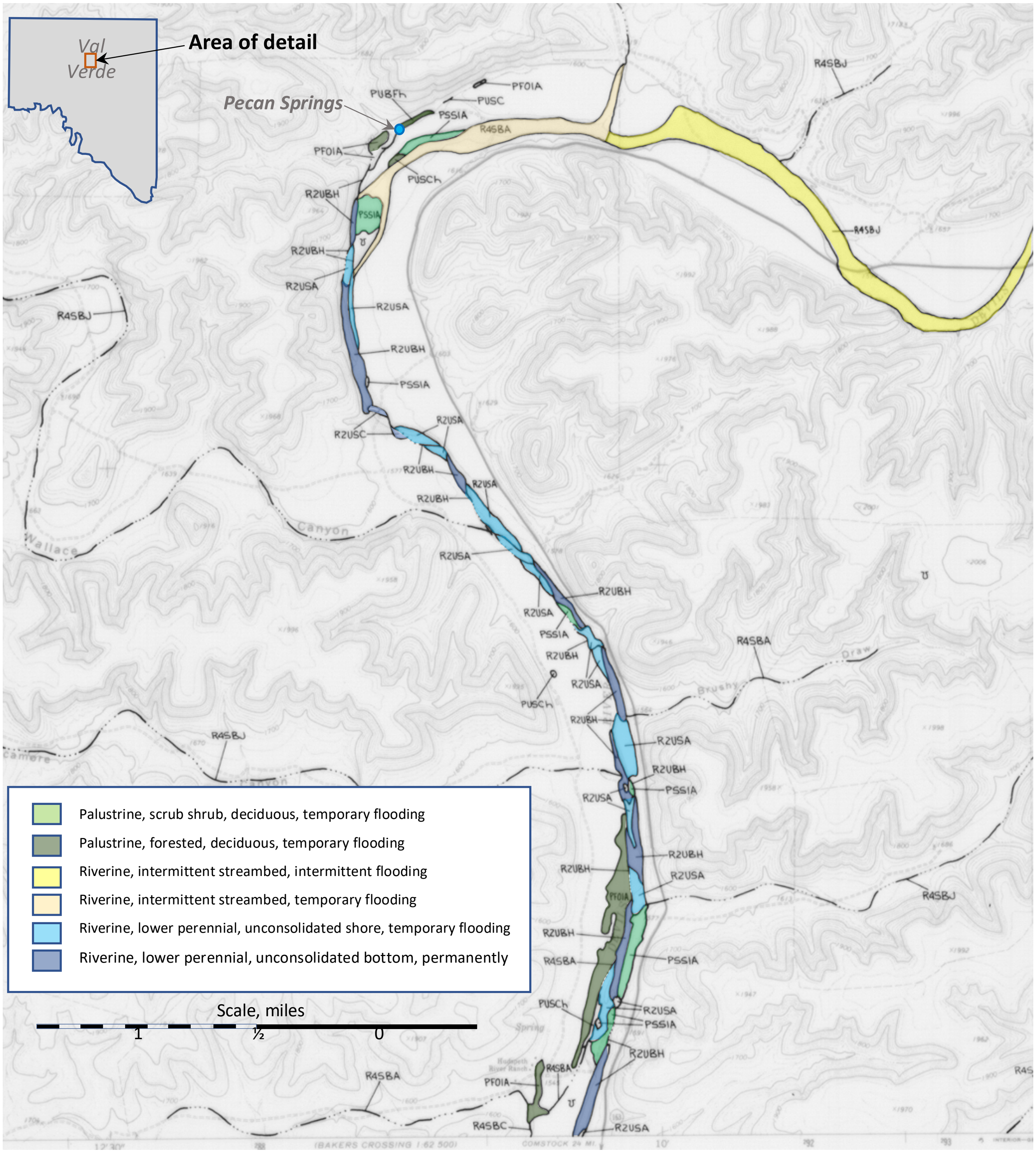

Figure 4-17. National Wetlands Inventory, Sycamore Canyon Sheet, based on aerial photography dated February 1985, a period of slightly below normal rainfall. Perennial water is mapped only below Pecan Springs.

San Felipe Springs

Brune (1975) cites periodic measurements at San Felipe Springs dating to 1889 (Figure 4-18), which indicate a long-term decline in discharge from 1889 to 1971, from about 100 cubic feet per second in 1900 to about 70 cubic feet per second in 1970. The extremely wet conditions in 1900 and then dry conditions during the 1950s drought greatly influence this pre-reservoir trend. Discharge increased again after the reservoir was completed. The trend line for 1972 to 2011 indicates relatively stable discharge controlled by the Amistad Reservoir surface elevation. The International Boundary and Water Commission has monitored discharge from San Felipe Springs since 1961. As Amistad Reservoir filled, groundwater levels in the area around the reservoir also increased, increasing the pressure head and flow at these springs. Spring flow since 1972 has varied with changes in reservoir surface elevation but does not show a strong trend as the reservoir influence dominates groundwater flow in the surrounding area.

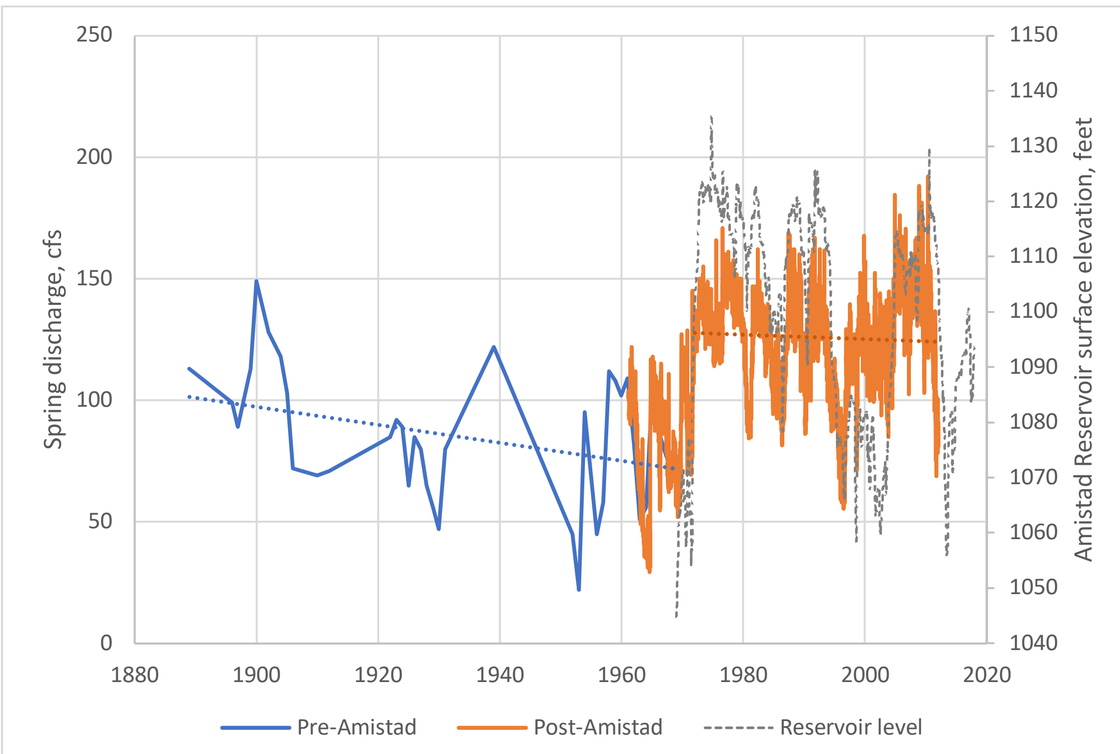

Figure 4-18. Discharge from San Felipe Springs in Del Rio, in cubic feet per second. Data from Brune, 1975 and International Boundary and Water Commission, 2018.

Goodenough Springs

Goodenough Springs represents a major regional point of discharge from the Edwards Trinity (Plateau) Aquifer. Goodenough Springs was formerly the third largest spring in Texas. Mean annual discharge was just under 100,000 acre-feet per year between 1921 and 1960, before Amistad Reservoir was constructed. This represents nearly a quarter of the total modeled groundwater discharge to streams in Anaya and Jones' 2009 regional model, which covers 44,000 square miles of west-central Texas. The springs are now located under approximately 150 feet of water in the reservoir and flow has been reduced by the added pressure of the water column.

Goodenough Springs is located on the U.S. side of the Rio Grande, along an east-west trending segment of a fault, and in an area with numerous northeast-southwest trending faults (Figure 4-19). Numerous subsidence areas associated with the collapse of subsurface karst features, are also mapped in the area.

The source of water feeding the spring has been debated for years. Most current models assume that discharge from Goodenough Springs originates in Val Verde County and adjoining parts of Texas, and the International Boundary and Water Commission allocates 100 percent of the flow from Goodenough Spring to the United States. However, Thomas and others (1963) note that Goodenough Springs "discharge is not derived solely from local sources, for the fluctuations do not correspond with those of water levels in wells or of stream discharge in the adjacent Devils River basin." Reeves and Small (1973) noted that groundwater elevation contours indicated that "much or all of the sources of these springs are to the north and northeast," but "it is also possible that an unknown quantity of water may be derived from sources to the northwest and west." Stafford, Klimchouk, Land, and Gary (2009) postulate a recharge source for Goodenough Springs in northern Mexico based on observed pre-inundation fluctuations in spring flow in response to precipitation events in Mexico at times when no rain fell on the U.S. side of the border.

Thomas and others (1963) noted that the recession curves for Goodenough Springs and Devils River discharge approached a straight-line trend when graphed on a semi-log plot, as in Figure 4-20. He used this relationship to estimate that "if there were no replenishment to the reservoirs from which these flows are derived, the flows would be decreased by about 50 percent every 2 years." This suggests a relatively small total volume of groundwater in storage in the contributing zone, equal to something on the order of four times the average annual discharge, or about 1.4 million acre-feet.

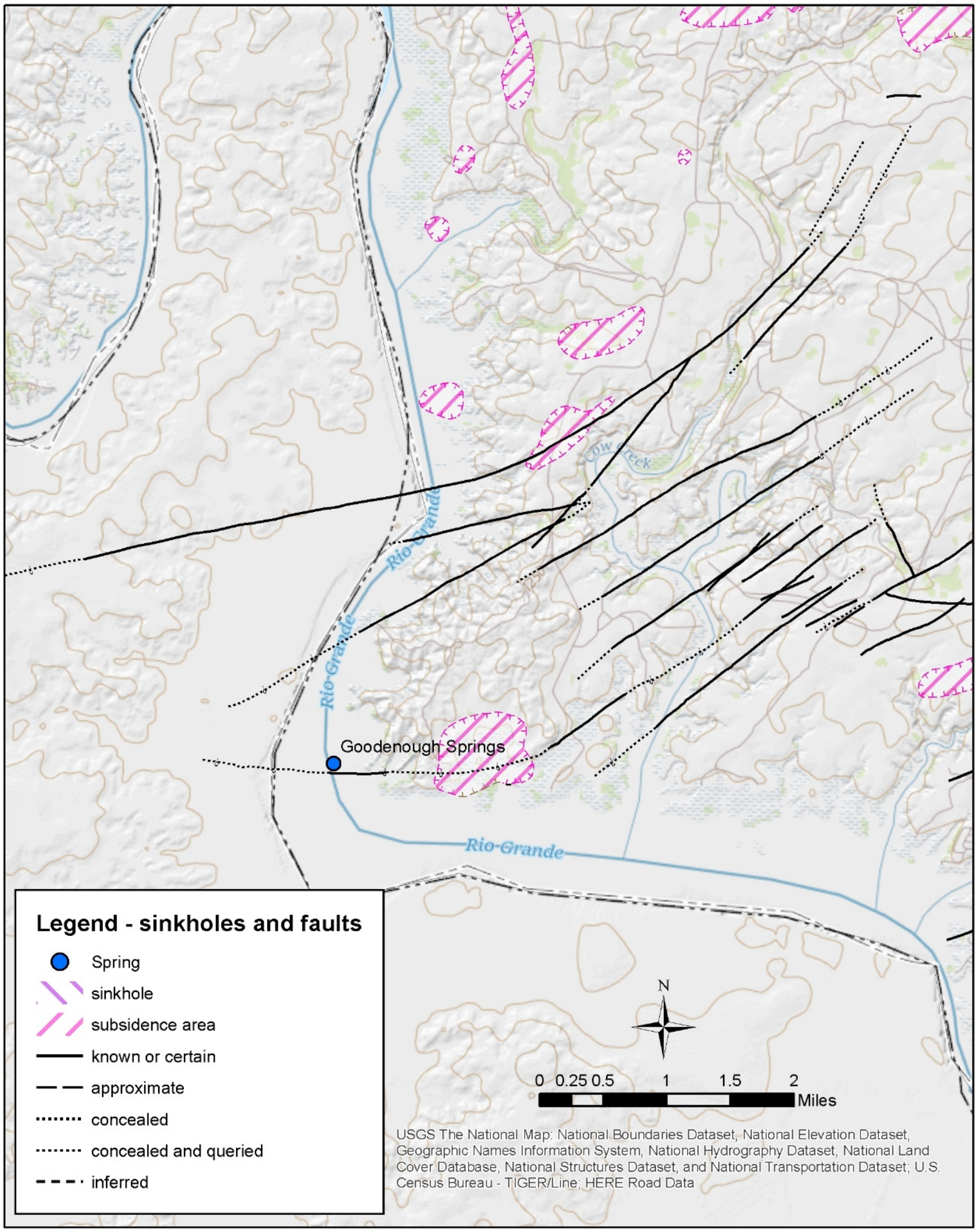

Figure 4-19. Location of Goodenough Springs relative to mapped faults and subsidence features. Data from National Park Service, 2018.

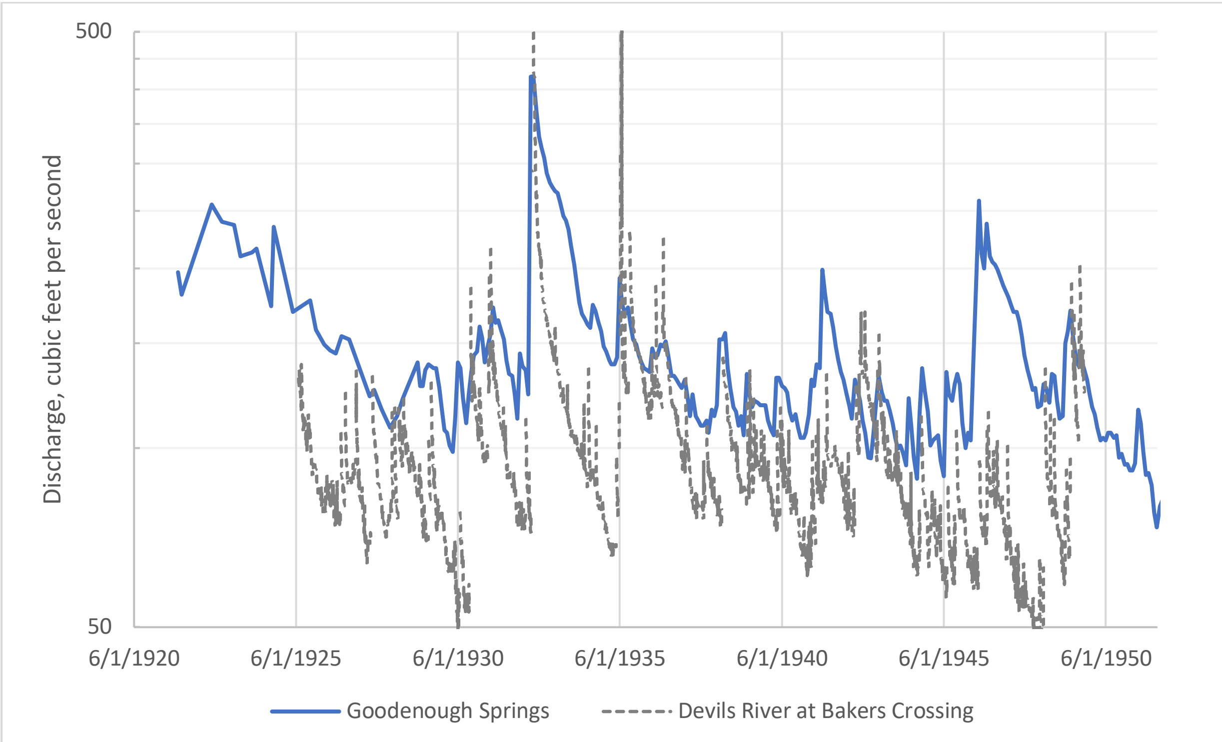

Figure 4-20. Discharge from Goodenough Springs and the Devils River at Bakers Crossing, 1920 to 1952. Discharge from Goodenough Springs responds to increased streamflow in the Devils River in 1932 and 1935, but not in 1942 or 1947, suggesting that other areas outside the Devils River drainage also contribute to Goodenough Springs. Data from Heitmuller and Reece, 2003 and USGS, 2018a.

Such a low estimate of the groundwater volume contributing to spring flow could be consistent with total estimated recoverable storage estimates if groundwater in the Trinity aquifer unit does not actively contribute to spring and stream baseflow. Anaya (2018) finds that the Edwards aquifer unit contains only 20 percent of the total volume of groundwater in storage in Val Verde County, or approximately 2 million acre-feet.

A Mexican source for some of Goodenough Springs discharge fits observations that some increases in spring flow do not correlate with runoff events in the U.S., while the large cavern network extending deep below Amistad Reservoir (Kamps and others, 2009) provides a plausible pathway for flow to move beneath the Rio Grande and to discharge on the U.S. side of the border. However, current Mexican estimates of the recharge to the Cerro Colorado-La Partida aquifer, the Edwards equivalent in Coahuila, total only 5,270 acre-feet per year (Secretaría de Medio Ambiente y Recursos Naturales, 2015), which represents only 5 percent of the historical discharge from Goodenough Springs. In general, hydrological data for this area of Mexico is sparse.

Resolving the source of Goodenough Springs is important to understanding and managing groundwater in Val Verde County. Goodenough Springs represent a large part of the water budget for groundwater models of the area. If a large part of the water budget actually originates outside the model domain, these models are not properly calibrated and estimates of aquifer properties and the groundwater volumes available for use are likely in error.

Additional discussion of groundwater residence time, the source of recharge to Goodenough Springs, and groundwater mixing is included in the discussion of groundwater quality and in Appendix B, which describes how radiocarbon, tritium, and other geochemical tracers can be used as an independent line of evidence to estimate groundwater mean residence time, total storage volume, and flows between aquifers.

Effects of pumping on recharge, streamflow, and surface water/groundwater interactions

Available water level records do not demonstrate any widespread, long-term effects of current pumping on recharge, streamflow, or groundwater-surface water interaction in Val Verde County. Localized effects may be present near some larger capacity wells but cannot be distinguished from background variability, given the available network of observation wells.

Quantitative evaluation of the effects of potential future pumping on recharge, streamflow, and groundwater-surface water interaction requires an appropriately scaled, calibrated, and validated numerical model of coupled groundwater and surface water processes. Such a model is not currently available and key inputs needed to develop one are not well constrained.

Qualitative evaluation suggests that pumping in most parts of Val Verde County is unlikely to significantly affect recharge. Recharge from precipitation in Val Verde County is limited by the low annual rainfall, high evapotranspiration, and rapid runoff. Groundwater is typically more than 100 feet below ground surface, except along some stream courses. The groundwater is too deep for most plant roots to reach except along narrow riparian corridors, so lower water table elevations will not significantly reduce losses to evapotranspiration. The water levels in the aquifer are deep enough that there is no “rejected” recharge, and infiltration rates are restricted by the soil properties and the characteristics of stream-bed conduits rather than groundwater levels. However, large-scale pumping along perennial reaches of one of the rivers or near Amistad Reservoir could induce inflow from surface waters to the aquifer but would not add to the total volume of groundwater in storage.

Pumping may affect the lateral movement of groundwater in Val Verde County and surrounding areas. Large-scale pumping over an extended period may produce a cone of depression in the potentiometric surface sufficient to induce lateral groundwater flow into the county from surrounding areas. This is especially likely in the southern portion of Val Verde County where the Edwards aquifer unit is thicker and larger volumes of groundwater can be produced. Confined groundwater conditions in the southern part of the county will also tend to create a wider cone of depression because the smaller confined aquifer storage coefficient results in greater drawdown for a given pumping volume. Groundwater flow in the thinner Edwards aquifer unit north of the Maverick Basin appears to be separated into distinct groundwater basins coincident with the surface water drainages. Pumping in the upstream portion of one basin is unlikely to affect adjacent basins, even if the aquifer is locally dewatered, because the gradient created by the pumping will probably not be sufficient to induce flow across the divide between the surface water basins.

Pumping has the potential to reduce streamflows. Baseflow in the lower Pecos River, the Devils River, and Sycamore and San Felipe creeks is supplied by spring discharge, so these streams are highly likely to be affected by pumping that produces widespread changes in the groundwater potentiometric surface. Any effects will depend strongly on the location of pumping wells relative to the springs and the nature of any karst conduits between those wells and surface water features.

Similarly, groundwater-surface water interactions are vulnerable to changes associated with pumping. Spring discharge requires a potentiometric surface at or above the spring orifice. Groundwater drawdown below this level will stop any spring flow, and any reduction in groundwater levels near spring locations will tend to reduce spring flow as the pressure in karst conduits is reduced. Continued reductions in groundwater levels could result in stream reaches that are currently gaining water from springs to become losing reaches where streamflow is captured by the groundwater. Our analysis of water quality data also demonstrates that reservoir water is infiltrating into the aquifer in the Del Rio area. Pumping could induce further reservoir water infiltration if it creates a potentiometric surface that slopes away from the reservoir or increases the gradient already present in areas near Del Rio.

The Bureau of Economic Geology at the University of Texas at Austin is conducting a research project (as of September 2018) to evaluate groundwater-surface water relationships along the Devils River near Dolan Crossing. The goal of the project is to better understand relationships between groundwater withdrawals, spring discharge, streamflow, and the availability of fish habitat in Dolan creek and the Devils River. The work includes assessing groundwater-level trends at monitoring wells, assessing rainfall-runoff response of major springs feeding the Devils River, and developing a stage-discharge relationship for the Devils River. The results of this work are expected to improve the characterization of groundwater-surface water relationships (Figure 4-21).

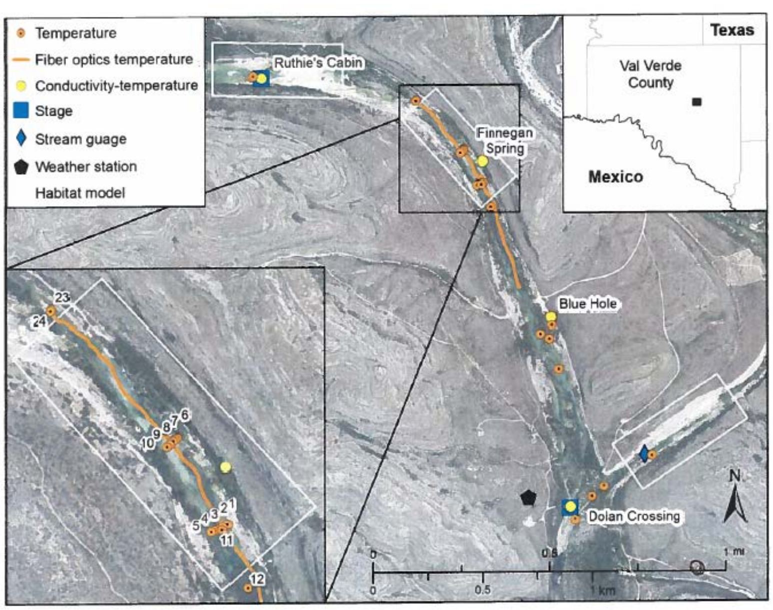

Figure 4-21. Monitoring points in the University of Texas Bureau of Economic Geology research project.

Groundwater Quality

Water quality data provide a means to evaluate several aspects of the hydrogeological system, including the connection between the Edwards and Trinity portions of the aquifer, the effects of Amistad Reservoir on the groundwater system, groundwater flow paths, occurrence of salinity, and groundwater residence time.

Water quality is good in most wells completed in the Edwards section of the Edwards-Trinity (Plateau) Aquifer and the water is typically suitable for all municipal, agricultural, and industrial applications. Water quality data for 213 fresh samples collected from Edwards wells since 1972 and 36 brackish samples collected between 1939 and 1969 (Table 4-4) show the groundwater to be a calcium bicarbonate type with near neutral pH and low total dissolved solids content. The groundwater is typically hard and is saturated with respect to calcite. Wells completed in the Trinity Glen Rose Formation and some wells completed in the Edwards Aquifer contain groundwater with higher total dissolved solids (TDS) content, primarily calcium and sulfate ions from reaction with gypsum in the subsurface. These brackish wells are mostly in the Del Rio area, but also occur in other parts of the county.

Table 4-4. Average groundwater quality for fresh and brackish Edwards-Trinity (Plateau) Aquifer wells. Data from TWDB groundwater database. Units (except pH) in milligrams per liter.

Analyte	Fresh Edwards	Brackish Edwards and Glen Rose
pH	7.4	7.5
Calcium	84.5	591
Magnesium	12.9	44.5
Sodium	28.9	33.5
Potassium	1.6	2.0
Bicarbonate	239	189
Chloride	42	74.1
Sulfate	59	1,431
TDS	370	2,285

Groundwater-Amistad Reservoir Water Mixing

The Edwards-Trinity (Plateau) Aquifer's low TDS calcium-bicarbonate chemistry is distinct from the chemistry of surface water in the Rio Grande upstream of Amistad Reservoir and the Pecos River, while the Devils River chemistry closely matches the groundwater chemistry. Amistad Reservoir water chemistry represents a mixture of the inputs from surface water and groundwater sources. A graphical representation called a Piper diagram, which plots the ratios of dissolved calcium, magnesium, sodium, potassium, bicarbonate, chloride, and sulfate ions in water samples (Figure 4-22), illustrates the mixing relationships between the different water sources contributing to Amistad Reservoir.

The primary solutes in groundwater are calcium and bicarbonate, with lesser amounts of magnesium derived from exchange with dolomitic limestone in the subsurface. Goodenough Springs, the largest spring in Val Verde County, is taken as representative of karst conduit groundwater chemistry. Data points for the springs represent one 2005 sample collected from the spring orifice beneath the reservoir and the median ion concentrations in U.S. Geological Survey samples collected in 1967 and 1968, before the reservoir filled (Kamps and others 2006). Median values of chemical constituents in Devils River water from 104 samples collected at Pafford Crossing between 1978 and 1995 (Mast and Turk, 1999) plot close to the groundwater, as expected given the spring-dominated baseflow in the Devils River.

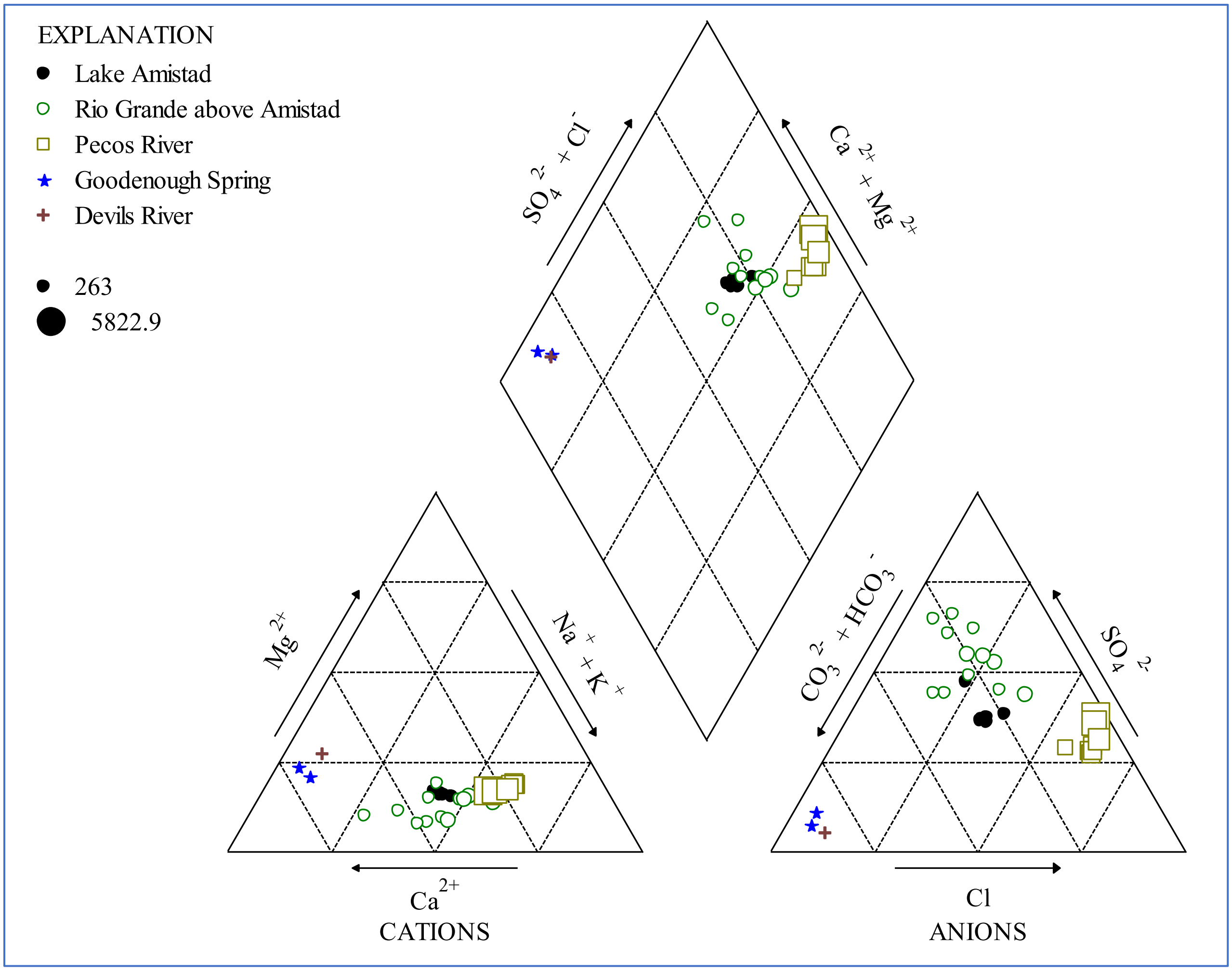

Figure 4-22. Piper diagram of the water chemistry for Amistad Reservoir, the Rio Grande, the Pecos River, the Devils River and Goodenough Springs. Symbols for each sample are scaled by the total dissolved solids content of the sample, which range from a minimum of 263 milligrams per liter in Goodenough Springs to a maximum of 5,823 milligrams per liter in the Pecos River. Data from TCEQ, 2018a, Mast and Turk, 1999, and Kamps and others, 2009.

The Pecos River water chemistry (TCEQ, 2018a) varies widely in terms of total salinity, but all the samples plot close together on the Piper diagram, owing to their similar ratios of major ions. The Pecos River water is dominated by sodium and chloride, with lesser amounts of magnesium and sulfate. Water quality data for the Rio Grande upstream of Amistad Reservoir (USGS, 2007; TCEQ, 2018a) have a wider compositional range than groundwater or Pecos River inputs.

Rio Grande water is distinguished by its relatively high sulfate anion content and a mix of sodium and calcium cations. Amistad Reservoir water chemistry represents a ternary mixture of the Rio Grande, Pecos River, and groundwater components. The reservoir composition plots closer to the Pecos River than to groundwater, despite the volumetrically larger contribution of combined flows from the Devils River and Goodenough springs, because most of the salt content is derived from the high TDS Pecos River water.

The water chemistry of the Devils River at Pafford Crossing has slowly changed since Amistad Reservoir filled. The average specific conductance of water samples analyzed by the TCEQ and USGS between 1967 and 2017 increased from 350 to 400 micro-siemens per centimeter over the 50-year period. Water quality changes may be related to groundwater mixing with more saline reservoir water driven by fluctuations in reservoir and groundwater elevations relative to each other.

Groundwater quality data also show how Amistad Reservoir water has mixed with and displaced groundwater in downgradient areas. Piper diagrams for three wells at increasing distance from the reservoir (Figures 4-23 through 4-25) show varying amounts of reservoir influence. The ground water chemistry in Well 7033501, located three-quarters of a mile south of the reservoir, changes relatively rapidly. In June 1969, it already contained more sodium and chloride than typical groundwater. By 1976 the chloride and sulfate content of the well water was close to that of the reservoir and did not change appreciably over the next decade. The sodium content of the well water remains intermediate between the 1969 groundwater composition and the reservoir composition, perhaps reflecting cation exchange reactions in the aquifer. Well 7033604, located 1.8 miles southeast of the reservoir near the intersection of U.S. Highways 90 and 377, shows a gradual evolution from a groundwater signature to a reservoir water signature over the period from 1968 to 2004. At these wells, the groundwater potentiometric surface is lower than the elevation of the reservoir surface and reservoir water has migrated into the aquifer.

In contrast, Well 7123502, located north of Amistad Reservoir near Comstock, is well within the area where the groundwater potentiometric surface was affected by the reservoir, but has not been affected by migration of solutes contained in the reservoir water and maintained a stable chemistry from 1968 through 2015 (Figure 4-25). Because the groundwater elevation in Well 7123502 is higher than the elevation of the reservoir surface, the direction of groundwater flow at this location remains toward the reservoir.

While the water pressure effects of reservoir elevation changes propagate both upgradient and downgradient from the reservoir, solutes contained in the water have only migrated downgradient with the physical flow of the water. However, pumping within the area influenced by the pressure effects of the reservoir could change the groundwater potentiometric surface and potentially induce flow from the reservoir toward the pumping well. Under such conditions, changes in groundwater chemistry could serve as a useful indicator that the pumping well was drawing in surface water from the reservoir and not just groundwater from the surrounding aquifer.

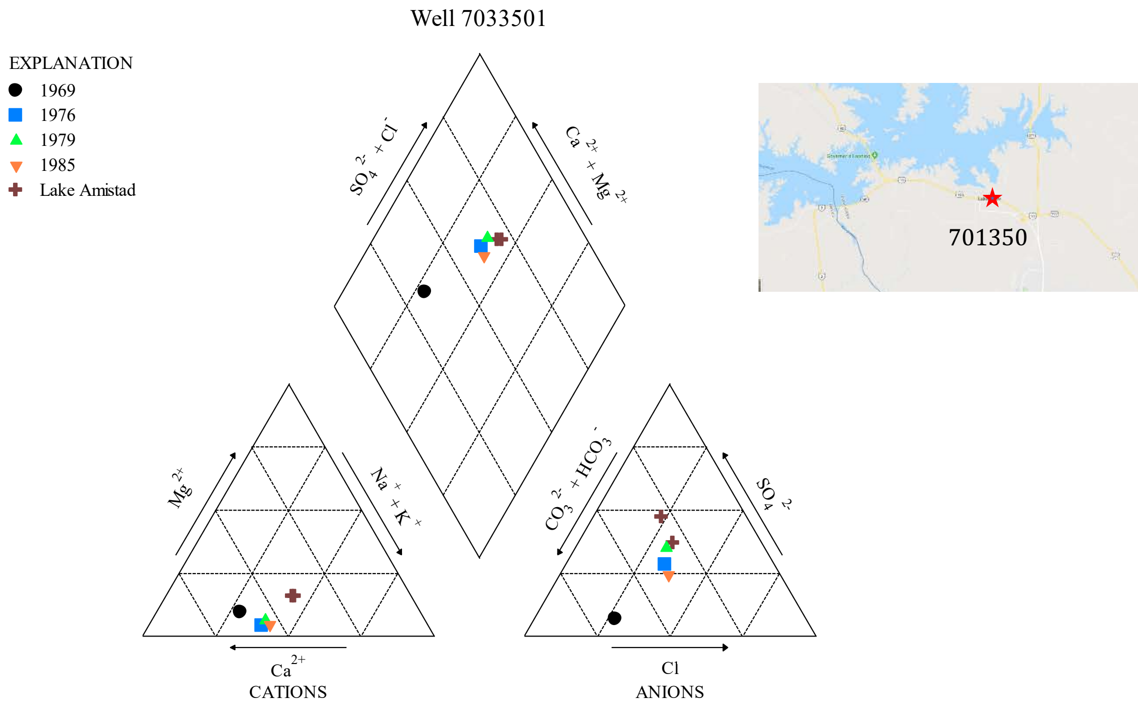

Figure 4-23. Piper diagram for Well 7033501, 0.75 miles southeast of Amistad Reservoir. Groundwater chemistry in this area is dominated by the reservoir influence by 1976. Data from TWDB and TCEQ, 2018a.

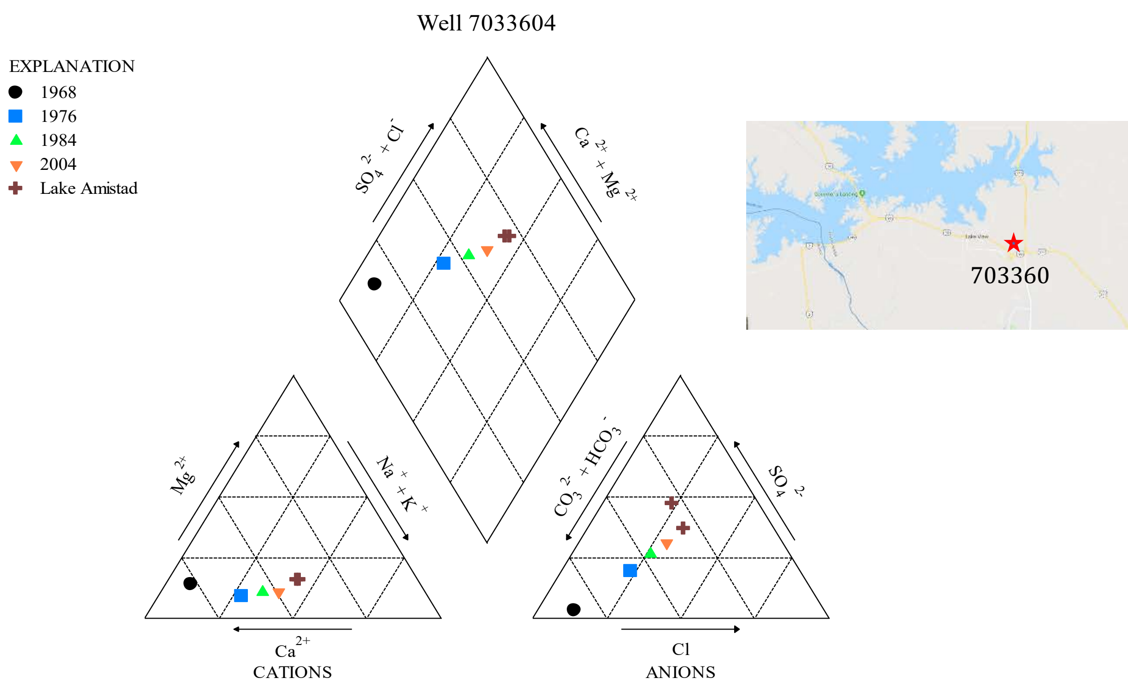

Figure 4-24. Piper diagram for Well 7033604, 1.8 miles southeast of Amistad Reservoir. Groundwater chemistry in this area has progressively moved toward reservoir composition during the period of 1968 to 2004. Data from TWDB and TCEQ.2018a.

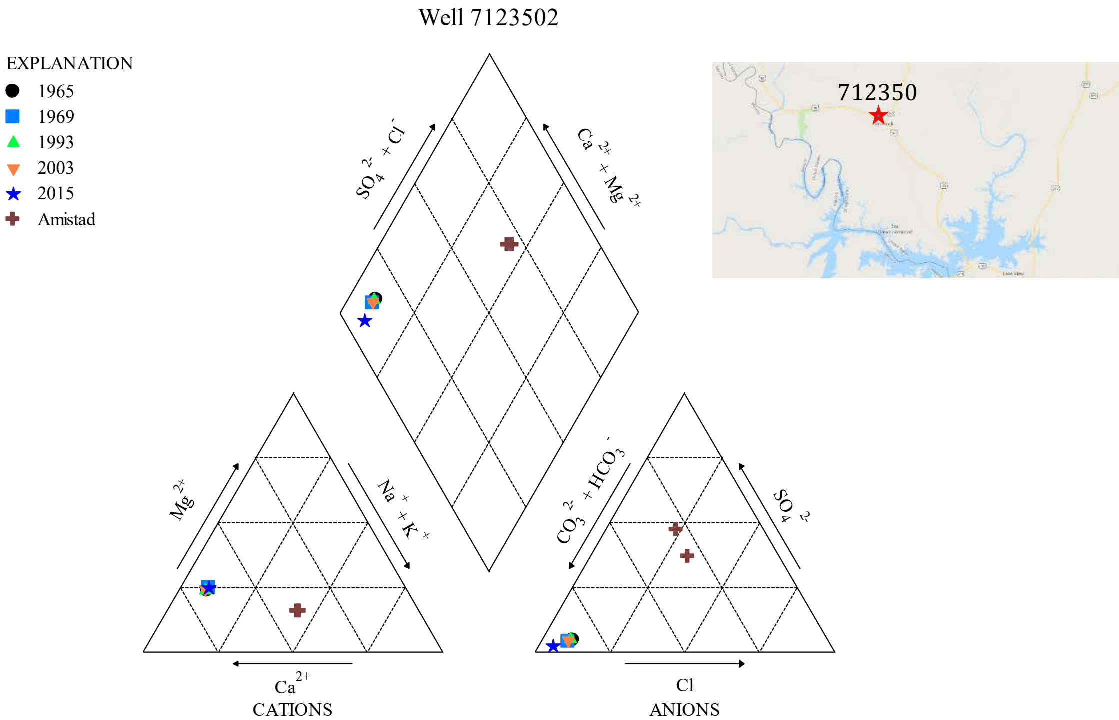

Figure 4-25. Piper diagram for Well 7123502, located 5.75 miles north of Amistad Reservoir near Comstock. The groundwater chemistry in this area has not changed appreciably since the reservoir filled. Data from TWDB and TCEQ, 2018a.

LBG-Guyton (2001) sampled San Felipe Springs and several City of Del Rio wells for micro-particulate analysis to evaluate their connection to surface waters. Micro-particulate analysis identifies surface-water bioindicators such as plant debris, algae, diatoms, insects, rotifers, and other identifiable particulates found only in surface-water bodies. Micro-particulate analysis is used by the Texas Commission on Environmental Quality to identify groundwater under the influence of surface water under the surface water treatment rule. The micro-particulate analysis results for the three City of Del Rio wells are all classified as "low", while water collected from the springs ranged from "low" at West San Felipe Spring to "moderate" at East San Felipe Spring. A sample from the Tierra del Lago well near Amistad Reservoir was also rated as "moderate."

Geochemical assessment of groundwater flow paths, mixing, and residence time

Chemical and isotopic analyses suggest that the mean age of groundwater discharged from the major springs in Val Verde County may range from 2 years to over 30 years. Spring discharge has minimal water-rock interaction, suggesting conduit recharge through sinkholes and fractures along surface drainages, and exhibits limited mixing with groundwater from the aquifer matrix under normal flow conditions. These observations generally support the matrix-conduit model of groundwater flow but place certain constraints on the aquifer storage and flow parameters and the degree of connection between matrix and conduit. Appendix B includes an evaluation of isotopic and geochemical indicators in 55 groundwater and spring water samples collected in Val Verde County by the TWDB between 2002 and 2010.

Geochemical data for Val Verde, Crockett, and Sutton counties suggest that most of the flow from the major springs moves along flow-paths distinct from the groundwater found in the aquifer matrix, rather than integrating flow from the entire contributing area upgradient from the point of discharge. This is possible in a karstic system where flow along major conduits is several orders of magnitude faster than groundwater flow in the aquifer matrix. Furthermore, it suggests that the conduit system does not simply aggregate diffuse flow from the matrix, but instead has a largely separate source of recharge. The obvious candidate for conduit recharge is captured surface water runoff that enters sinkholes or major fractures in the upper, intermittent reaches of the alluvial system. This conduit flow appears to largely remain distinct from groundwater that originates as diffuse recharge under normal flow conditions, although under drought conditions matrix groundwater is likely to be more important.

Nunu, Bertetti, and Green (2017) show that the distribution of groundwater calcium concentrations generally follows the surface drainage network in the Devils River watershed (Figure 4-26), with higher calcium concentrations in active recharge areas along the major surface drainage features and lower calcium concentrations away from the drainages. This distribution follows the pattern outlined by Nance (2010) where an increasing magnesium-to-calcium ratio is a measure of longer groundwater residence time, especially in areas capped by Buda Limestone.

Brackish Groundwater

Several wells in Val Verde County produce brackish groundwater, characterized by total dissolved solids content exceeding 1,000 milligrams per liter. Most brackish groundwater in the Del Rio area acquires salinity by dissolution of evaporite minerals in the McKnight Formation in the Maverick Basin, while brackish water in other parts of the county represents a mixture of Edwards aquifer unit groundwater and deeper, more saline groundwater associated with the Glen Rose Limestone Formation in the Trinity Aquifer.

A Piper diagram of the major ion chemistry of groundwater from brackish wells grouped according to their geographic location (Figure 4-27) shows a broad dispersion in compositional space representing a three-component mixing of groundwater types. One mixing component is fresh Edwards aquifer unit groundwater and spring water, which plots to the lower left in the calcium bicarbonate region of the plot. A second component is brackish groundwater in the Glen Rose Limestone, which plots in the lower right-hand corner of the cation graph and toward the center of the anion graph, representing a mix of sodium chloride and sodium sulfate type waters. The third component is brackish groundwater from wells in the Salt Creek drainage, near Del Rio, which plots in the extreme lower left of the cation graph and in the upper corner of the anion graph, representing a calcium sulfate type water. Brackish groundwater samples from wells in the northwest part of the county (NW trend) and along a line between Langtry and Comstock (Langtry) are similar to the Glen Rose groundwater, suggesting that these wells are influenced by Glen Rose Limestone waters migrating into the Edwards Aquifer along faults or fractures. Brackish wells in the Zorro Creek area, near Laughlin Air Force Base, have compositions intermediate between the Glen Rose Limestone and Maverick Basin groundwater types.

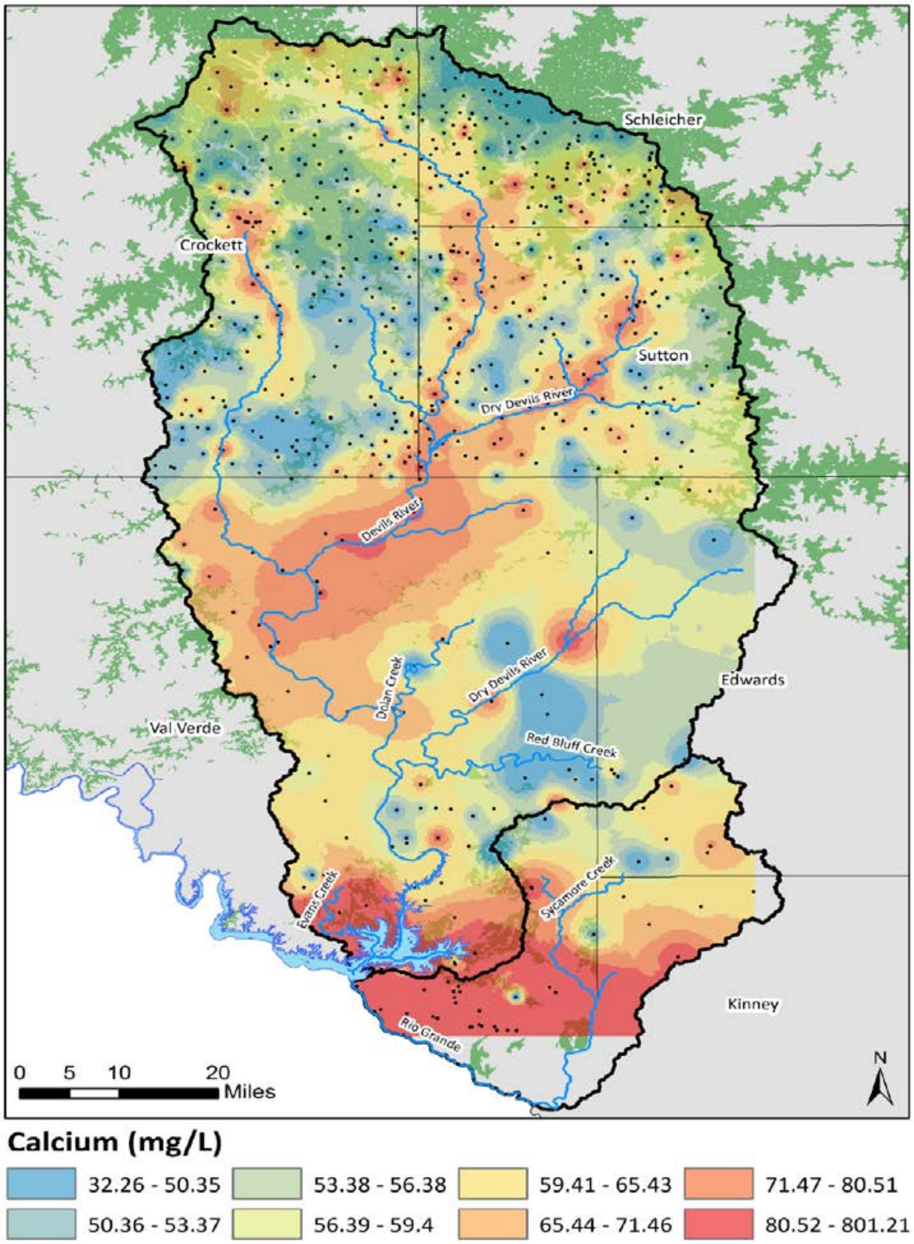

Figure 4-26. Calcium distribution in Val Verde and neighboring counties. From Nunu, Bertetti and Green, 2017.

The limited number of brackish wells in Val Verde County, and their geographic specificity, suggests there is little interaction between groundwater in the Trinity Aquifer and the shallower Edwards Aquifer groundwater. While some regional discharge from the Trinity probably occurs along the Rio Grande, we have no evidence that it is volumetrically important in the Val Verde area. Available data suggest that locally the Trinity Aquifer is relatively stagnant.

Additional research on brackish groundwater resources in Val Verde County is being conducted by the TWDB as part of the Brackish Resources Aquifer Characterization System (BRACS) study of the Edwards-Trinity (Plateau) Aquifer. The study is expected to be completed in late 2020.

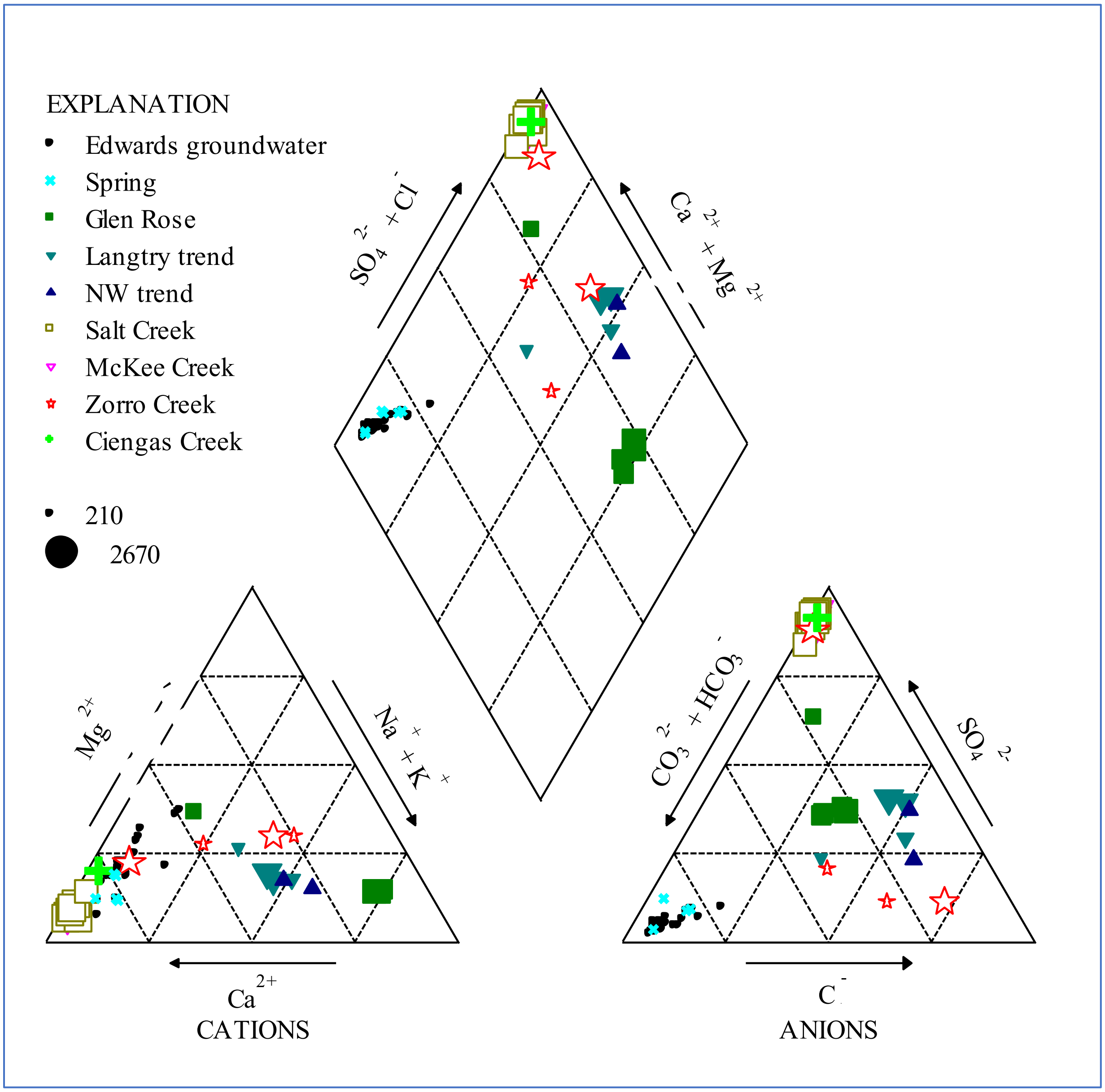

Figure 4-27. Piper diagram of fresh and brackish water samples from the Edwards aquifer unit. Glen Rose Limestone groundwater and spring water samples are also plotted for comparison. Symbol size is proportional to total dissolved solids content.

5.0 Groundwater Models

Key findings

- Available groundwater models were developed for varying purposes, conceptualize the hydrogeological systems differently, and are calibrated to different parameter values, but all meet their calibration targets.
- The models can be used to evaluate measures such as total groundwater storage and residence time for comparison with independently derived estimates.
- Models need to incorporate higher temporal and spatial resolution than the regional Edwards-Trinity (Plateau) Aquifer GAM to assess compliance with desired future conditions, but data to support more detailed models are generally lacking.
- Several lines of evidence suggest that a large part of the Val Verde water budget actually originates outside the model domain; if so, these models are not properly calibrated and estimates of aquifer properties and the groundwater volumes available for use are likely in error.
- Targeted groundwater monitoring is needed to support refinements to groundwater models and groundwater management. Data gaps exist concerning key factors such as groundwater-surface water interactions, aquifer storage, and recharge.
- The Val Verde County Model is potentially better suited for evaluating groundwater management options than the regional Edwards-Trinity (Plateau) Aquifer GAM or the watershed-based Devils River Watershed model.

Numerical groundwater models are computer tools used to represent and understand aquifer flow systems. When properly calibrated, models may also be used to simulate groundwater conditions for a given set of assumptions. The level of complexity and usefulness of groundwater flow models are generally constrained by the availability of data and the range of conditions reflected in the available data. The relative scarcity of historical measurements for much of Val Verde County constitutes a challenge for modeling the Edwards-Trinity (Plateau) Aquifer groundwater flow system.

Several different groundwater flow models have been developed to evaluate groundwater conditions in all or parts of Val Verde County (Wet Rock Groundwater Services, 2010; Eco-Kai and Hutchison, 2014; Toll, Fratesi, Green, Bertetti, and Nunu, 2017). We examined model documentation and the hydrogeological parameters used in each of these models to assess their applicability for groundwater management in Val Verde County. Since the TWDB does not have access to the actual model files in some instances, we cannot formally review model design or calibration; rather, we offer general insights on the conceptual framework and boundary conditions as presented in the model reports. Additional data may be needed to resolve disparate model predictions. Therefore, we have limited our review to a brief overview of the models and their applicability for groundwater management in Val Verde County.

Regional and Val Verde County Models

The TWDB developed two groundwater models for the Val Verde County area that have been used as a basis for subsequent modeling efforts by various local entities. The Edwards-Trinity (Plateau) groundwater availability model (Anaya and Jones, 2009) evaluated regional groundwater flow and availability over much of Central Texas (Figure 5-1). The TWDB also developed a separate model of Kinney County groundwater (Hutchison, Shi, and Jigmond, 2011) at the request of the Kinney County Groundwater Conservation District to evaluate the effects of potential groundwater withdrawal on springs and river flows. Wet Rock Groundwater Services (2010) used the Edwards-Trinity (Plateau) Aquifer GAM framework, with modified pumping distributions, to evaluate the effects of potential pumping on regional groundwater levels, and used the Kinney County groundwater model (Hutchison, Shi, and Jigmond, 2011) to assess potential impacts on spring flow at San Felipe and Las Moras springs.

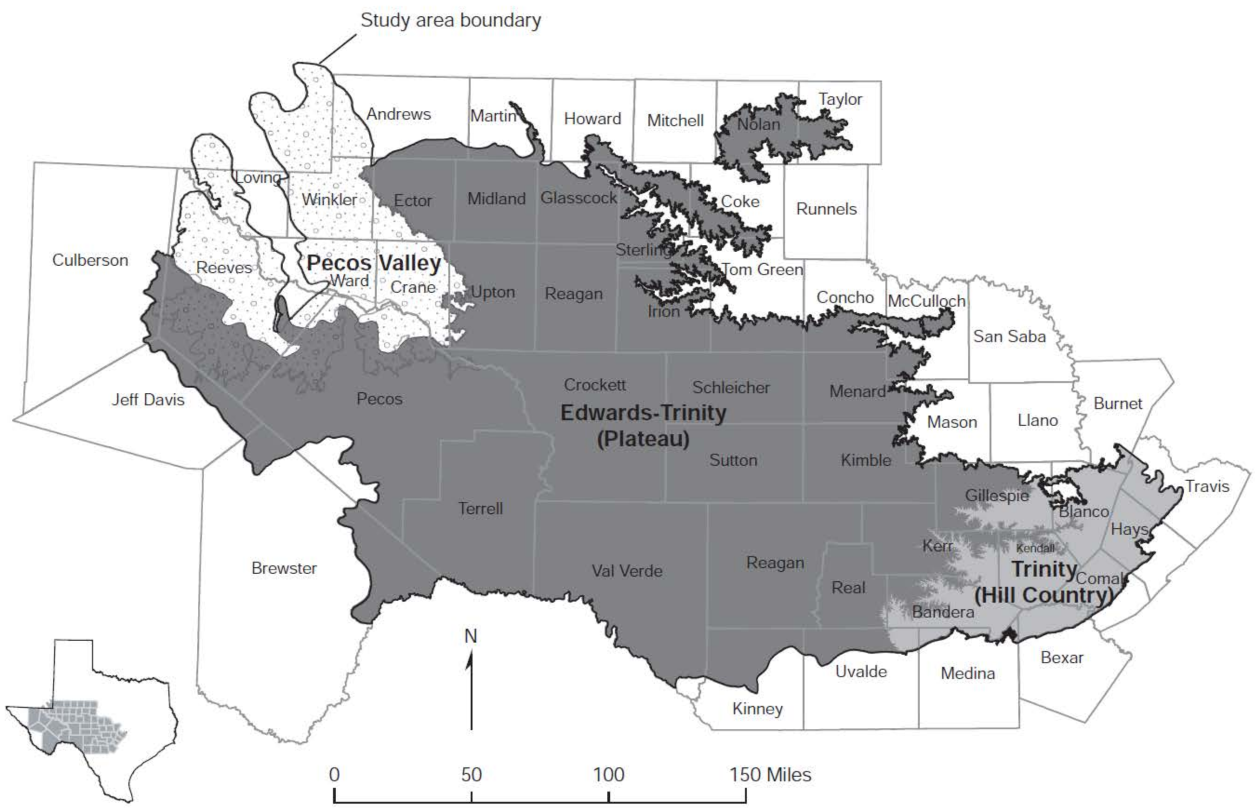

Figure 5-1. Extent of the model domain for the Edwards-Trinity (Plateau) GAM. From Anaya and Jones, 2009.

The 2011 Kinney County model was updated and modified to evaluate the effects of potential large-scale pumping and to develop groundwater management guidelines applicable to Val Verde County (EcoKai and Hutchison, 2014). The Val Verde County model (Eco-Kai and Hutchison, 2014) has a one-half mile grid spacing and uses monthly time steps to more closely model spatial and temporal variability in the groundwater system. The model features a network of high hydraulic conductivity model cells underlying the surface drainage system to represent the conduit flow pattern associated with the karst aquifer. Monthly recharge is calculated from data on rainfall and evaporation, with a precipitation threshold level below which no recharge occurs and a variable lag term to simulate dependence on prior conditions. The Val Verde County model is calibrated to observed groundwater levels and spring flow in Las Moras, McKee, and Cantu springs.

Devils River Watershed Model

Toll, Fratesi, Green, Bertetti, and Nunu (2017) used a different approach to model groundwater in the Devils River watershed in Val Verde, Crockett, and Sutton counties. Figure 5-2 illustrates the domain of this groundwater model. They used a semi-distributed surface-water model, the Hydrologic Modeling System (HEC-HMS), developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center to determine runoff and recharge components of the water budget from gridded daily precipitation data. The surface water model is calibrated to gaged flows at Pafford Crossing. The recharge component from the surface water model is used as input to a groundwater flow model. The groundwater model represents the upper 130 feet of the Edwards aquifer unit as a network of highly conductive karst conduits underlying the river channels. It uses the MODFLOW-USG program to create an unstructured grid with higher spatial resolution around the conduit features and lower resolution for the aquifer matrix away from the streams.

Lower Pecos River Watershed Model

Green, Toll, Bertetti, and Hill (2016) developed a multi-county groundwater flow model of the lower Pecos River watershed that includes the portion of the watershed that contributes to the volume of river flow that discharges to Amistad Reservoir. As such, this model extends over much of the western portion of Val Verde County. The FEFLOW modeling package was used as the modeling code rather than the MODFLOW code. The model consists of two layers, one each for the Edwards and Trinity rock units. Unlike the Devils River watershed model, the lower Pecos River watershed model does not include a coupled surface water model that is coupled to the groundwater model.

Model Parameters

Table 5-1 summarizes critical aquifer properties in the available groundwater models for Val Verde County. The aquifer properties used in the Devils River Watershed Model (Toll and others, 2017) describe a groundwater system with more rapid flow along discrete channels and greater overall groundwater storage than the GAM model. The Val Verde County Model has much higher hydraulic conductivities than the GAM model, while storage values are comparable.

Layer 1 of the GAM, representing the entirety of the Edwards aquifer unit, has a spatially averaged hydraulic conductivity of 6.65 feet per day, while Layer 2 of the GAM, representing the Trinity Aquifer, has a hydraulic conductivity of 2.5 feet per day. The Devils River Watershed model has a hydraulic conductivity distribution of the aquifer matrix with values comparable to those used in the GAM, but with hydraulic conductivity in the conduit channels 100 to 1000 times higher than the matrix. The Devils River Watershed model also use specific storage and specific yield values for the aquifer matrix that are between 2 and 20 times higher than those used by the GAM. The high hydraulic conductivity channels represented in the Devils River Watershed Model was designed to simulate more rapid system response to short-term changes in external conditions, such as storm events, but the greater volume of groundwater in storage may damp model response to long-term stresses.

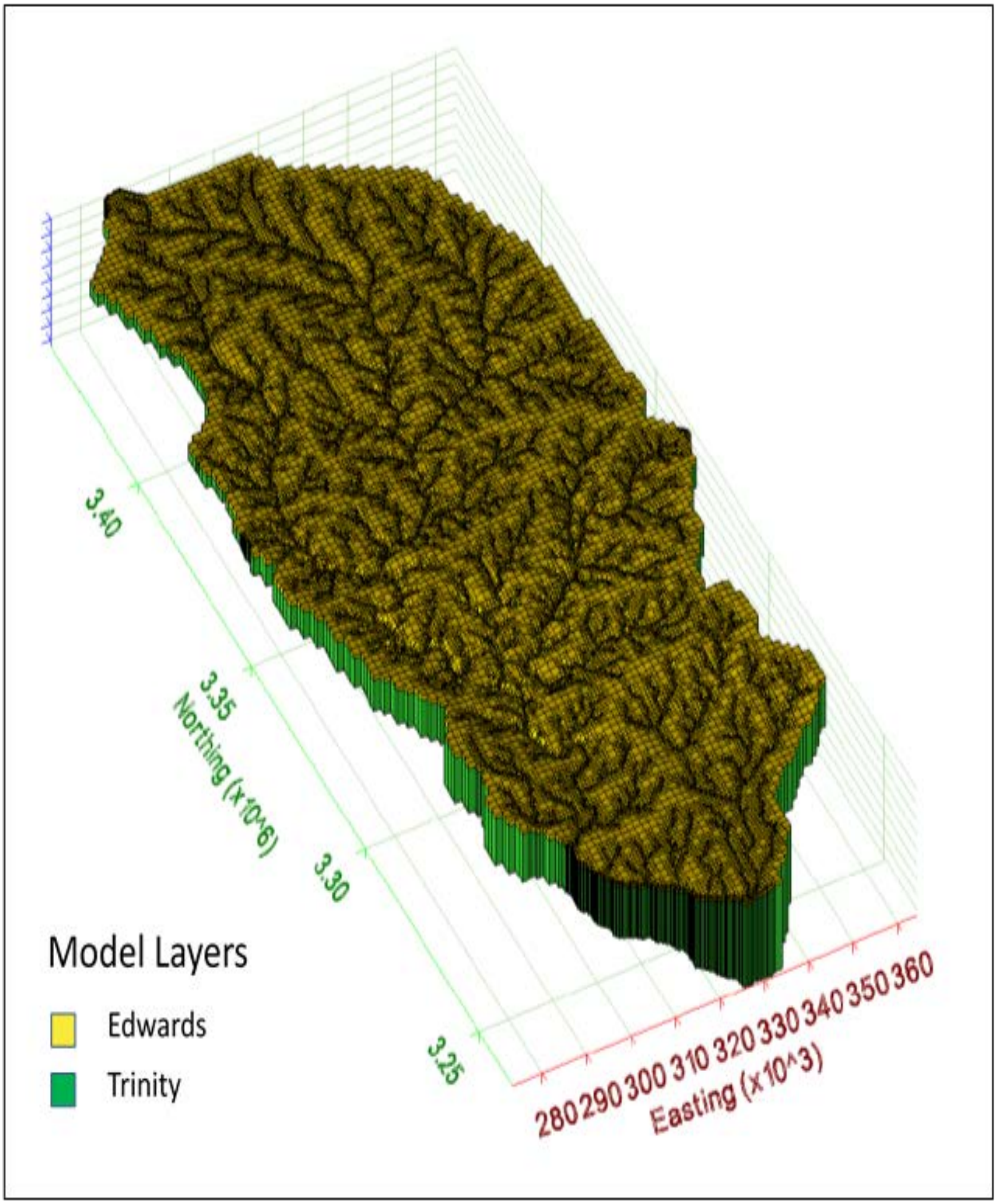

Figure 5-2. Oblique view of the Devils River Watershed model (Toll and others, 2017).

Table 5-1. Aquifer properties in the different groundwater models of the Val Verde County area.

Model	Layer/feature	Hydraulic conductivity, feet per day	Specific yield, dimensionless	Specific storage, per foot	Conductance, feet per day
Devils River Watershed Model (Toll and others, 2017)	Layer 1 – matrix	6.6	1.2×10^{-2}	NA	NA
	Layer 2 – all	3.3	1.2×10^{-2}	1.0×10^{-5}	NA
	Layer 1 conduit (higher order)	3,280	1.0×10^{-4}	NA	32,800
	Layer 1 conduit (lower order)	328	1.0×10^{-4}	NA	32,800
Val Verde County Model (values estimated from figures) (EcoKai and Hutchison, 2014)	Pecos drainage, matrix	7.24	NA	2.9×10^{-6}	NA
	Pecos drainage, channels	104	NA	9.7×10^{-6}	NA
	Devils drainage, matrix	14.1	NA	4.9×10^{-6}	NA
	Devils drainage, channels	110	NA	1.5×10^{-6}	NA
	Sycamore drainage, matrix	148	NA	2.3×10^{-6}	NA
	Sycamore drainage, channels	377	NA	1.0×10^{-7}	NA
Edwards-Trinity (Plateau) GAM (Anaya and Jones, 2009)	Layer 1 – Edwards	6.65	0.005	5×10^{-6}	NA
	Layer 2 – Trinity	2.5	0.003	1×10^{-6}	NA

NA = not applicable

The Val Verde County Model also specifies matrix and conduit values for hydraulic conductivity and specific storage (Table 5-1 and Figures 5-3 and 5-4). The model report does not list any specific yield data and appears to assume all storage is under confined conditions. Storativity is calculated on a cell-by-cell basis as the product of specific storage and aquifer thickness.

The water budget for the Edwards-Trinity (Plateau) Aquifer (Table 5-2), as estimated by the Edwards-Trinity (Plateau) GAM, shows total net discharges from the aquifer of 113,868 acre-feet per year, including 105,844 acre-feet per year to Amistad Reservoir and the springs and streams that drain to the reservoir, plus modeled pumping of 8,024 acre-feet per year. Total net inflow to the aquifer of 114,097 acre-feet per year includes 50,489 acre-feet per year in recharge and 63,608 acre-feet per year in lateral flows from adjacent counties. Most of these flows come into or from the Edwards Aquifer, which accounts for approximately 90 percent of the net inflows and outflows. The water budget for the Val Verde County Model features recharge of just over half the GAM value but finds lateral inflows from adjacent counties totaling more than four times the volume determined in the GAM. The Val Verde County Model balances the increased inflows with larger discharges to springs, streams, and the Rio Grande, which more closely match values determined in this report.

Data presented in this report suggest that some components of the GAM-derived water budget are underestimated. For example, we estimate the median baseflow in the Devils River from 1972 to 2017 at 178,000 acre-feet per year, or more than twice the GAM value for total baseflow to streams. Similarly, the median flow from San Felipe Springs from 1972 to 2011 was over 93,000 acre-feet per year (International Boundary and Water Commission, 2018), while Goodenough Springs discharge to Amistad Reservoir was estimated at nearly 52,000 acre-feet per year based on an August 2005 measurement by a cave dive team (Kamps, Tatum, Gault, and Groeger, 2008). These values are all higher than the GAM estimates and suggest that model calibration could be improved with respect to local conditions.

Table 5-2. Modeled net flows in the Edwards-Trinity (Plateau) Aquifer in Val Verde County, in acre-feet per year. From Anaya and Jones (2009) and EcoKai and Hutchison, 2014.

Val Verde Water Budget (1980 to 2000 averages)	Edwards-Trinity (Plateau) GAM (Anaya and Jones, 2009)	Val Verde County Model (EcoKai and Hutchison, 2014)
Recharge	50,489	26,183
Inflow from adjacent counties	63,608	293,844
Inflow from Amistad	na	26,597
Total inflows	114,097	346,623
Pumping	8,024	2,432
Discharge to springs and streams	85,926	130,591
Baseflow to Rio Grande and Amistad	19,918	90,653
Baseflow to Rio Grande below Amistad	na	123,813
Total outflows	113,868	347,488

Applicability to Groundwater Management

The available groundwater flow models have varying applicability for groundwater management and the appropriateness of one model or another depends on the management issue under consideration. The Edwards-Trinity (Plateau) Aquifer GAM (Anaya and Jones, 2009) is regional in scale. With a one-mile grid cell spacing, annual stress periods, and broadly defined aquifer properties, it is best suited to long-term evaluation of dispersed processes that establish the overall water budget for the region. Examples of applications that are suitable for GAMs include required technical inputs such as groundwater budgets to groundwater management plans. However, GAMs are not intended to represent local resource management decisions and are not appropriate for modeling groundwater behavior around a spring or single well.

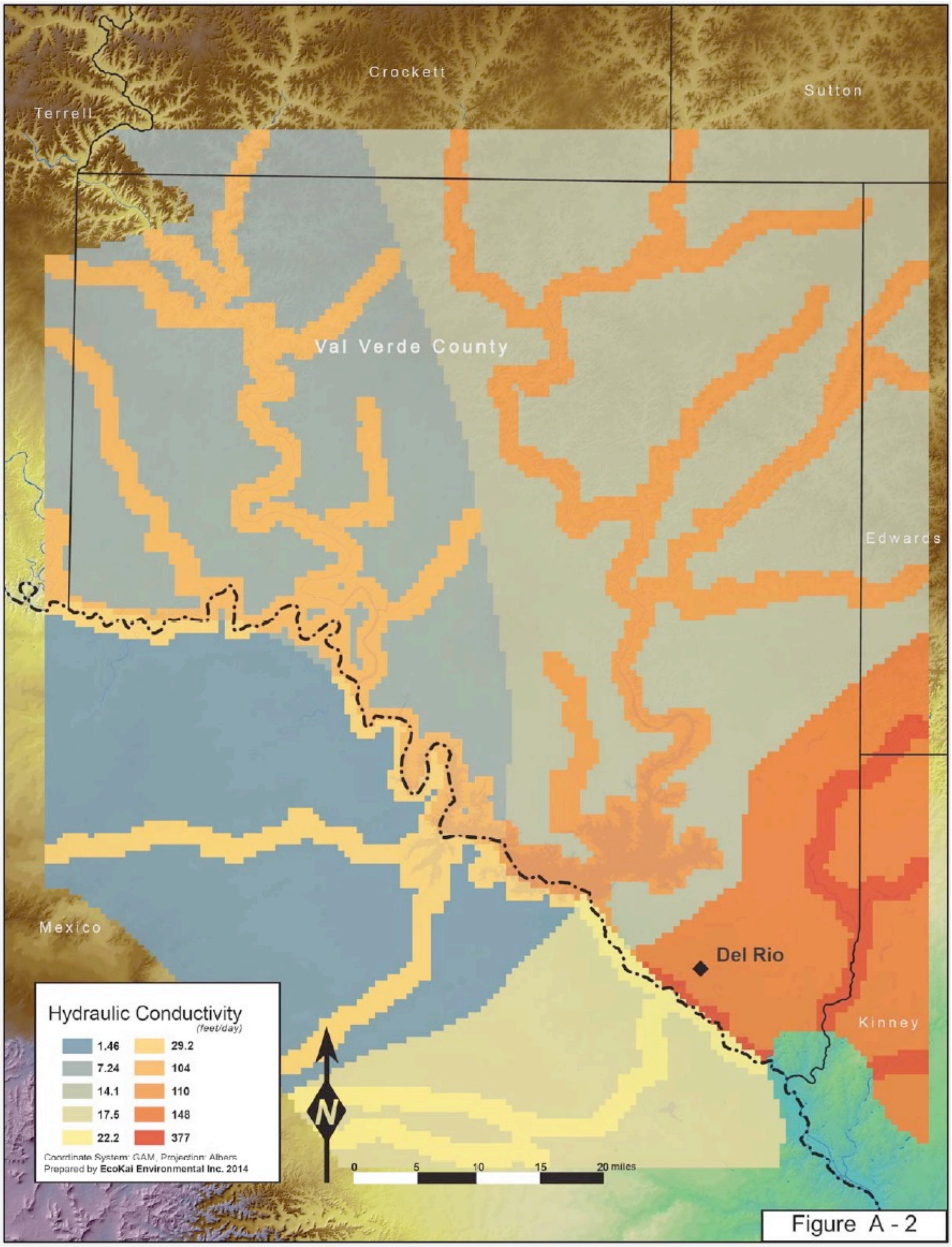

Figure 5-3. Hydraulic conductivity distribution in the calibrated Val Verde County Model, from EcoKai and Hutchison, 2014.

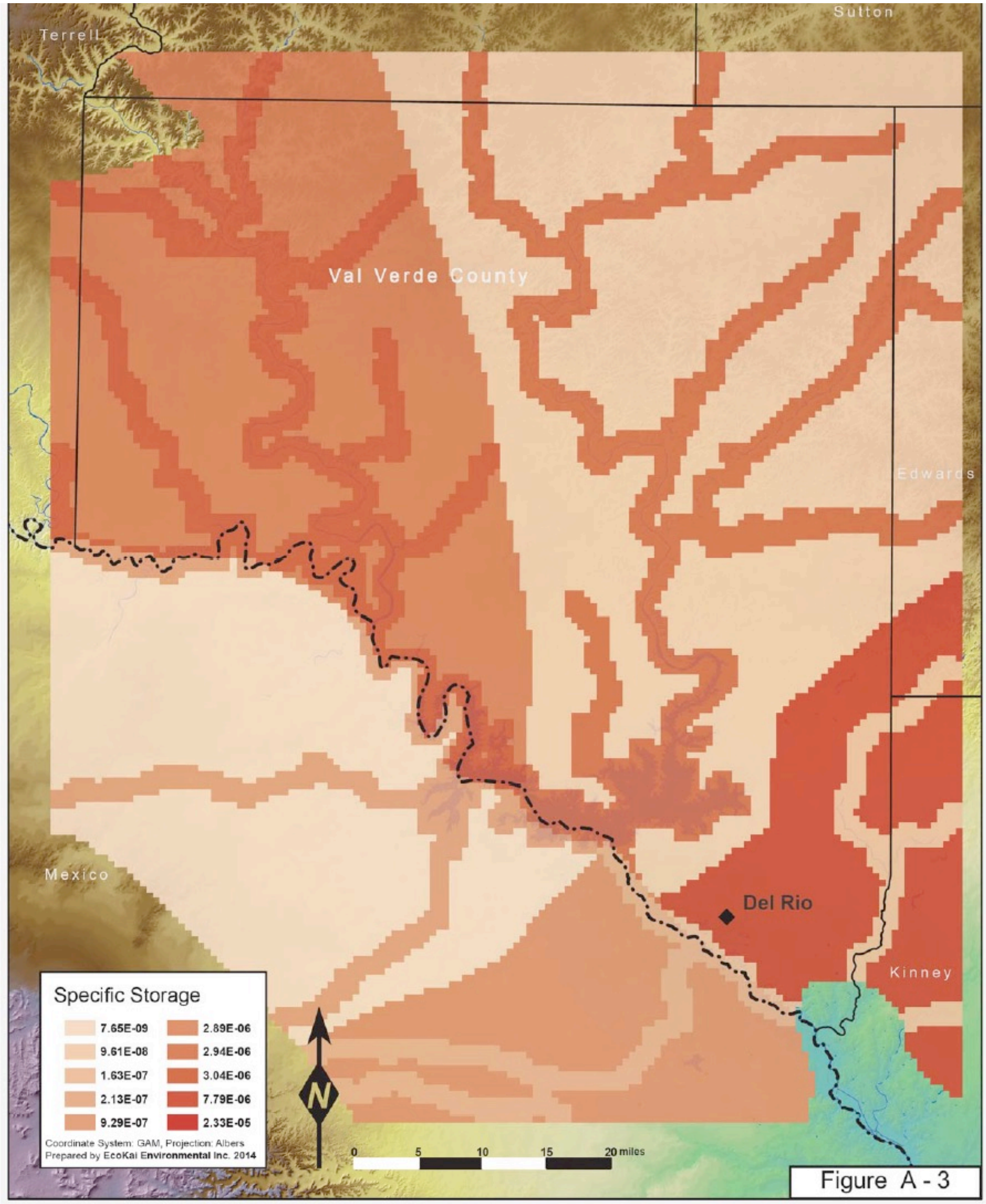

Figure 5-4. Specific storage distribution in the calibrated Val Verde County Model, from EcoKai and Hutchison, 2014.

The Wet Rock (2010b) model runs utilize existing GAM inputs and inherit the general characteristics and limitations of the regional model. Wet Rocks' water resource evaluation for the Weston Ranch (Wet Rock, 2010a) determines a groundwater recharge value more than four times higher than what was used by Anaya and Jones (2010), but their groundwater modeling report (Wet Rock 2010b) implies that the GAM Run 09-035, Scenario 10 (Hutchison, 2010) served as the base case for evaluating the effects of potential pumping at Weston Ranch and makes no mention of revising the recharge values.

The Val Verde County Model is potentially better suited for evaluating groundwater management options in Val Verde than the Edwards-Trinity (Plateau) Aquifer GAM. The refined grid size, monthly time step, more detailed representation of subsurface hydrogeology, inclusion of adjacent areas in Mexico, and model calibration to spring flows all represent improvements over the regional GAM, where adequately supported by new data. Continued refinement of the Val Verde County Model as more data become available probably represents the best path forward for supporting groundwater management objectives in Val Verde County. In particular, the hydraulic conductivity distribution in the model needs more validation with field measurements, and boundary conditions should reflect the separation between watershed basins in the northern half of Val Verde County.

The Devils River Watershed Model represents a very different approach that could be applied on a watershed basis. For example, Figure 5-5 illustrates the application of this model to simulating the behavior of springs in the Devils River watershed to conditions ranging from no pumping to a theoretical high volume (10,000 gallons per minute) well field near Juno. The figure compares a "no pumping" scenario in the left panel, groundwater pumping consistent with that in the Edwards-Trinity (Plateau) Aquifer GAM in upgradient counties in the middle, and the effects of the hypothetical well field on the right panel. This model has many intriguing features, including the explicit linkage between surface runoff processes and groundwater recharge, use of gridded precipitation input, and the grid refinement around high conductance conduit channels. The model does not encompass the whole area of Val Verde County and adds complexity beyond what is supported by the model documentation and the available data. Applying a coupled surface water-groundwater model with permeable conduits to the whole of Val Verde County would require further extrapolation and conjecture given the relative scarcity of data outside the Devils River drainage. While an integrated hydrological model of Val Verde County remains a worthwhile goal, it may not be a practical alternative, pending additional monitoring, data collection, and hydrogeological study.

Data Gaps and Data Needs

Water level measurements are the fundamental record required to assess groundwater resources. The current network of observation wells does not provide adequate spatial or temporal detail over the extent of Val Verde County. Establishing a representative network of at least 25 to 30 wells with known well completion and collecting regular water level measurements would give an appropriate and improved technical basis from which to support future groundwater management. Current observation wells should be logged and evaluated for installation of instrumentation to collect daily water level measurements at suitable wells with suitable completion. Additional observation wells are needed in several parts of the county, including the Pecos River drainage, the Dry Devils River drainage, and some reaches of Dolan and Sycamore creeks. Selected wells in these areas should be equipped with data loggers. Mechanisms to share observation well data with the International Boundary and Water Commission are also being pursued at the TWDB, and active cooperation with the Commission will be essential for future groundwater management in Val Verde County.

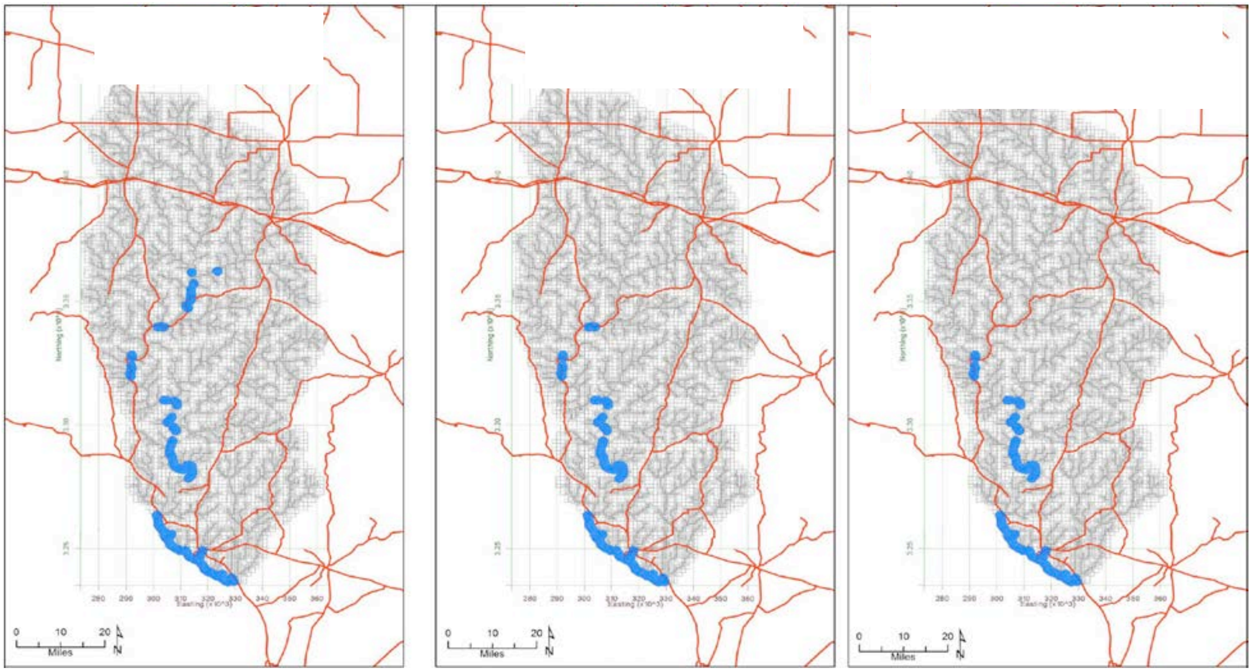

Figure 5-5. Simulation of spring locations (shown in blue) based on various groundwater pumping scenarios (Toll and others, 2017).

Aquifer properties are poorly defined in most of Val Verde County because there are few data on aquifer responses to pumping stresses. These data are needed to estimate critical parameters such as aquifer hydraulic conductivity and storage. Preferably, aquifer tests could be designed and conducted on wells constructed for this purpose and located where data are most needed. Alternatively, data collection from wells near active high-capacity municipal supply or irrigation wells could be used to simulate an aquifer test and estimate these aquifer properties. In addition to aquifer tests, other techniques, such as dye tracers, may be useful for estimating aquifer properties at larger scales.

Better definition of the Trinity Aquifer and how it communicates with the Edwards Aquifer is needed. Current (2018) research on the relationship between the Edwards and Trinity aquifers is focused on the Edwards (Balcones Fault Zone) Aquifer east of Val Verde County and unlikely to provide specific insights to Val Verde County. Data presented in this report suggest that Trinity Aquifer in Val Verde County is largely stagnant and brackish and does not contribute much flow to area springs and streams, but direct measurements of groundwater conditions in the Trinity aquifer unit are lacking.

6.0 Surface Water

Key findings

- Measured flow in the Devils River at Pafford Crossing is influenced by Amistad Reservoir water level and is not a good measure of conditions in the upper, spring-fed reaches of the river.
- Flow measurements at the Devils River Bakers Crossing gage have been inconsistent over time, complicating interpretation of any long-term trends.
- Low-flow gain-loss studies on the Devils River show similar patterns of spring discharge to the river between 1928 and 2006 surveys for the reaches where comparable data are available.

Perennial surface water resources in Val Verde County include the Rio Grande, Amistad Reservoir, Pecos River, Devils River, and San Felipe Creek (Figure 6-1). These surface water features are regional points of discharge for the groundwater system. Annual flows from Goodenough Springs, the Devils River, and San Felipe Springs are estimated to account for approximately 23 percent of the flow in the Rio Grande below Amistad Reservoir (Green, 2013).

Flow in the Rio Grande upstream of Val Verde County comes primarily from the Rio Conchos, which joins the Rio Grande near Presidio, Texas, about 350 river miles upstream. Storage in Amistad Reservoir is allocated to the United States and Mexico under a 1944 Treaty. Texas' share of the U.S. storage is fully allocated. Amistad Reservoir typically operates in tandem with Falcon Reservoir, which is 340 river miles downstream. About 90 percent of the water released from Amistad Reservoir flows through Falcon Reservoir for use in the lower Rio Grande Valley, with the remaining 10 percent going to municipal and agricultural water rights holders between Amistad and Falcon reservoirs (Purchase, Larsen, Flora, and Reber, 2001, TWDB, 2017).

Because the U.S. share of flow in the lower Rio Grande is fully allocated under existing permits, any reduction in flow to the Rio Grande from tributaries in Val Verde County could affect downstream users. Val Verde groundwater is a major component of flow in the Lower Rio Grande. Current groundwater discharge in Val Verde County totals 330,000 acre-feet per year, as noted in the Section 4 discussion of springs, or about 30 percent of the 1.01 million acre-feet U.S. share of the firm annual yield of the Amistad-Falcon reservoir system (U.S. Bureau of Reclamation, 2016). Regional water resources are already under stress. The *2017 State Water Plan* (TWDB, 2017) projects annual water needs (projected shortages) of 708,000 to 797,000 acre-feet between 2020 and 2070. Any reduction in spring discharge will proportionately increase the projected shortages.

The Pecos River flows south from the Southern Rocky Mountains in New Mexico through West Texas and into Amistad Reservoir, draining a watershed of 44,000 square miles. Pecos River water is allocated entirely to the United States. Several reservoirs impound water for irrigation along the Pecos River; one is Red Bluff Reservoir at the Texas-New Mexico state line, completed in 1936. Total annual flow and baseflow at the mouth of the Pecos in Val Verde County generally declined between about 1970 and 2000 (Figure 6-2), which has been attributed to increasing upstream

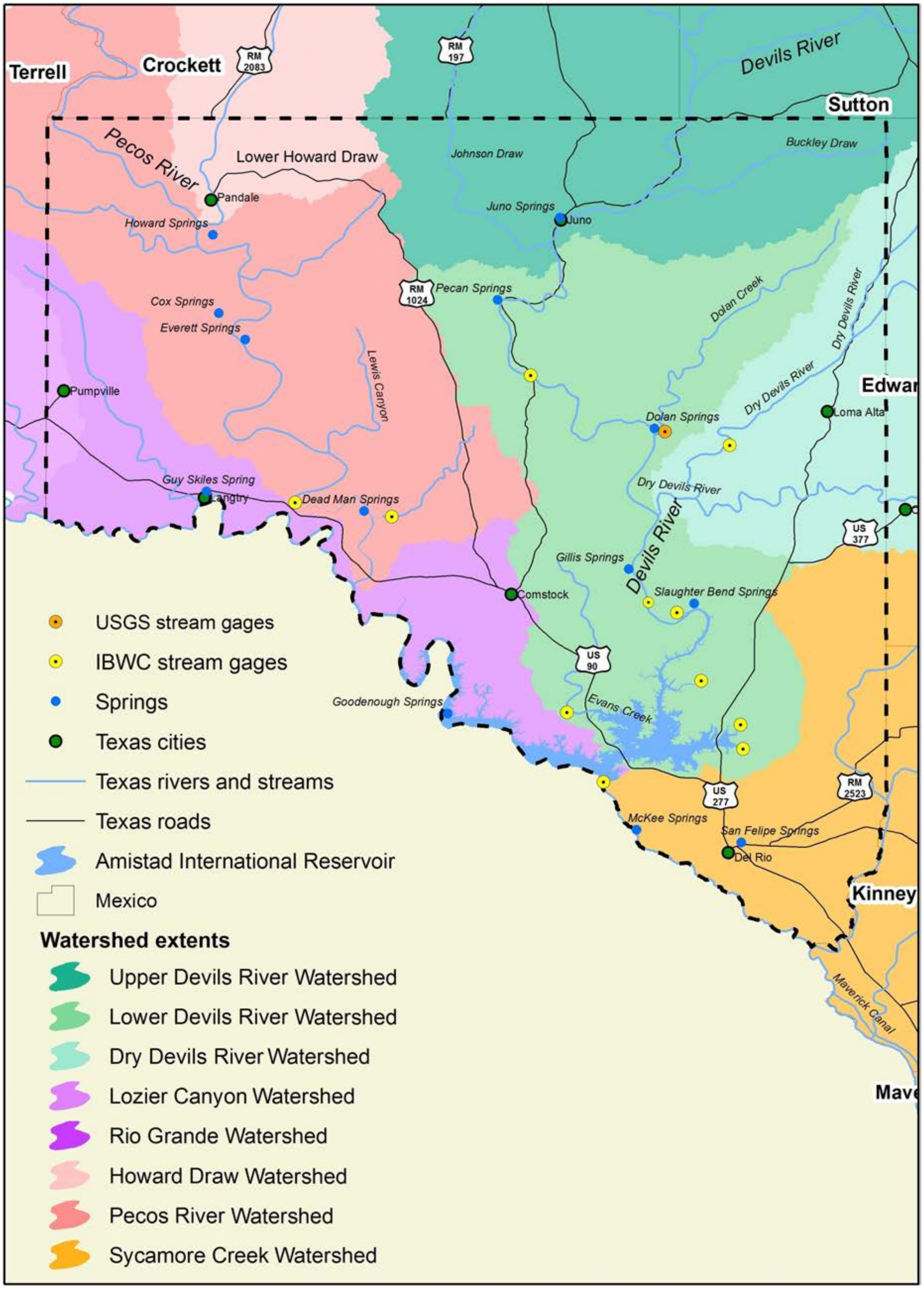

Figure 6-1. Surface water features in Val Verde County. From Toll and others (2017).

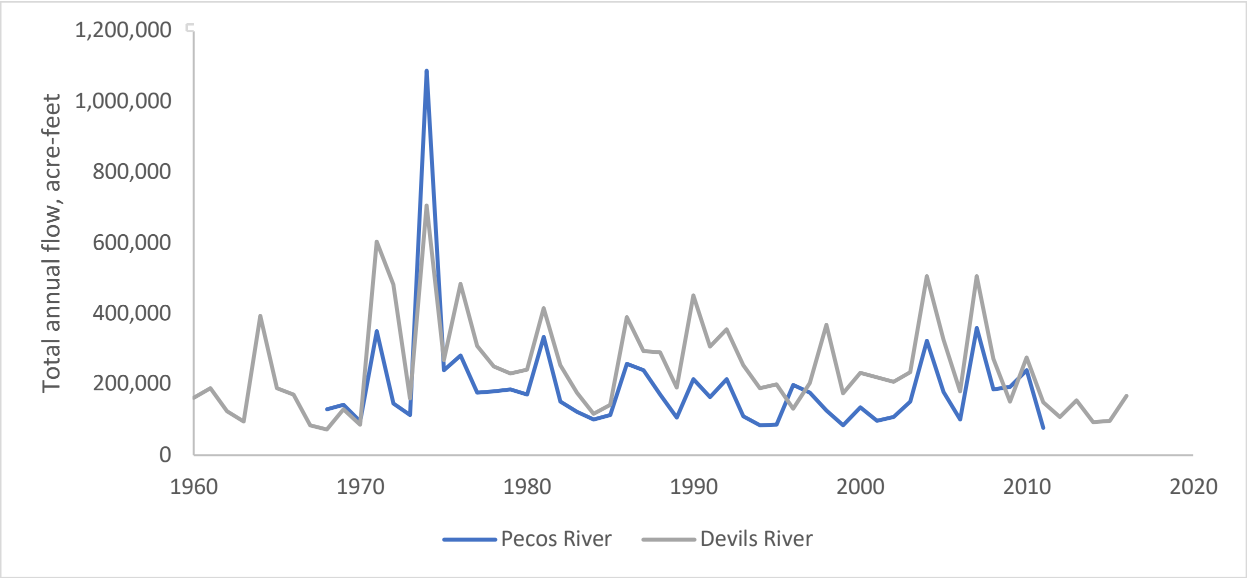

Figure 6-2. Total annual flow of the Devils River, 1960 to 2017, and Pecos River, 1968 to 2011. Data from International Boundary and Water Commission (2018a).

surface and groundwater use (Purchase, Larsen, Flora, and Reber, 2001). For the 30-year period of 1980 to 2010, International Boundary and Water Commission data indicate no significant trend in total flow (International Boundary and Water Commission, 2018). The salinity of the Pecos River water at the Red Bluff Dam, near the New Mexico border, can be as high as 6,000 milligrams per liter because of salts dissolved from deposits in the Delaware Basin (Hart, Jensen, Hatler, and Mecke, 2007). The hydrology and chemistry of the lowermost section of the Pecos River in Val Verde County is determined largely by the consistent fresh flows of Independence Creek, which enters the Pecos in Crockett County (Basnet, Hauck, and Pendergrass, 2013). Streamflow in Independence Creek is maintained by springs draining the Edwards-Trinity (Plateau) Aquifer. The Pecos River contributes an estimated 26 percent of salt loading to Amistad Reservoir while representing only 9.5 percent of the reservoir's total annual inflows (Texas Water Resources Institute, 2010).

The Devils River drains an area of 4,305 square miles. There has been minimal development in the watershed. There are no dams or other control structures on the river and land use in the watershed is primarily ranching, with low-density rural housing. Several stream gaging sites on the Devils River and contributing streams (Figure 6-3) are operated by the USGS and the International Boundary and Water Commission.

Streamflow can increase quickly to peak values exceeding 100,000 cubic feet per second in response to large rainstorms. The estimated peak flow at Pafford Crossing during the June 1954 flood was 393,000 cubic feet per second, eclipsing the previous record of 370,000 cubic feet per second set during the flood of September 1932 (Breeding, 1954). Base flow, representing flow between storm events, from springs above Pafford Crossing averages from 100 to 500 cubic feet per second. Streamflow in the Devils River typically decreases quickly following storm events, indicating minimal bed and bank storage (Figure 6-4).

Streamflow at the Pafford Crossing gage on the Devils River is influenced by Amistad Reservoir, and base flow increased after the reservoir filled. When the dam was completed in 1969 and the reservoir filled over the next few years, groundwater levels rose in the area within about 10 miles of the reservoir. The increased water levels resulted in increased spring flow, and consequent increases in streamflow at locations near the reservoir. Because Amistad is a flood control reservoir and does not maintain a near-constant surface elevation, reservoir level changes since 1970 continue to affect measured streamflow at the Pafford Crossing gage and complicate any trend analysis for this location. While streamflow measurements have a declining trend between 1972 and 2017 (Figure 6-5), this may have more to do with the extended periods of drawdown in Amistad Reservoir in the 1990s and 2010s than with changes in the groundwater system feeding the Devils River.

We computed baseflow using the baseflow index method (Wahl and Wahl, 1985) using five-day minimum flows to assess turning points in the hydrograph. In practice, the baseflow index method assigns most flow in the Devils River to baseflow, with only brief periods of stormflow following precipitation events. We find that the baseflow index is a more accurate depiction of baseflow in the karst environment of Val Verde County than baseflow separation techniques using recursive digital filters, as proposed by Eckhardt (2004) or Nathan and McMahon (1990). These baseflow separation algorithms assign a smaller fraction of total flow to baseflow when using commonly accepted input values. The infrequent nature of storm events in West Texas and the limited bed and bank storage available along the Devils River imply that most flow in this river should be classified as baseflow. Baseflow separation using water quality data might help distinguish direct runoff, conduit, and matrix flow components (Miller, Johnson, Susong, and Wolock, 2015), but such information is not currently available.

We evaluated trends in both average annual baseflow and total annual discharge between 1972 and 2017 in daily gage data reported by the International Boundary and Water Commission (IBWC) (2018a) using the non-parametric Mann-Kendall trend test (Salmi, Maatta, Anttila, Ruoho-Airola, and Amnell, 2002). Both total discharge and average baseflow have a decreasing trend that is significant at the 99 percent confidence level for the years from 1972 through 2016, the last complete year of record available. The significance of the trends is largely based on high flows recorded at the beginning of the period in 1974 and low flows recorded at the end of the period during the 2011 to 2014 drought. The Mann-Kendall test indicated no significant trends in either total discharge or average baseflow for the period from 1975 to 2011.

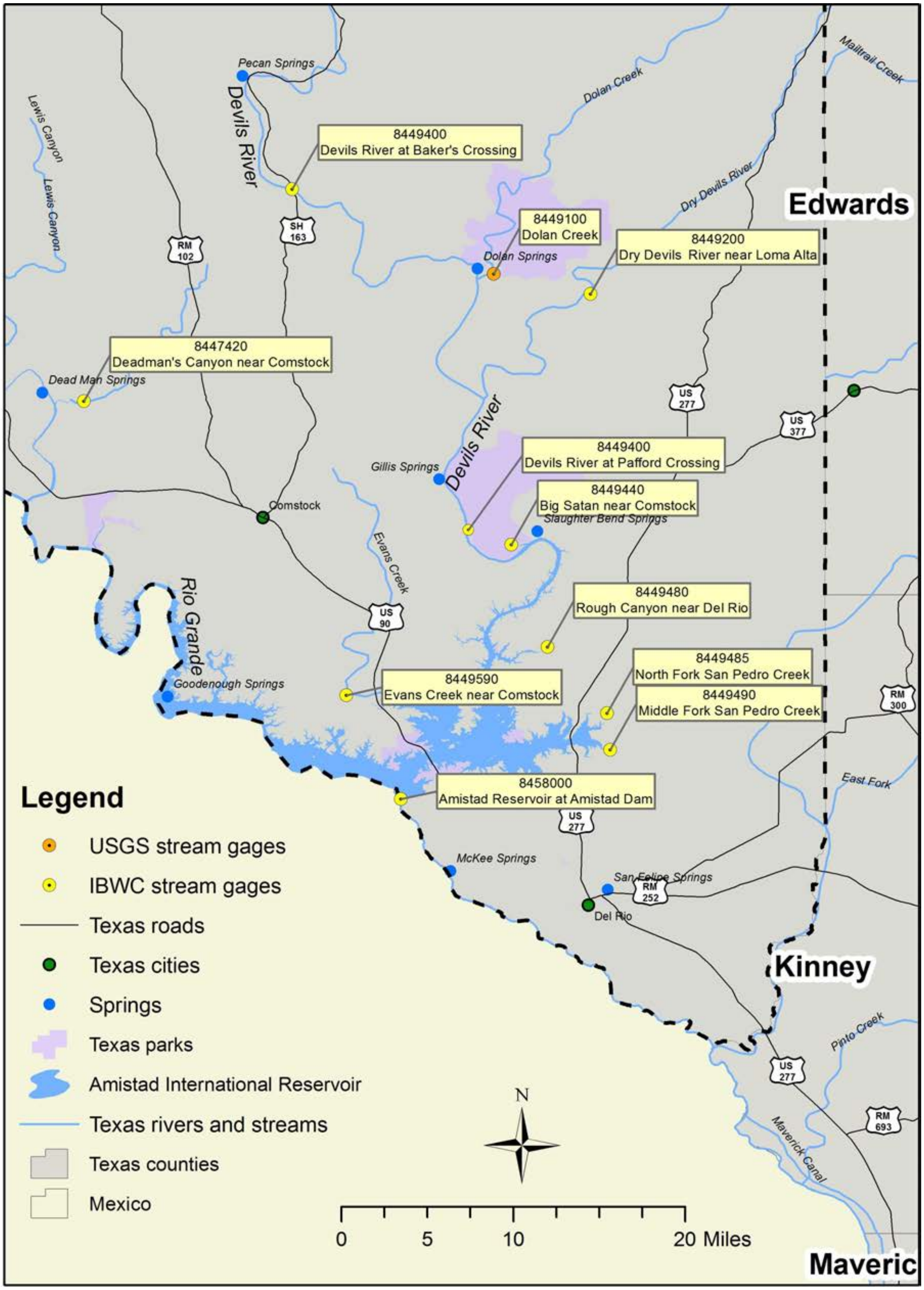

Figure 6-3. Locations of stream gages in the Devils River and adjacent watersheds (adapted from Toll and others, 2017)

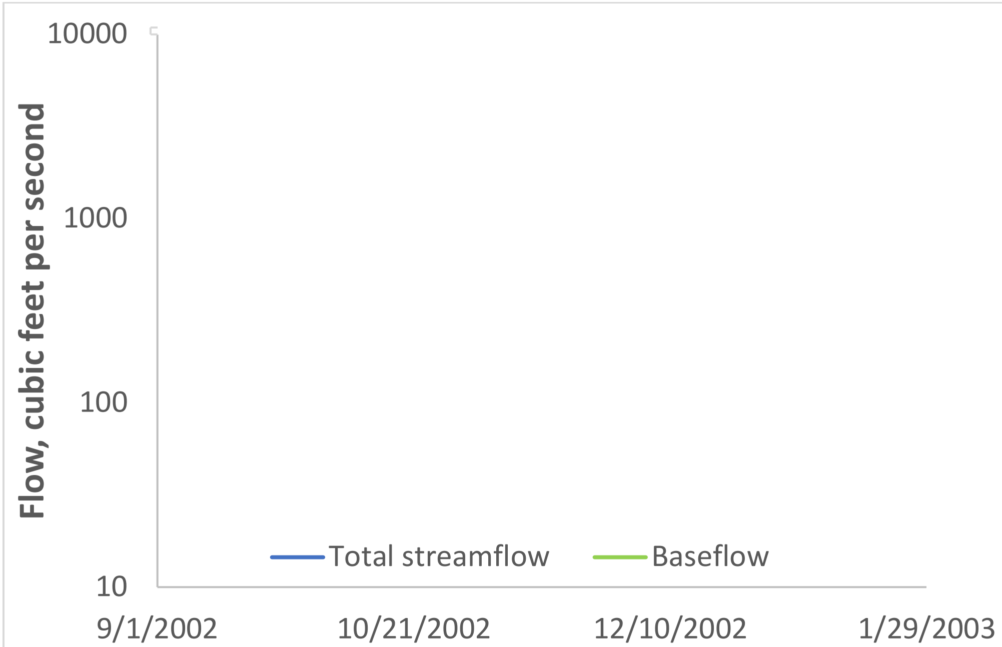

Figure 6-4. Comparison of total streamflow and baseflow at the Devils River Pafford Crossing gage during 2002 storm events.

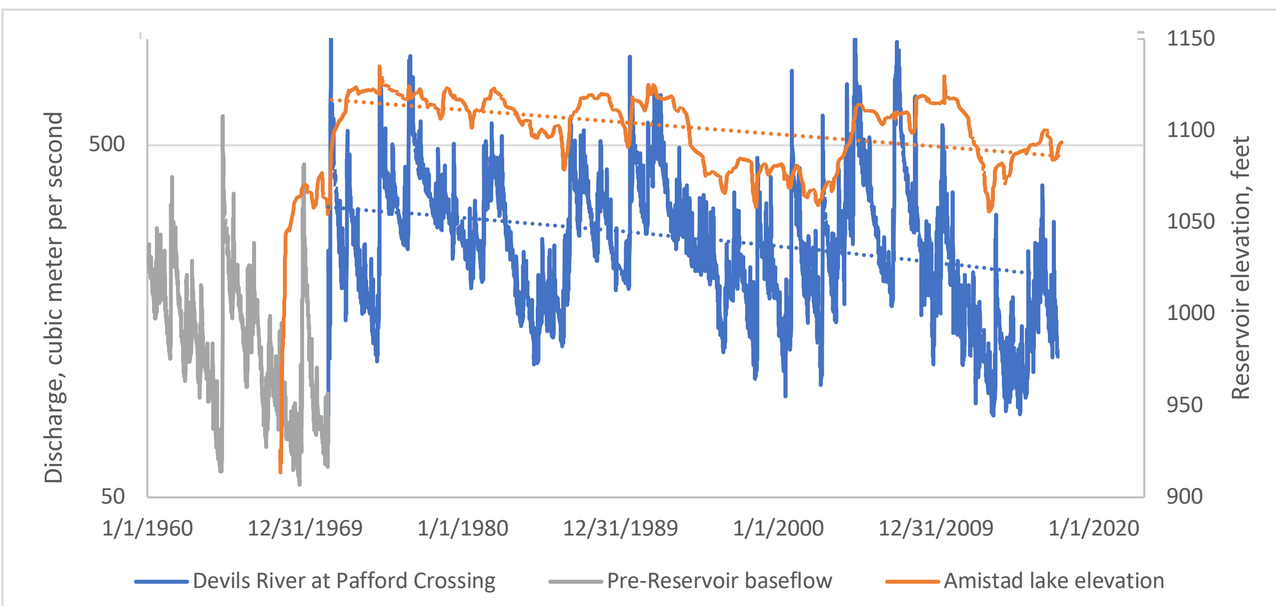

Figure 6-5. Comparison of Amistad Reservoir surface elevation and Devils River baseflow measured at Pafford Crossing. Decadal trends in stream baseflow mimic variability in reservoir elevation. Linear trend lines for baseflow and reservoir elevation are shown as dotted lines. Data from International Boundary and Water Commission, 2018.

The Bakers Crossing gage location is outside the Amistad Reservoir area of influence and potentially provides a better measurement point for assessing long-term trends in flow on the Devils River. The U.S. Geological Survey collected streamflow measurements at Bakers Crossing during two periods, from 1925 to 1949 and from 1963 to 1973 (U.S. Geological Survey, 2018a), and the International Boundary and Water Commission has collected unpublished measurements from 2004 to present (Smith, 2018).

Unfortunately, flow measurements for this site are missing from 1949 to 1963 and from 1973 to 2004. Figure 6-6 shows stream baseflow for the Bakers Crossing and Pafford Crossing sites. Although incomplete, the Bakers Crossing data indicate a change in median flow from 88 cubic feet per second for the period from 1925 through 1949 to 41 cubic feet per second for the period from 1963 to 1973. Flooding and stream channel changes on the Devils River, associated with extreme rainfall from Hurricane Alice in June 1954 may have affected subsequent measurements at this site. No groundwater level data are available for wells in the vicinity prior to 1955, so it is difficult to evaluate potential changes in hydrogeological conditions between the measurement periods of 1925 to 1949 and 1963 to 1973.

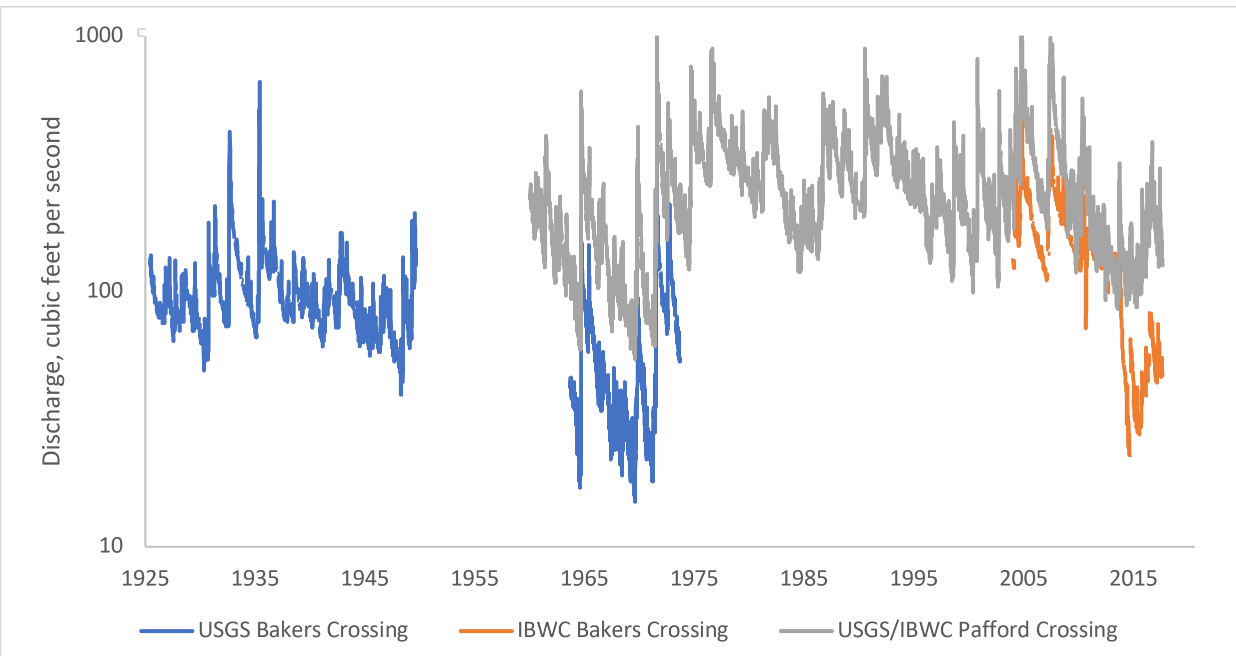

Figure 6-6. Baseflow at the Bakers Crossing and Pafford Crossing gages on the Devils River. Data from International Boundary and Water Commission, 2018.

The International Boundary and Water Commission resumed measurements at the Bakers Crossing site in 2004. Measurements between 2004 and 2013 are anomalous. Median baseflow for 2004 through October 2013 is 153 cubic feet per second, well above the median for either preceding period, then falls abruptly starting in November 2013. Median baseflow for the period from November 2013 through September 2017 is 47 cubic feet per second. The 2004 to 2013 baseflow is nearly equal to the flow measured at Pafford Crossing, while earlier and later measurements indicate significant streamflow gain between the two gaging stations, consistent with the known spring discharge in the intervening river reach. International Boundary and Water Commission field discharge measurements, started in 2013, confirm gaged measurements from 2013 to 2017. The measurements from 2004 to 2013 appear to be biased high.

The TCEQ adopted environmental flow standards for the Pecos River and Devils Rivers in February 2014 (Tables 6-1 and 6-2). The adopted environmental flow standards apply to new appropriations of water. It is extremely unlikely that any new appropriations could be granted in Val Verde County. The environmental flow standards support a sound ecological environment through a schedule of flow quantities at defined measurement points. Minimum flows and the number of pulses vary by season and by year, depending on whether the rivers are in subsistence, dry, average, or wet hydrologic conditions (TCEQ, 2014). Hydrological conditions are determined by calculating the 12-month cumulative antecedent flow for each season for the period of record for the measurement point and then calculating the specific 12-month cumulative antecedent flow that would occur 10 percent of the time (Subsistence Condition), 15 percent of the time (Dry Condition), 50 percent of the time (Average Condition) and 25 percent of the time (Wet Condition)(TWDB, 2014)). In any given season, the hydrologic condition would be determined by comparing the actual 12-month antecedent flow value to the calculated values.

The TCEQ adopted environment flow standards for USGS Gage 08446500, Pecos River near Girvin, Texas, and for International Boundary Water Commission Gage 08-4494.00, Devils River at Pafford Crossing near Comstock. The adopted standards would apply to any new appropriation in the Pecos and Devils river watersheds. It is extremely unlikely that a new appropriation of water, to which the adopted environmental flow standards apply, could be granted in the Pecos or Devils river watersheds. As a result, the environmental flow standards for the Pecos and Devils rivers are unlikely to have any practical impact on groundwater management in Val Verde County.

Table 6-1. Environmental flow standards for the Pecos River near Girvin, Texas (USGS Gage 08446500) specified by 30 TAC §298.530(3).

Season	Hydrologic condition	Subsistence flow, cfs	Base flow cfs	Seasonal pulse (1 per season)
Winter	Subsistence	8.7	22	NA
Winter	Dry	N/A	22	
Winter	Average	N/A	27	
Winter	Wet	N/A	32	
Spring	Subsistence	6.8	14	Trigger: 72 cfs Volume: 1,199 af Duration: 6 days
Spring	Dry	N/A	14	
Spring	Average	N/A	19	
Spring	Wet	N/A	25	
Fall	Subsistence	6.3	13	Trigger: 100 cfs Volume: 1,419 af Duration: 7 days
Fall	Dry	N/A	13	
Fall	Average	N/A	18	
Fall	Wet	N/A	27	

cfs = cubic feet per second; af = acre-feet; NA = not applicable

Table 6-2. Environmental flow standards for the Devils River at Pafford Crossing near Comstock (International Boundary and Water Commission Gage 08-4494.00), as specified under specified under 30 TAC §298.530(4).

<table>
<tr><th>Season</th><th>Hydrologic condition</th><th>Subsistence</th><th>Baseflow, cfs</th><th>Seasonal pulse (1 per season)</th><th>Annual pulse (1 per year)</th></tr>
<tr><td>Winter</td><td>Subsistence</td><td>84</td><td>175</td><td rowspan="4">NA</td><td rowspan="12">Trigger: 3,673 cfs
Volume: 34,752 af
Duration: 13 days</td></tr>
<tr><td>Winter</td><td>Dry</td><td>NA</td><td>175</td></tr>
<tr><td>Winter</td><td>Average</td><td>NA</td><td>200</td></tr>
<tr><td>Winter</td><td>Wet</td><td>NA</td><td>243</td></tr>
<tr><td>Spring</td><td>Subsistence</td><td>91</td><td>160</td><td rowspan="4">Trigger: 558 cfs
Volume: 17,374 af
Duration: 7 days</td></tr>
<tr><td>Spring</td><td>Dry</td><td>NA</td><td>160</td></tr>
<tr><td>Spring</td><td>Average</td><td>NA</td><td>207</td></tr>
<tr><td>Spring</td><td>Wet</td><td>NA</td><td>253</td></tr>
<tr><td>Fall</td><td>Subsistence</td><td>87</td><td>166</td><td rowspan="4">Trigger: 1,872 cfs
Volume: 27,781 af
Duration: 9 days</td></tr>
<tr><td>Fall</td><td>Dry</td><td>NA</td><td>166</td></tr>
<tr><td>Fall</td><td>Average</td><td>NA</td><td>206</td></tr>
<tr><td>Fall</td><td>Wet</td><td>NA</td><td>238</td></tr>
</table>

cfs = cubic feet per second; af = acre-feet; NA = not applicable

Streamflow Gain-Loss Studies

The Texas Board of Water Engineers (1960) reported data from several low-flow streamflow studies on the Devils River conducted in the 1920s. The TCEQ conducted another streamflow study in 2006. Data from the 1921, 1925, 1928, and 2006 studies (Figure 6-7 and Appendix A) show very similar patterns of spring-flow contribution to the Devils River between Beaver Lake (mile zero) and Pafford Crossing (aka Rubboard Crossing, at mile 53.7). Amistad Reservoir now fills the Devils River stream channel starting just below Pafford Crossing so we cannot compare current conditions in the lower portion of the river with measurements from before the reservoir was constructed.

The August 1925 study covered the entire length of the Devils River from Beaver Lake to the Rio Grande. It found three major areas of groundwater discharge to the river: the reach between Pecan Springs and Bakers Crossing; the 4-mile reach above Dolan Creek; and a 7-mile reach just below Pafford Crossing. It found 1.6 cubic feet per second flow in the Devils River just below Beaver Lake, but this water infiltrated the stream bed within 0.2 miles. There was no flow in the river for the next 13.8 miles down the stream bed, until just below Pecan Springs (Texas Board of Water Engineers, 1960). Another gain-loss study conducted in February 1928 found somewhat lower flows overall, but found streamflow gains in the same river reaches, with minimal gain between these areas of groundwater discharge.

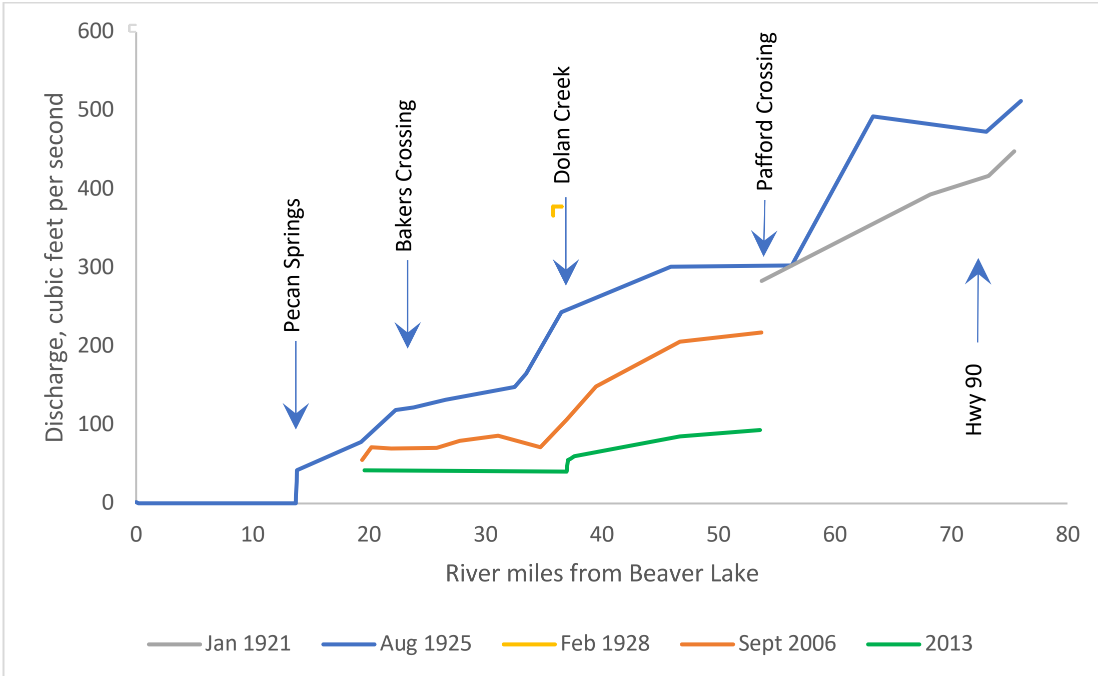

Figure 6-7. Summary of streamflow gain-loss studies of the Devils River. Sources: Texas Board of Water Engineers, 1960; TCEQ, 2006; and Green, Fratesi, Toll, and Nunu, 2017.

The TCEQ surface water quality monitoring group also conducted a gain-loss study of the Devils River in September 2006 (Figure 6-8). The data from the 2006 study are similar to the 1928 results for the 17.3 river miles where they overlap. While the similarities between these points in time measurements do not demonstrate that river flow today is identical to what is was 90 years ago, they do suggest that the overall patterns of groundwater-surface water interaction in this reach of the river remain essentially unchanged. Finally, a 2013 gain-loss study by Bennett, Gary, Green, and Urbanczyk, conducted during the 2011 to 2014 drought (cited in Green, Fratesi, Toll, and Nunu, 2017), found lower flow in the river overall and smaller gains in flow between Dolan Creek and Pafford Crossing.

Data from the International Boundary and Water Commission gage at Bakers Crossing do not match the 2006 or 2013 gain-loss measurements. The gaged flow of the Devils River at Bakers Crossing was 132 cubic feet per second on September 28, 2006, compared with the TCEQ measurement of 69.6 cubic feet per second at their flow point #6 that was taken at approximately the same time. The undated measurement by Bennett and others of 40.2 cubic feet per second just upstream of Bakers Crossing is significantly lower than the minimum flow measured by the International Boundary and Water Commission in 2013.

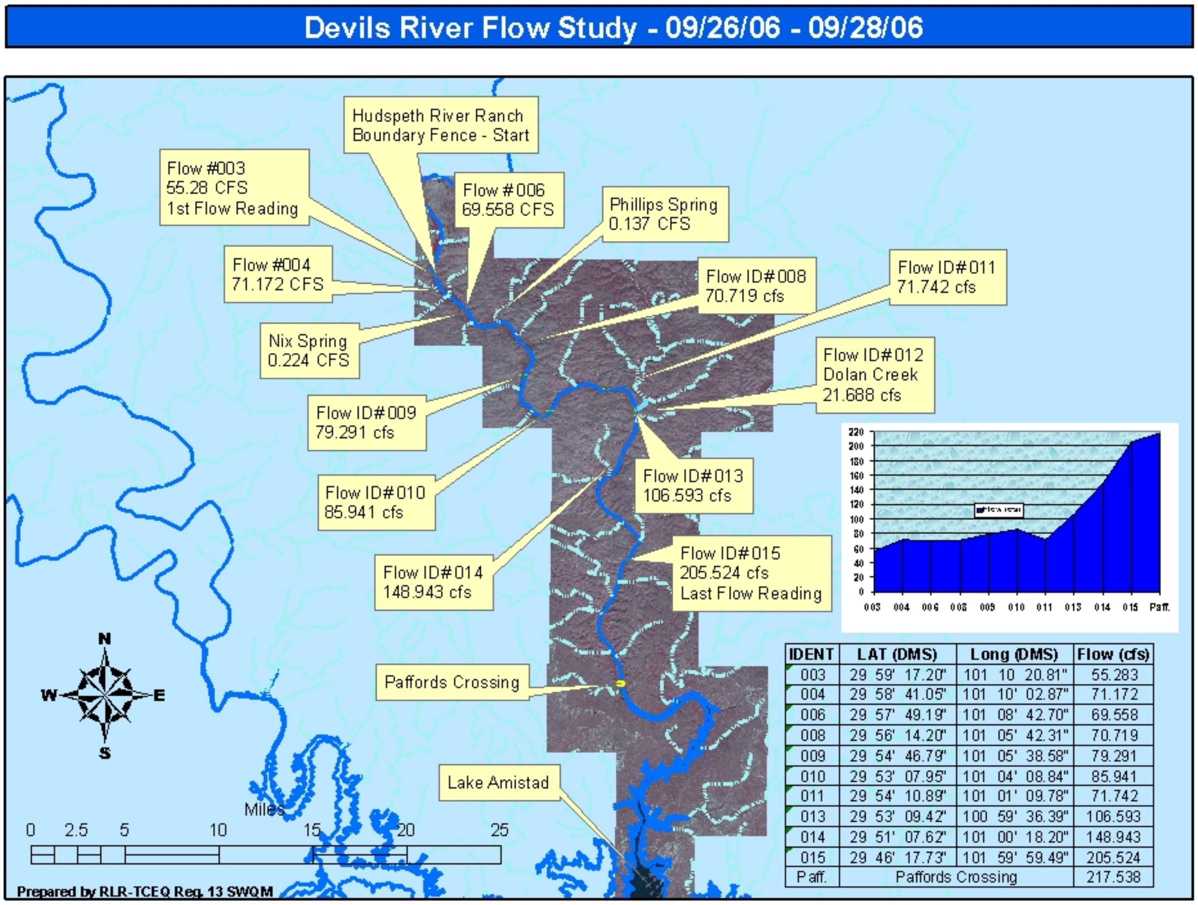

Figure 6-8. TCEQ streamflow measurements on the Devils River, September 2006.

7.0 Water Supplies and Demands

Key findings

- Estimated existing groundwater supplies in Val Verde County exceed the projected demand through 2070, except for small projected needs associated with oil exploration and production.
- Past groundwater use and pumping data are inconsistent and incomplete. A better accounting system is needed if more active groundwater management is planned.
- We estimate that groundwater pumping for all uses in Val Verde County has averaged about 4,700 acre-feet per year since 2001 and has increased from about 2,200 acre-feet per year in the 1980s and 3,000 acre-feet per year in the 1990s.

Supply and Demands

The short- and long-term water supplies and water demands for Val Verde County are described in the 2016 Plateau Region water plan (Ashworth, Herrera, and Brown, 2016). Val Verde County is expected to grow from a projected 2020 population of 54,694 to 82,161 by 2070, an increase of 50 percent over the 50-year planning period, leading to increased water demand.

The Plateau Region water plan (Ashworth, Herrera, and Brown, 2016) shows existing groundwater supplies from the Edwards Trinity (Plateau) Aquifer remaining constant from 2020 through 2070 at 24,988 acre-feet per year and the total water supply, including surface water from the Rio Grande, at 37,266 acre-feet per year throughout the planning period. Modeled available groundwater supplies based on the desired future conditions adopted in 2018 increase to 50,000 acre-feet throughout the planning period.

Water demand in Val Verde County increases from 16,777 acre-feet per year in 2020 to 21,127 acre-feet per year in 2070, an increase of 26 percent (Table 7-1). Demand growth is primarily from the City of Del Rio, Laughlin Air Force Base, and County-other water user groups, while mining, livestock, and irrigation water uses are projected to be stable or decreasing from 2020 through 2070 (Ashworth, Herrera, and Brown, 2016). While the total projected demand remains less than the projected groundwater supply throughout the 50-year planning period, the regional planning group identifies unmet water needs in the mining sector between 2020 and 2060, despite surpluses for other water user groups (Table 7-2).

Water use and pumping

To date, groundwater development in Val Verde County and surrounding areas has been limited in scope and pumping volumes remain small. Most wells are used for ranch supply and livestock. Submitted Drillers Reports since about 2005 indicate that additional high-capacity irrigation wells have been constructed recently but reported irrigation water usage has not increased. Aerial imagery suggests that most of the wells have not been used in the last 10 years.

Table 7-1. Val Verde County water user group demand projections, 2020 to 2070, in acre-feet per year.

	2020	2030	2040	2050	2060	2070
Del Rio	10,645	11,144	11,649	12,229	12,837	13,435
Laughlin AFB	1,012	1,107	1,208	1,269	1,268	1,268
County-other*	1,937	2,267	2,596	2,959	3,331	3,694
Mining	190	249	259	223	192	171
Livestock	533	533	533	533	533	533
Irrigation	2,460	2,364	2,274	2,185	2,101	2,026
Total	16,777	17,664	18,519	19,398	20,262	21,127

*County-other refers to residential, commercial, and institutional water users in cities with less than 500 people or to utilities that provide less than 250,000 gallons of water per day.

Table 7-2. Val Verde County water surplus/needs, 2020 to 2070, in acre-feet per year.

	2020	2030	2040	2050	2060	2070
Del Rio	16,255	15,756	15,251	14,671	14,063	13,465
Laughlin AFB	1,287	1,192	1,091	1,030	1,031	1,031
County-other*	2,576	2,246	1,917	1,554	1,182	819
Mining	-4	-63	-73	-37	-6	15
Livestock	0	0	0	0	0	0
Irrigation	335	431	521	610	694	769
Total	22,469	21,592	20,747	19,878	19,024	18,169

*County-other refers to residential, commercial, and institutional water users in cities with less than 500 people or to utilities that provide less than 250,000 gallons of water per day.

Different investigators have come up with different historical use figures for Val Verde County. Differing estimates of historical use can impact model predictions of the effects of future pumping. The fact that different models cover different areas of interest and use different calibration time periods makes it difficult to directly compare these effects. Given the small total volumes of groundwater involved, these differences are probably not very significant, but better processes for collecting groundwater use data may be more important as groundwater use increases. The pumping estimates from previous models and revised estimates calculated as described in the following paragraphs are listed in Table 7-3.

Table 7-3. Water use estimates in various groundwater models, in acre-feet per year.

Model	1969-1980	1980s	1990s	2000s
Val Verde County	1,167	2,445	2,419	5,754
Devils River Watershed			14,000	14,000
GAM, Val Verde County		4,728	8,401	7,326
This report		2,195	3,046	4,683

Total groundwater volumes used in Val Verde County from 2000 through 2014, as listed in the TWDB historical water use estimates, are shown in Table 7-4. As noted by Eco-Kai and Hutchison (2014), data for 2007 through 2009 municipal use appear to have been switched from groundwater to surface water; in Table 7-4, municipal use is labeled as groundwater for all years. Municipal use remains anomalously low for 2007 through 2009.

The Val Verde County model (Eco-Kai and Hutchison, 2014) also notes that Del Rio's water supply from San Felipe Springs does not represent any additional pumping stress on the aquifer beyond the natural discharge from the springs, which is separately accounted for in the groundwater model water balance. The city has two water supply wells that may be used to supplement spring flow for future water supplies, but these are not currently in use (City of Del Rio, 2016). We estimated municipal pumping by subtracting Del Rio water production data from TWDB municipal water use estimates. For the years in which Del Rio production data were not available, we estimated it based on the average ratio of Del Rio production to total municipal use from 2000 to 2013, excepting the years 2000 and 2007 to 2009, which had suspect statistics. We estimated municipal groundwater pumping for these years as 25 percent of the countywide reported municipal use, to reflect the approximate volume of groundwater pumped by municipal users other than the City of Del Rio. Updated values for municipal pumping and other categories of water use are listed in Table 7-5.

Irrigation use of groundwater in Val Verde County is reported inconsistently and does not appear to reflect recent increases in irrigated acreage in the upper Devils River area and along the Sycamore Creek drainage north of Del Rio. Despite recent growth, groundwater use for irrigation remains restricted to limited areas in Val Verde County, covering a total of about 1,110 acres.

Historical imagery from Google Earth shows that the irrigated area along the Devils River upstream from Juno doubled from 150 to 300 acres sometime between October 2008 and November 2009, while the reported irrigation usage of groundwater was zero for 2009. Google Earth historical imagery also shows that a total of seven center-pivot systems were installed on the Weston Ranch, 11 miles northeast of Del Rio, between 2004 and 2005, covering an area of almost 800 acres. Google Earth imagery shows active irrigation in 2005, 2006, and 2008, while reported groundwater use for irrigation in Val Verde County was 18 acre-feet in 2008.

Images acquired by the National Agricultural Imagery Program in 2008, 2010, 2012, 2014, 2015, and 2016 indicate some degree of irrigation under the Weston Ranch center-pivots each year (Figure 7-1), although the National Agricultural Statistics Service Crop Scape cropland data layer does not consistently identify crop type or irrigated area for these fields, most likely because of the poor condition of the vegetation under the pivots. Crop production in Val Verde County requires at least one acre-foot of irrigation water per acre of land over the growing season. Based on the estimated center-pivot areas, annual groundwater use for irrigation probably increased to around 900 acre-feet per year for 2005 through 2010, but subsequently declined to approximately 750 acre-feet per year from 2011 to 2016.

Table 7-4. TWDB historical groundwater use estimates for Val Verde County, 2000 through 2015, acre-feet per year.

Year	Municipal	Mining	Irrigation	Livestock	Total non-municipal	Total
2000	14,455	0	270	614	884	15,339
2001	14,457	0	316	618	934	15,391
2002	14,471	0	322	550	872	15,343
2003	15,015	0	230	472	702	15,717
2004	15,049	0	107	426	533	15,582
2005	15,130	0	146	490	636	15,766
2006	11,365	0	150	472	622	11,987
2007	7,312	0	34	415	449	7,761
2008	8,867	9	18	506	533	9,400
2009	9,144	23	0	496	519	9,663
2010	11,537	37	276	466	779	12,316
2011	13,280	9	143	467	619	13,899
2012	12,933	0	67	414	481	13,414
2013	11,663	0	4	334	338	12,001
2014	10,850	0	21	268	289	11,139
2015	9,202	0	59	270	329	9,531

The mining and manufacturing sector, which includes oil and gas production, uses a relatively small volume of groundwater in Val Verde County, although it also appears to under-report water use for most years. Toll and others (2017) states that the average annual extraction of groundwater in the Devils River watershed is not well constrained due to un-metered wells and un-reported water pumping by the oil and gas industry. We estimated groundwater use by the oil and gas industry using data from Wood Mackenzie (2016) on the average water use per well during the first decade of the hydraulic fracturing boom between 2005 and 2015 (Figure 7-2), and the annual number of drilling permits issued in Val Verde County (Figure 7-3) by the Texas Railroad Commission (2018). The volume of water used per well for directional drilling and hydraulic fracturing has increased sharply as the technology has evolved. Water use per well in the Midland Basin increased from a few hundred thousand gallons per well in 2006 (~1 acre-foot per well) to nearly 12 million gallons per well (36 acre-feet per well) in 2015 (Wood Mackenzie, 2016). Water use per hydraulic fracturing well decreased after around 2013, as producers seek to recycle more of the produced water (Driver and Wade, 2013; Scanlon, Reedy, and Nicot, 2014).

Table 7-5. Revised groundwater pumping estimates for Val Verde County, acre-feet per year. Adapted from multiple sources, as described in text.

Year	Municipal	Mining, oil, and gas	Irrigation	Domestic and Livestock	Total
2000	3,764	38	270	614	4,686
2001	2,291	54	316	618	3,279
2002	3,907	21	322	550	4,800
2003	5,600	39	230	472	6,341
2004	6,589	48	107	426	7,179
2005	5,522	92	896	490	7,000
2006	1,092	19	900	472	2,483
2007	1,904	27	814	415	4,622
2008	2,308	48	948	506	4,868
2009	2,381	42	930	496	4,750
2010	2,787	7	1,206	466	4,466
2011	2,317	15	750	467	3,549
2012	3,484	25	750	414	4,673
2013	2,538	43	750	334	3,665
2014	2,825	46	750	268	3,889
2015	3,764	36	750	270	4,802

Estimated oil and gas use of water averaged 16 acre-feet per year from 1990 to 2000 and 49 acre-feet per year for 2000 to 2015, peaking at 170 acre-feet in 2016 (Figure 7-3). We estimated the oil and gas water use for the broader area of the Devils River watershed in Val Verde, Crockett, and Sutton counties based on reported active oil lease areas within the Devils River watershed in each county. The Devils River watershed includes an estimated 66 percent of oilfield wells in Val Verde County, 50 percent of wells in Crockett County, and 90 percent of wells in Sutton County. While these are rough estimates, they provide some real constraint on the timing and magnitude of oil industry groundwater abstraction in northern Val Verde County and adjacent areas of the Devils River watershed. Estimated oil and gas use in the Devils River watershed area averaged 334 acre-feet per year for 1990 to 2000, and 1,585 acre-feet per year for 2000 to 2015. Oil and gas groundwater use in the watershed area is estimated to have peaked in 2013, at about 4,250 acre-feet.

Overall, groundwater pumping for all uses in Val Verde County has averaged about 4,700 acre-feet per year since 2001 and has increased from about 2,200 acre-feet per year in the 1980s and 3,000 acre-feet per year in the 1990s (Figure 7-4).

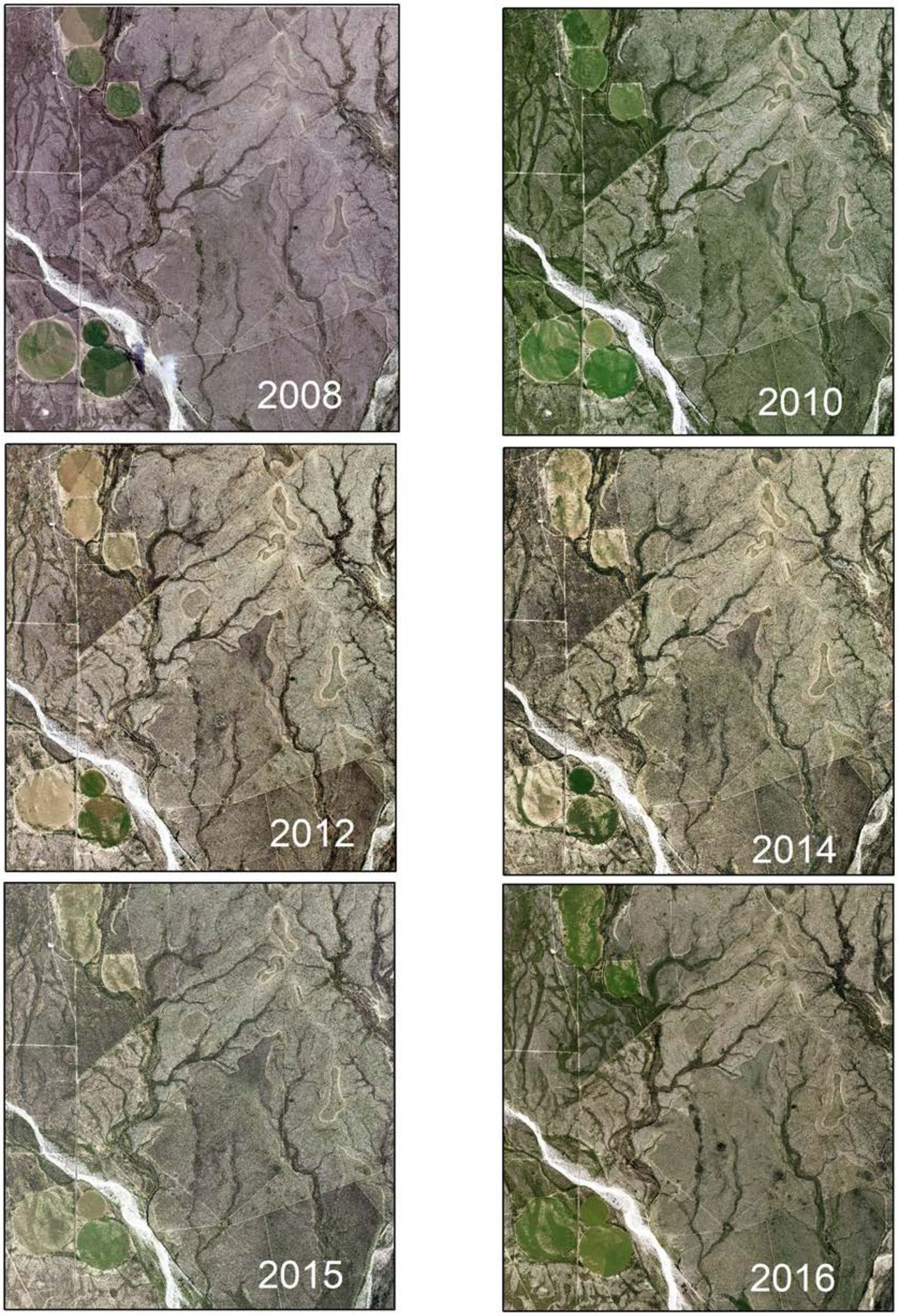

Figure 7-1. National Agricultural Imagery Program images of irrigated areas northeast of Del Rio, 2008 to 2016.

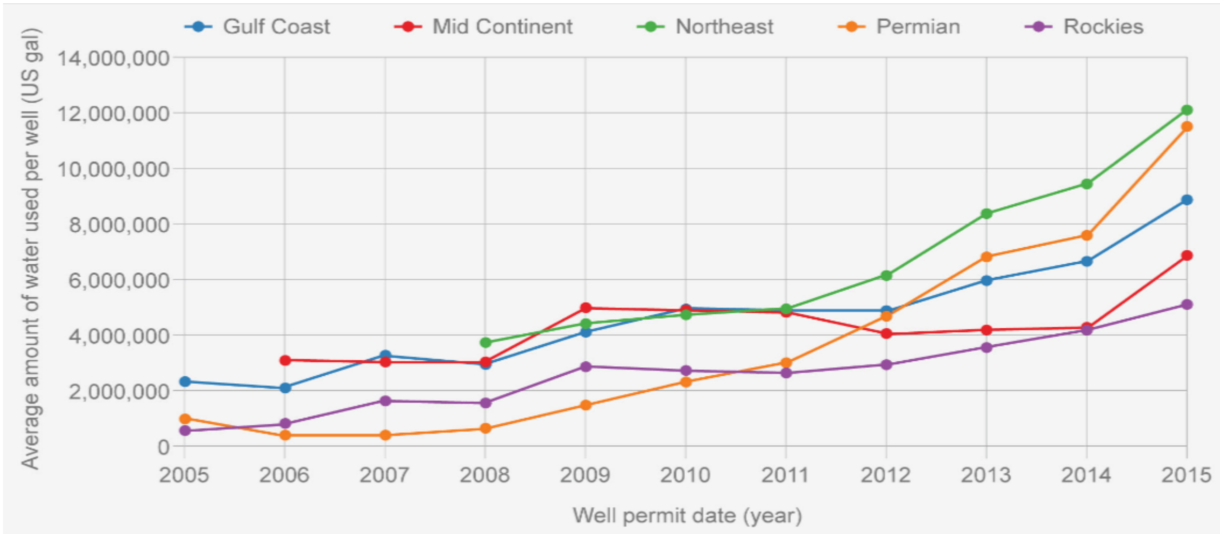

Figure 7-2. Water use per well for hydraulic fracturing operations in the United States. From Wood Mackenzie, 2016.

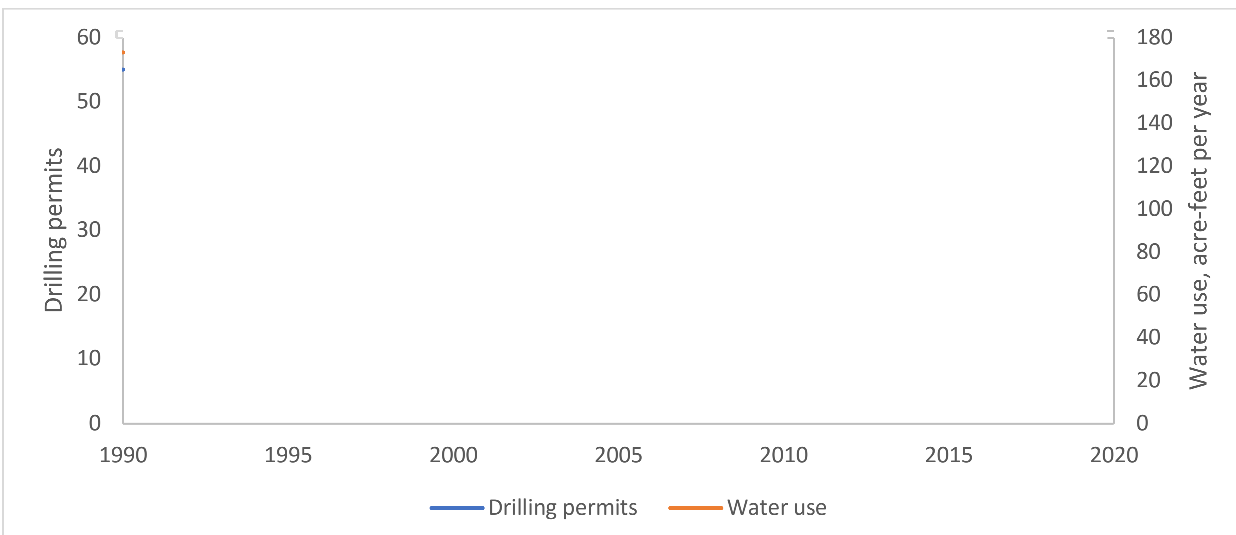

Figure 7-3. Oil and gas drilling permits and estimated water use in Val Verde County, 1990 to 2018. Permit data from Texas Drilling.com, 2018. Permian Basin water use per well for 2005–2015 from Wood Mackenzie, 2016. Water use per well is shown decreasing for 2016 and 2017, reflecting increasing water reuse in hydraulic fracturing in Texas.

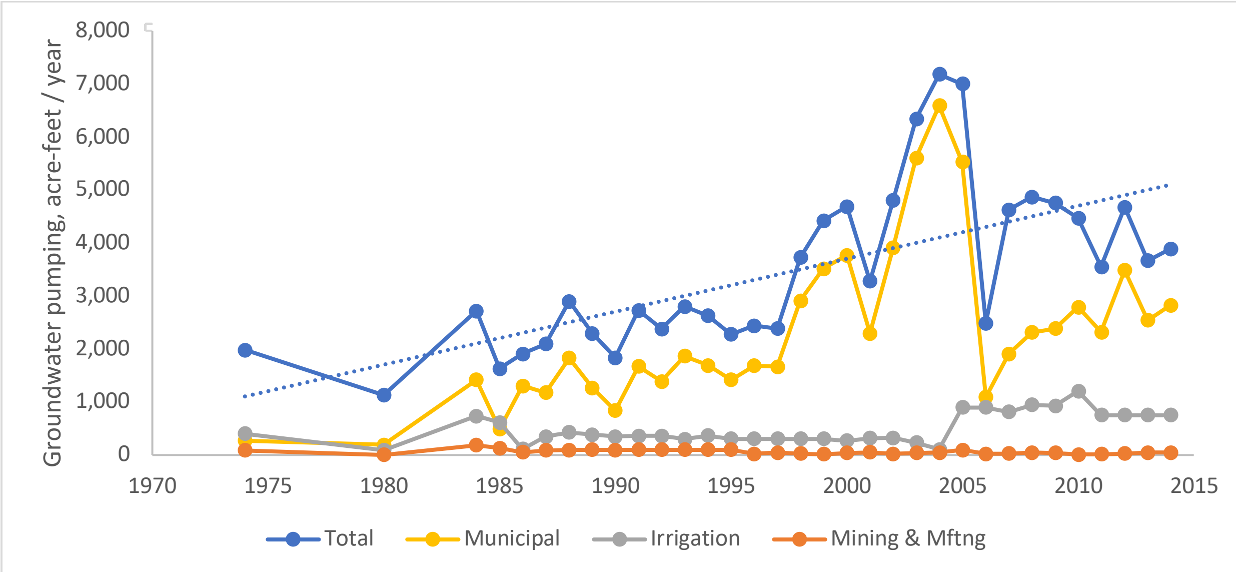

Figure 7-4. Estimated groundwater pumping in Val Verde County, 1974 to 2014, reflecting revised figures for municipal, mining, and irrigation uses developed in this report.

8.0 Groundwater Management and Feasibility of Hydrologic Triggers

Key findings

- The currently adopted desired future condition for the Edwards-Trinity (Plateau) Aquifer may not adequately address all potential groundwater management concerns in Val Verde County. Because there is no mechanism to enforce compliance with the desired future conditions, rule of capture serves as the current groundwater management approach.
- Index wells and hydrological triggers would be feasible strategies for groundwater management in Val Verde County. There is no current management entity to formally define or implement hydrologic triggers in the county.
- Both additional field data and improved groundwater flow modeling would assist the development of groundwater management strategies.
- TWDB recorder wells, combined with existing water well data from long-term monitoring, can provide a reasonable basis for developing hydrologic triggers for portions of the county.
- Additional technical and stakeholder input is needed to develop management objectives before specific trigger values based on groundwater levels can be determined.
- Four groundwater management zones generally based on watershed areas may be appropriate options for Val Verde County.
- The groundwater observation well network should be expanded to support groundwater management strategies and objectives.

Val Verde County participates in water planning activities as part of the Region J (Plateau) Planning Group and Groundwater Management Area 7 but is not currently part of any groundwater conservation district. Managing groundwater in the Edwards-Trinity (Plateau) Aquifer would involve consideration of historical groundwater usage, consideration of private property interests, complex groundwater-surface water interactions, and ecological and species habitat concerns. There are several areas in Texas where the Edwards (Balcones Fault Zone) Aquifer discharges through major springs, and the process through which groundwater management has developed in those areas may inform the path forward for Val Verde County.

Approaches to county-level groundwater management should be viewed in light of regional groundwater management strategies, such as those in Groundwater Management Area 7. Some springs in Val Verde County represent the discharge points for a regional groundwater flow system that extends well outside the area of the county. The surface water drainage systems that recharge groundwater in Val Verde County extend into neighboring counties, New Mexico, and Coahuila, Mexico. Groundwater management may require cooperation across political boundaries. Within Texas, regional groundwater management objectives are addressed through a public process by establishing desired future conditions identified by groundwater conservation district representatives through the regional groundwater management areas.

Desired Future Conditions and Modeled Available Groundwater

The desired future condition for the Edwards-Trinity (Plateau) Aquifer in Val Verde County is tied to the discharge at San Felipe Springs. The desired future condition was adopted in March 2018 by groundwater district representatives in Groundwater Management Area 7. Val Verde County, having no groundwater conservation district, is not directly represented in Groundwater Management Area 7 and does not have the ability to enforce compliance with the desired future condition. The desired future condition is: "Total net drawdown in Val Verde County in 2070, as compared with 2010 aquifer levels, shall be consistent with maintenance of an average annual flow of 73-75 million gallons per day at San Felipe Springs" (TWDB, 2018c). The desired future condition statement and explanatory report developed by Groundwater Management Area 7 do not address where groundwater levels would be measured, how often they would be measured, or how they would be evaluated to determine a total net drawdown.

The modeled available groundwater for Val Verde County, representing the average annual pumping that would achieve the desired future condition, was calculated by the TWDB to be 50,000 acre-feet per year through 2060 (Jones, 2018). The modeled available groundwater value was developed using the Val Verde County Model and simulated the operation of three individual hypothetical well fields northwest of Del Rio pumping an aggregate of 50,000 acre-feet per year.

Because the currently adopted desired future condition focuses on San Felipe Springs, it may not adequately address all potential groundwater management concerns in Val Verde County. As noted previously in this report, San Felipe Springs discharge is strongly influenced by water levels in Amistad Reservoir, such that spring flow is a poor indicator of overall groundwater conditions in the county. In addition, the drainage basin contributing to flow from San Felipe Springs may represent only a small part of Val Verde County. Groundwater management decisions based solely on San Felipe Springs discharge will not reflect groundwater conditions in the Devils River or Pecos River drainage basins. As discussed later in this section, a separate management zone may be appropriate for the Devils River watershed to better evaluate the effects of pumping on the Devils River and to address other potential management objectives such as maintaining streamflow and aquatic endangered species habitat.

Feasibility of Hydrologic Triggers

Trigger levels related to index well water levels or spring discharges are established mechanisms for groundwater conservation districts to manage groundwater resources. Hydrologic triggers can be established to provide decision makers with data to implement strategies to address changing hydrologic conditions such as water supply or water quality concerns. For example, the Barton Springs Edwards Aquifer Conservation District has defined hydrologic triggers such that (1) decisions can be made with sufficient time to implement beneficial response measures, (2) triggers represent aquifer- or watershed-wide conditions, and (3) triggers are simple to implement. Water levels in index wells, or discharge measurements at specified springs, can both serve as the starting point for groundwater management and as indicators of the overall status of the groundwater system for drought response.

Edwards Aquifer Triggers

Several groundwater conservation districts that manage the Edwards Aquifer express their desired future conditions in terms of minimum spring flows or index well water levels. The Clearwater Underground Water Conservation District specifies desired future conditions for the Edwards (Balcones Fault Zone) Aquifer in terms of preferred and minimum monthly total spring discharges under drought-of-record conditions, while desired future conditions for other aquifers in the district are expressed in terms of average drawdown with respect to 2000 water levels (Clearwater Underground Water Conservation District, 2018).

Index well water levels or spring discharge volumes also serve as drought response triggers for the Clearwater district. Their values can be measured and monitored in real time. As the water level or discharge volume approaches or exceeds certain agreed-upon values, indicating stress on the groundwater system, management actions are triggered to progressively reduce demand and prevent critical thresholds from being exceeded. The Clearwater district triggers drought response actions when either the five-day running average of the daily maximum spring discharge value or the precipitation deficit index exceeds specific thresholds for each level of drought response (Clearwater Underground Water Conservation District, 2016).

The Edwards Aquifer Authority (EAA) also uses a combination of index well and spring discharge measurements for managing groundwater resources to protect aquatic endangered species habitat, which also may be a potential management objective in Val Verde County. The EAA uses water level measurements in the J-17 and J-27 wells to manage the San Antonio Pool and the Uvalde Pool of the Edwards Aquifer, respectively. The EAA uses three different devices to measure water levels to ensure accuracy. Each well is measured every 15 minutes. Every day, the highest water level recorded between the hours of 12 a.m. and 8 a.m., when demand is typically lowest, is reported as the daily high. Daily maximum discharge measurements at Comal, Hondo, and San Marcos springs are similarly collected. This data are used for determining and enforcing groundwater production curtailments during periods of high aquifer demand and/or drought. Critical drought periods are initiated when the 10-day average of any one trigger drops below the threshold for that stage of response, but the response action is not removed until all applicable triggers are above the threshold value (Edwards Aquifer Authority, 2018).

City of Del Rio Drought Triggers

The City of Del Rio drought contingency plans address trigger response actions based on the flow from San Felipe Springs and water levels in the Bedell Street Storage Reservoirs (Ashworth, Herrera, and Brown, 2016). Progressive trigger points are linked to conservation goals in response to increasing drought severity (Table 8-1).

Possible Val Verde County Hydrologic Triggers

A combination of spring discharge and index well measurements could be used as hydrologic triggers to support the management of groundwater resources in Val Verde County. Spring discharge could be directly linked to potential management goals such as minimum streamflow requirements. Spring discharge can be readily determined from water level measurements in the spring pool or in a shallow monitoring well adjacent to the spring and an established stage-discharge relationship. Index well water levels in the aquifer should have a demonstrated correlation with groundwater management goals, such as maintaining streamflow or endangered species habitat. Ideally, index well trigger levels should also have a predictive capability so that management options can be implemented proactively, before problems develop. Therefore, index wells may be located upgradient of critical springs or reaches of streams depending on the nature of the hydrologic feature to be protected.

Table 8-1. City of Del Rio drought triggers and response actions. From Ashworth, Herrera, and Brown, 2016.

Stage and description	1-Mild	2-Moderate	3-Severe	4-Extreme	5-Emergency
Trigger	Water levels < 100% full; San Felipe Spring flow <40 mgd.	Water levels < 30 feet; San Felipe Spring flow <25 mgd.	Water levels < 25 feet; San Felipe Spring flow <20 mgd.	Water levels < 20 feet; San Felipe Spring flow <15 mgd.	Water levels < 15 feet; San Felipe Spring flow <10 mgd.
Conservation goal (percent reduction in pumping)	Reduce water demand to 95% of the 30-day average prior to initiation	Reduce water demand to 90% of the 30-day average prior to initiation	Reduce water demand to 80% of the 30-day average prior to initiation	Reduce water demand to 70% of the 30-day average prior to initiation	Notify TCEQ

mgd = million gallons per day

As an example of this approach, Well 5456403, northeast of Juno, is one candidate for an index well in the Devils River watershed. Well 5456403 is located on the north side of the Devils River about a mile northeast of Juno and 21 river miles upstream from Bakers Crossing. Water levels in Well 5456403 are moderately correlated with the streamflow at Bakers Crossing. Groundwater elevation measurements are available for the period 1955 to 2015. Water levels in the well are most highly correlated with stream baseflow measured one month after the groundwater level, indicating that groundwater levels have some limited predictive capacity for subsequent streamflow (Figure 8-1).

Additional technical and stakeholder input is needed to develop management objectives before specific trigger values based on groundwater levels can be determined.

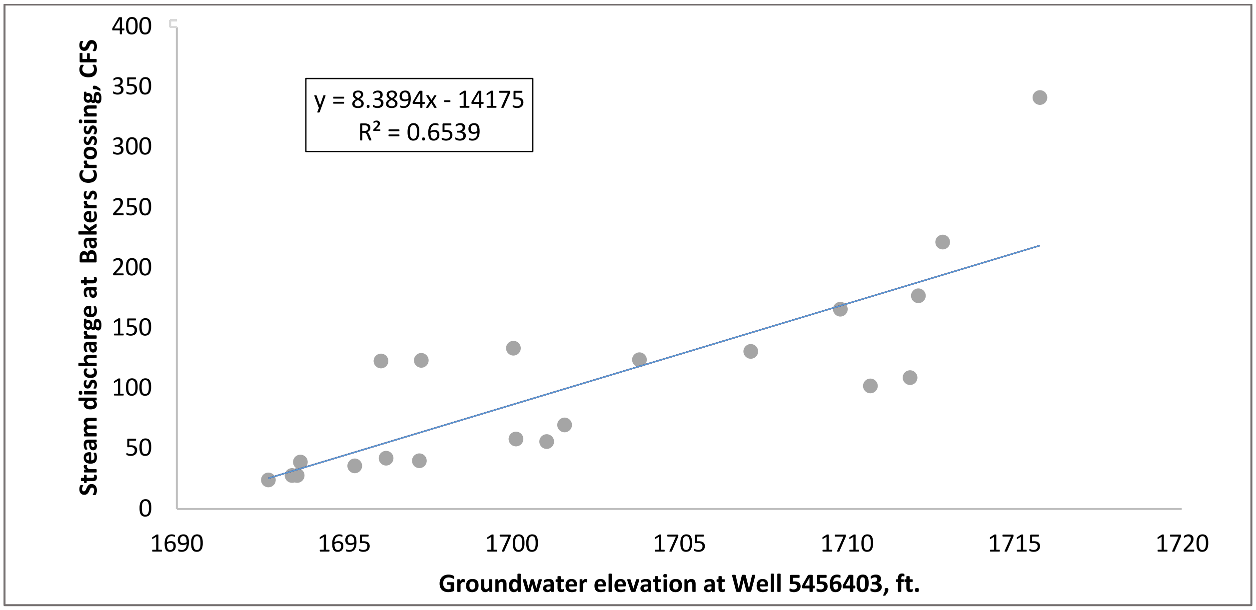

Figure 8-1. Correlation between stream discharge at Bakers Crossing and groundwater levels at Well 5456403. Stream measurements are lagged one month after corresponding groundwater level measurements. Data from U.S. Geological Survey, 2018a and TWDB, 2018.

Similar correlations between spring flow or streamflow and groundwater levels in the contributing basin potentially could be developed for the Pecos and Sycamore/San Felipe drainages. Eco-Kai and Hutchison (2014) evaluated correlations between San Felipe Springs discharge and groundwater elevations in several wells in the Del Rio area, finding a good correlation for wells 7033604, 7041209, and 7042205 during both wet and dry periods. Well 7042205 was destroyed in 2004 and is no longer available for monitoring. Only two wells in the Pecos River watershed in Val Verde County have more than 15 water-level observations recorded by the TWDB, and neither well has been measured since 1990. No useful correlations can be developed from the existing data for the Pecos River watershed area.

The TWDB and International Boundary Water Commission have identified or installed a network of observation wells in Val Verde County. Some of these wells may not be currently suitable for use as index wells for the application of hydrologic triggers due to construction deficiencies, accessibilities, or other concerns that could affect the quality and usability of measurements. However, other wells may be appropriate as index wells with further evaluation. One of the considerations important to the selection of index wells is the evaluation of groundwater level trends over time. Even though most of the possible index wells are monitored sporadically (see Figures 4-8 and 4-9) – usually annually and in a number of cases less frequently – the hydrographs of TWDB recorder wells suggest that overall groundwater levels in the Edwards-Trinity (Plateau) Aquifer show little variation over time. Figure 8-2 shows hydrographs of continuously monitored shallow (#7001701 - 90 feet deep) and deep (#5463401 - 710 feet deep) recorder wells. These data provide helpful context that could extend to possible use of other wells that do not currently have a continuous record of monitoring.

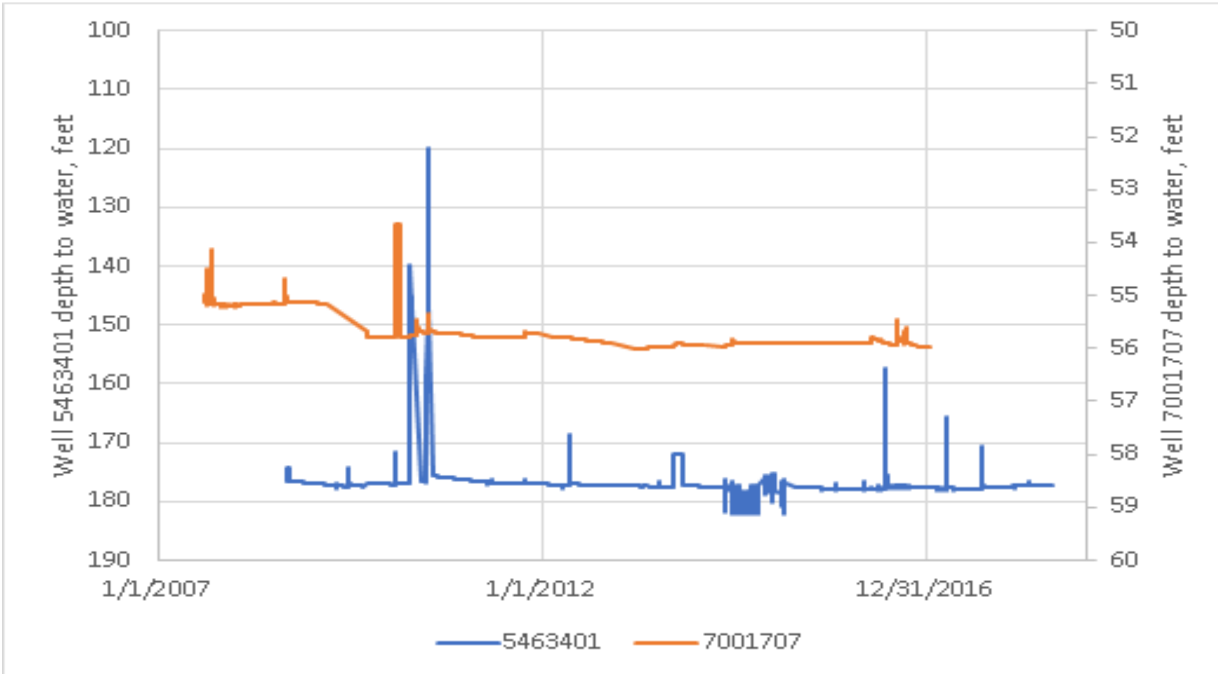

Figure 8-2. Hydrographs of TWDB Recorder Wells in the Devils River watershed show little overall variation in water levels over a 10-year period. Data from TWDB, 2018.

In addition to considering county-specific data, the selection of possible index wells and hydrologic triggers may be influenced by conditions outside Val Verde County. For example, the main springs feeding the lower Pecos River are along Independence Creek in Terrell County, while the Sycamore Creek watershed extends into Kinney and Edwards counties. As previously discussed, Amistad Reservoir water levels, which reflect conditions in a large, bi-national watershed, strongly influence flow from San Felipe Springs.

Southwest Research Institute (Green, 2016) identified and evaluated possible hydrologic triggers applicable to groundwater in Val Verde County. Rather than measurement of groundwater levels in the aquifer, this approach would rely on stream discharge measurements, with "triggers" set at pre-determined flow criteria. The approach features individual streamflow triggers for three separate watersheds: the Pecos River, Devils River, and San Felipe Springs. When considered together, the three watersheds cover nearly all of Val Verde County. The approach was structured similar to that used by the Edwards Aquifer Authority for the J-17 Index Well in the Edwards Aquifer. Water levels in the J-17 well are used as the basis for implementing various stages of a water conservation program designed to reduce groundwater usage in times of drought and to protect levels of spring flow that are important to maintaining critical habitats for endangered species. In the approach identified by Southwest Research Institute, multiple stage responses would be tied to discharge rates measured at the Pecos River (Langtry Gaging Station), the Devils River (Pafford Crossing Gaging Station), and San Felipe Springs. Table 8-2 illustrates this approach as applied to the Devils River, which is based on over 55 years of stream gage measurements.

Table 8-2. Possible hydrologic trigger criteria based on Devils River discharge measurements at Pafford Crossing Gaging Station (Green, 2016).

Stage	Trigger (cubic feet per second)	Days	Percent
I	<159	4916	24.1
II	<121	2419	11.9
III	< 90	1014	5.0
IV	< 68	207	1.0
V	< 61	41	0.2

Note: Historical record is from January 1, 1960, to October 18, 2015

Groundwater Management Zones

The Texas Water Code §36.108(d-1) gives groundwater conservation districts latitude in managing certain aspects of the groundwater resources within its territory. Recognizing that within districts there can be considerable variation in groundwater occurrence, aquifer properties, groundwater flow, and groundwater use patterns, the Texas Water Code allows districts to establish management zones whereby custom-developed criteria can be applied to the management of groundwater within the district. Aquifers can be managed separately in subdivisions within the district, and different areas of management may be identified to deal with aquifer variability or water quality. Several districts have established different management zones, some with different desired future conditions, to facilitate appropriate management.

Based on our review of available data, Val Verde County has sufficient hydrogeologic variability to support the establishment of aquifer management zones in the event a groundwater conservation district is established. Four separate groundwater management zones, based on approximate watershed boundaries, could be defined in Val Verde County as shown in Figure 8-3. Groundwater contributing to flow in the Pecos River, Devils River, and Sycamore/San Felipe Creek drainages occupies generally separate flow systems. Threatened and endangered wildlife populations in each of these drainages may need to be managed separately, while the Sycamore/San Felipe Creek system also supports the Del Rio water supply. The area around Amistad Reservoir probably also requires special management considerations. Groundwater near the reservoir is strongly influenced by reservoir levels and pumping in these areas could draw water from the reservoir, which could be incompatible with management of the binational Rio Grande and the needs of Texas users who rely on water from Amistad Reservoir.

More detailed hydrogeological assessment will be needed to define the boundaries of the groundwater drainage basins and of the area of potential surface water impact around Amistad Reservoir. Additional water level monitoring through the establishment of a representative monitor well network will be integral to defining management zones and supporting other potential groundwater management objectives. Additionally, groundwater geochemistry and micro-particulate analysis may all play a role in refining the boundaries of possible management zones.

Amistad Groundwater Zone

The Amistad Groundwater Zone would cover the area where groundwater levels and flow in the Edwards-Trinity (Plateau) Aquifer are believed to be affected directly by reservoir levels. Selected groundwater observation wells could serve as monitoring points to evaluate changing groundwater conditions, particularly as they could affect withdrawal points and spring flow hydraulically downgradient of the reservoir.

San Felipe Springs Groundwater Zone

The San Felipe Springs Groundwater Zone would cover the watershed area that contributes to the San Felipe Springs complex. However, groundwater outside this zone (in the vicinity of Amistad Reservoir) exerts influence on the flow characteristics of the springs, where groundwater levels and flow in the Edwards-Trinity (Plateau) Aquifer are believed to be affected directly by reservoir levels. Selected groundwater observation wells could serve as monitoring points to evaluate changing groundwater conditions, particularly as they could affect withdrawal points and spring flow hydraulically downgradient of the reservoir. Connections between the San Felipe drainage basin and the Sycamore Creek drainage basin need to be evaluated further; a separate management zone may be justified for Sycamore Creek.

Pecos River Groundwater Zone

The Pecos River Groundwater Zone extends over the western portion of the county. This area currently has few suitable observation wells that could serve as hydrologic triggers, but the Pecos River flow has been well characterized and would be a probable component of any groundwater management approach.

Devils River Groundwater Zone

The Devils River Groundwater Zone would cover the Devils River watershed area. This zone has a number of possible suitable observation wells, springs, and gaging stations that could be used for hydrologic trigger locations. The two TWDB recorder wells (Figure 8-2) have yielded nearly continuous water level measurements since the mid-2000s and would provide a useful baseline from which to measure possible future changes in groundwater levels.

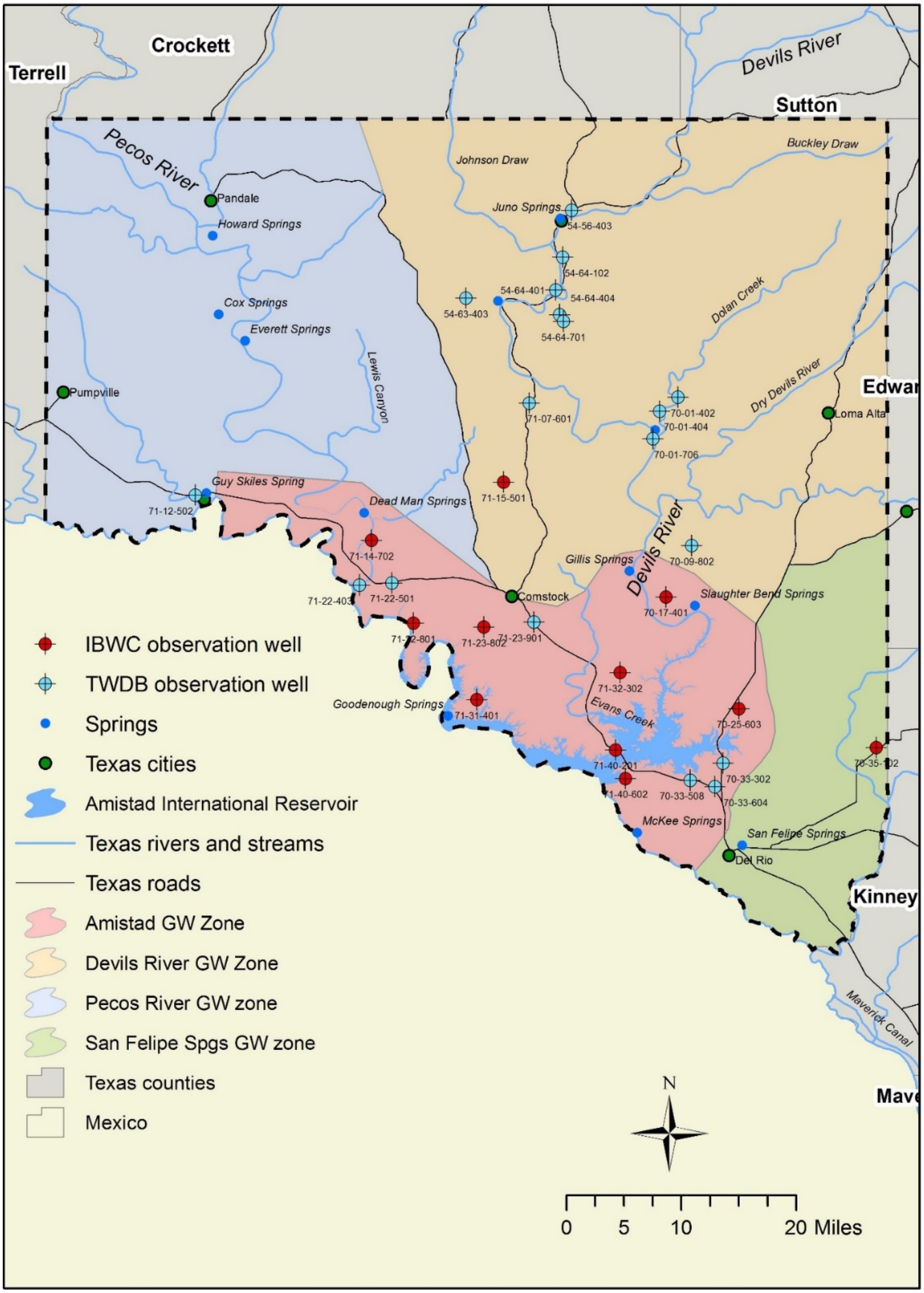

Figure 8-3. Map of possible groundwater management areas for Val Verde County.

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Appendix A

Low-flow gain loss studies of the Devils River, 1921-1928

From the Texas Board of Water Engineers, 1960, Channel gain and loss investigations, Texas streams, 1918 -1958; pp. 205-209.

LOW-FLOW INVESTIGATIONS - RIO GRANDE BASIN

Devils River January and October 1921

Reach: From a point about 30 mi above to mouth near Del Rio, Tex.

Date 1921	Stream	Location	River Miles	Water Temp.	Discharge, in cfs Main Stream	Tributary	Diversion	Remarks
Jan. 26	Devils River	At Rubboard Ford	0		283			
26	Smiths Spring	8 mi below Rubboard Ford	8			25		Estimate.
28	Devils River	At Rough Canyon Damsite	20		393			
27	Devils River	At Del Rio-Comstock road crossing	25		417			
27	Devils River	½ mi below Southern Pacific Railroad bridge	27.2		448			Rock channel.
Oct. 6	Devils River	At Rough Canyon Damsite	20		292			
7	Devils River	At Del Rio-Comstock road crossing	25		290			
7	Devils River	At Southern Pacific Railroad bridge	26.8		342			
7	Devils River	At Abandoned gage site at Devils River	27.8		344			

LOW-FLOW INVESTIGATIONS - RIO GRANDE BASIN

Devils River August 8-13, 1925

Reach: From Beaver Lake to Del Rio-Comstock highway crossing, Val Verde County, Tex.

During this investigation the stream was at a constant stage and the measurements represent natural conditions.

Date 1925	Stream	Location	River Miles	Water Temp.	Discharge, in cfs Main Stream	Tributary	Diversion	Remarks
Aug. 8	Devils River	Just below Beaver Lake	0		1.6			
8	Devils River	.2 mi below Beaver Lake	.2		0			
8	Juno Springs	At Juno	3.2			5.8		
8	Devils River	1.0 mi below Juno	4.2		0			
8	Devils River	Just above Pecan Springs Creek	13.7		0			
8	Devils River	Just below Pecan Springs Creek	13.8		42.2			
8	Devils River	At first crossing above Bakers Crossing	19.3		78.1			
8	Devils River	At Bakers Crossing - gaging station	22.3		119			
9	Devils River	1½ mi below Bakers Crossing	23.8		122			
9	Devils River	5½ mi below Bakers Crossing	26.6		132			
9	Devils River	7 mi below Bakers Crossing	32.5		148			
10	Devils River	3 mi above Dolan Creek	33.5		165			
10	Dolan Creek	At mouth	36.5			34.2		
10	Devils River	Just below Dolan Creek	36.5		243			Large increase from east side not measurable.
10	Dry Devils River	At mouth	45.4			0		
11	Devils River	½ mi below Dry Devils River	45.9		301			
12	Devils River	4½ mi above Sellers Ranch	56.3		303			
12	Swann-Shelton Springs	½ mi above Sellers Ranch	60.8			44.3		Part of inflow only - not possible to measure total.
13	Devils River	2½ mi below Sellers Ranch	63.3		492			Poor measurement - subject to error.
13	Devils River	At Del Rio-Comstock highway crossing	73.0		473			
13	Devils River	At Devils River - gaging station	76.0		512			Not measured - from recorder record.

LOW-FLOW INVESTIGATIONS - RIO GRANDE BASIN

Devils River — February 14-20, 1928 / February 7-11, 1928

Reaches: From Dolans Creek to Smith Ranch about 3 miles below Satan Creek near Comstock, Tex.
From Smith Ranch 3 miles below Satan Creek to a point ½ mile below Southern Pacific Railroad bridge near Del Rio, Tex.

During the investigations the river was at a constant stage, and the measurements represent the natural conditions.

Tributaries not listed were not flowing at the time these investigations were made.

Date 1928	Stream	Location	River Miles	Water Temp.	Discharge, in cfs Main Stream	Tributary	Diversion	Remarks
	From Dolans Creek to Smith Ranch about 3 mi below Satan Creek							
Feb. 14	Devils River	Just above Dolans Creek	0		118			
15	Dolans Creek	At mouth	.1			17.5		
15	Devils River	Just below Dolans Creek	.1		147			
15	6 springs	On left bank 1.1 mi below Dolans Creek	1.2			2.0		Estimate.
15	Devils River	1.3 mi below Dolans Creek	1.4		149			
15	Spring	On left bank 1.4 mi below Dolans Creek	1.5			.02		Estimate.
15	4 springs	On left bank 1.8 mi below Dolans Creek	1.9			.1		Estimate.
15	Spring	On left bank 2.6 mi below Dolans Creek	2.7			.3		Estimate.
15	Spring	On left bank 2.6 mi below Dolans Creek	2.7			1.0		Estimate.
15	Spring	On left bank 2.6 mi below Dolans Creek	2.7			.1		Estimate.
15	Devils River	3.1 mi below Dolans Creek	3.2		164			
16	Devils River	1,000 ft above Indian Creek	3.8		167			
16	Spring	On left bank 1.5 mi above Dry Devils River	6.5			.1		Estimate.
16	Spring	On right bank 1.5 mi above Dry Devils River	6.5			.1		Estimate.
16	Devils River	1.5 mi above Dry Devils River	6.55		203			
17	Devils River	At mouth of Dry Devils River	8.1		189			
17	Devils River	1.0 mi below Dry Devils River	9.2		189			
18	Devils River	1.5 mi above Deadman Creek	10.8		180			
18	Devils River	1.5 mi below Deadman Creek	13.4		200			

Date 1928	Stream	Location	River Miles	Water Temp.	Discharge, in cfs Main Stream	Tribu-tary	Diver-sion	Remarks
	From Dolans Creek to Smith Ranch about 3 mi below Satan Creek, continued							
Feb. 19	Devils River	2-3/4 mi above Satans Creek	16.8		205			
20	Devils River	1.0 mi below Satans Creek	20.7		193			
20	4 springs	On left bank 1.5 mi below Satans Creek	21.3			1.0		Estimate.
20	Swann-Shelton Spring	On left bank 1.5 mi below Satans Creek	21.3			25.7		
20	Spring	On left bank 1.8 mi below Satans Creek	21.5			.5		Estimate.
20	Spring	On left bank 1.8 mi below Satans Creek	21.5			1.5		Estimate.
20	Little Satan Creek	At mouth	22.0			.5		Estimate.
20	Devils River	3/4 mi above Smith Ranch house	22.3		232			
	From Smith Ranch 3 mi below Satan Creek to a point ½ mi below Southern Pacific Railroad bridge							
7	Devils River	3/4 mi above Smith Ranch house	0		242			
7	Unnamed spring	On right bank across from Smith Ranch house	.5			2.69		
7	Unnamed spring	In river channel 600 ft below Smith Ranch house	.6			-		Not measured.
7	12 springs	On left bank just below Smith Ranch house	.6-1.2			1.0		Estimate.
7	Devils River	3/4 mi below Smith Ranch house	1.3		275			
7	5 springs	On right bank .8 mi below Smith Ranch	1.55			1.54		
7	Spring	On right bank 1.1 mi below Smith Ranch	1.70			.2		Estimate.
7	Spring	On right bank 400 ft above Sellers Ranch	1.85			.50		
7	6 springs	On right bank at Sellers Ranch house	2.00			1.0		Estimate.
7	Spring	On right bank ¼ mi below Sellers Ranch house	2.2			.4		Estimate.
8	Lester Spring	On left bank .6 mi below Sellers Ranch house	2.7			.2		Estimate.
8	Spring	On left bank 1.2 mi below Sellers Ranch house	3.45			2.71		
8	Spring	On left bank 1.25 mi below Sellers Ranch house	3.50			.54		
8	Devils River	1½ mi below Sellers Ranch house	3.90		292			

Date 1928	Stream	Location	River Miles	Water Temp.	Discharge, in cfs Main Stream	Tribu-tary	Diver-sion	Remarks
	From Smith Ranch 3 mi below Satan Creek to a point ½ mi below Southern Pacific Railroad bridge, continued							
Feb. 8	Spring	On left bank 2 mi above Dam #1	5.75			0.1		Estimate.
8	Devils River	1½ mi above Dam #1	6.5		289			
9	Spring	On left bank 1.2 mi above Dam #1	6.55			.1		Estimate.
9	Spring	On left bank .9 mi above Dam #1	7.0			.53		
9	Spring	On left bank .6 mi above Dam #1	7.20			.8		Estimate.
9	Spring	On left bank .6 mi above Dam #1	7.20			.1		Estimate.
9	Spring	On right bank in Rough Canyon	7.25			1.0		Estimate.
9	5 springs	On left bank .5 mi above Dam #1	7.30			1.5		Estimate.
9	Spring	On left bank 1,000 ft above Dam #1	7.70			.08		
9	Devils River	At mouth of Bluff Creek 1,000 ft below Dam #1	8.00		301			
9	Spring	On left bank .3 mi below Dam #1	8.50			1.0		Estimate.
10	Devils River	1.0 mi below Dam #1	9.20		303			
10	Devils River	At Country Club ¼ mi below Damsite #9	11.8		301			
11	Devils River	At causeway 12 mi above Del Rio	14.0		315			
11	Spring	On right bank opposite gaging station	15.5			10.2		
11	Devils River	Just above Southern Pacific Railroad bridge	15.8		369			
11	Devils River	3,000 ft below Southern Pacific Railroad bridge	16.5		366			

Appendix B

Geochemical assessment of groundwater flow paths, mixing, and residence time

Geochemical assessment of groundwater flow paths, mixing, and residence time

Chemical and isotopic analyses suggest that groundwater discharged from the major springs in Val Verde County may range from 2 years to over 30 years old. Spring discharge has minimal water-rock interaction, suggesting that recharge occurs primarily through sinkholes and fractures along surface drainages, and exhibits limited mixing with groundwater from adjacent counties hydraulically upgradient of Val Verde County. These observations generally support the matrix-conduit model of groundwater flow and place certain constraints on the aquifer storage and flow parameters and the degree of connection between matrix and conduit. We present an evaluation of isotopic and geochemical indicators in 55 groundwater and spring water samples collected in Val Verde County by the TWDB between 2002 and 2010 (Appendix C). Together with TWDB analyses reported by Nance (2010) for Crockett and Sutton counties, we obtain a coherent regional model of groundwater recharge, storage, and flow.

Chemical and isotopic analyses have been used by many authors to assess groundwater flow and residence time in aquifers, but there has not been a comprehensive geochemical assessment of Val Verde groundwater to date. Groundwater residence time can provide a useful estimate of the aquifer storage volume independent of typical estimates based on aquifer geometry and hydraulic properties. Nance (2010) and Kreitler and others (2013) used water quality data to evaluate conceptual models of groundwater flow in portions of the Edwards -Trinity (Plateau) Aquifer, but neither evaluated data for Val Verde County. Musgrove and Banner (2004) examined the effects of soil-water reactions during recharge on Edwards Aquifer groundwater geochemistry, focusing on several caverns in the Balcones Fault Zone. Pearson and Retmann (1976) collected geochemical and isotopic data for Edwards aquifer unit wells representative of recharge, fresh water, transitional, and saline conditions, but included only a limited suite of samples from Val Verde County.

Radiocarbon and tritium contents in Edwards groundwater from Val Verde and neighboring counties (Figure B-1) exhibit a relatively tight linear trend that on casual inspection suggests a progressive age distribution from 'young' waters with around two tritium units (TU) and up to 85 percent modern carbon all the way to 'old' waters with no detectable tritium and around 10 percent modern carbon. But the discordant apparent ages suggested by the radiocarbon and tritium data show that the system is more complex. Apparent radiocarbon ages range from approximately 1,000 to 20,000 years, while tritium results suggest much more recent ages in the range of years or decades rather than millennia.

Mixing and reaction models can be developed to explain these age disparities but can also raise additional problems. Groundwater mixing schemes tend to produce non-unique age estimates. Mixing is a linear process in terms of water volume, but non-linear in terms of radio-isotope activity, which decays exponentially. As a result, a 50:50 mix of 'old' and 'young' water doesn't give an age corresponding to the average of the old and young end-members, and even a small fraction of recent water can greatly change the apparent activity of a mostly old sample. Radiocarbon concentrations in groundwater are also greatly influenced by reaction with non-radiogenic 'dead' carbon in the carbonate aquifer matrix. Much of this reaction can happen in the soil zone, with additional reaction along the flow path between recharge and discharge areas. Each process creates a different geochemical and isotopic 'fingerprint' depending on how much dissolved carbon was acquired in soil reactions and what flow path the water takes through the aquifer.

Because apparent radiocarbon ages of several thousand years for many groundwater and spring samples are inconsistent with hydrological constraints on the total storage volume of the groundwater system, we argue that the tritium ages of the groundwater provide a more realistic measure of groundwater residence time. Radiocarbon content primarily serves as an indicator of soil-water and water-rock reactions rather than age.

We believe that it is possible to make narrow estimates of groundwater age based on tritium concentrations in Val Verde groundwater because recharge tends to occur as infrequent discrete events that can be uniquely traced. Tritium is not affected by reaction with soil or aquifer materials, but accurate dating is complicated by difficulties in establishing the initial concentration of tritium in the groundwater and by potential mixing between older and younger groundwater components, which can result in a range of non-unique age estimates. As a result, tritium is generally used as an indicator that 'young' water, with an age of less than about 60 years, is present. While helium-3 data can be used together with tritium to provide better-constrained age estimates, no helium-3 samples were collected in Val Verde or neighboring counties.

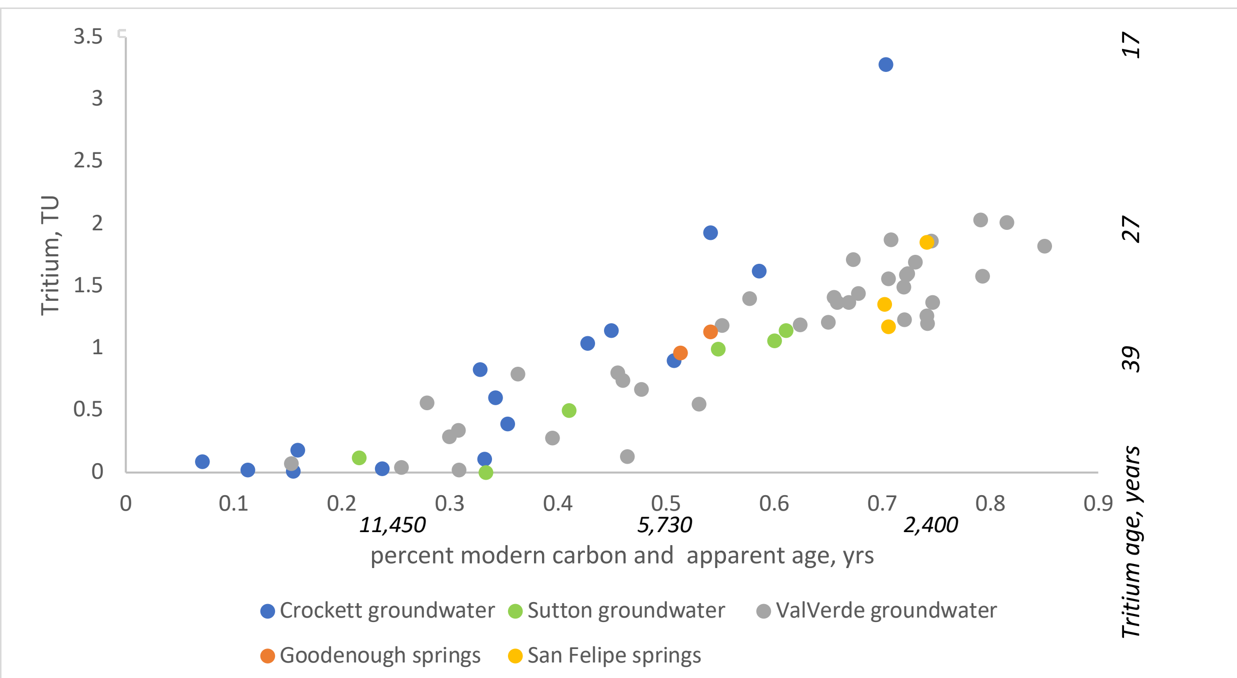

Figure B-1. Radiocarbon and tritium in groundwater samples from Val Verde and adjoining counties. There is a general pattern of increasing tritium with increasing percentage of modern carbon in the groundwater, but the relationship does not correspond to what would be predicted based on the half-lives of C-14 and tritium. Data from Nance (2010) and TWDB.

Tritium is an isotope of hydrogen with a half-life of 12.32 years (Lucas and Unterweger, 2000). Tritium is incorporated into water molecules, making it an ideal tracer for water movement in the hydrological cycle. Large amounts of tritium were produced in the atmosphere by nuclear weapons testing in the late 1950s and 1960s, with peak concentrations in 1963. Tritium is also produced at background concentrations by cosmic ray reactions with the upper atmosphere. The International Atomic Energy Agency established the Global Network of Isotopes in Precipitation (GNIP) to track environmental isotopes in the hydrological cycle. A network site in Waco, Texas, collected samples from December 1961 to March 1986 at a location relatively close to Val Verde County. Michel and others (2018) and Jurgens (2018) used data from the GNIP program and other sources to develop monthly tritium deposition estimates from 1953 to 2012 for 2-degree by 5-degree quadrangles covering the coterminous United States. While the 2- by 5-degree grid is coarse, and there can be large variations in tritium concentrations in precipitation within a quadrangle as a result of local meteorological effects, it represents a good starting point for local hydrological investigations.

Because precipitation sufficient to cause groundwater recharge is an infrequent event in west central Texas, tritium input to groundwater in this region is not a continuous function. We used stream discharge records for the Devils River at Comstock to identify the timing of potential recharge events and data from Jurgens (2018) to estimate the initial tritium content of each recharge event. From 1961 to 2007, there was a total of 14 potential recharge events, arbitrarily defined by storms that resulted in peak flows greater than about 15,000 cubic feet per second (400 cubic meters per second) in the Devils River at the Comstock gage (Figure B-2). The figure illustrates timing of potential recharge events with respect to the tritium input function. Data labels on the figure show dates and estimated tritium content (red) of potential recharge events where streamflow exceeded 400 cubic meters per second. Smaller storm events also contribute to recharge but are omitted in this analysis. There were no major recharge events during the tritium peak in 1961-1963. Later recharge events impart distinct decay curves based on the tritium content of the water recharged during that event. Tritium concentrations in precipitation during these storm events varied widely, depending on the direction the storm was traveling relative to nuclear test sites, timing relative to nuclear tests, how much rain had already fallen from the air mass, and other factors, resulting in unique decay curves for each potential recharge event (Figure B-3).

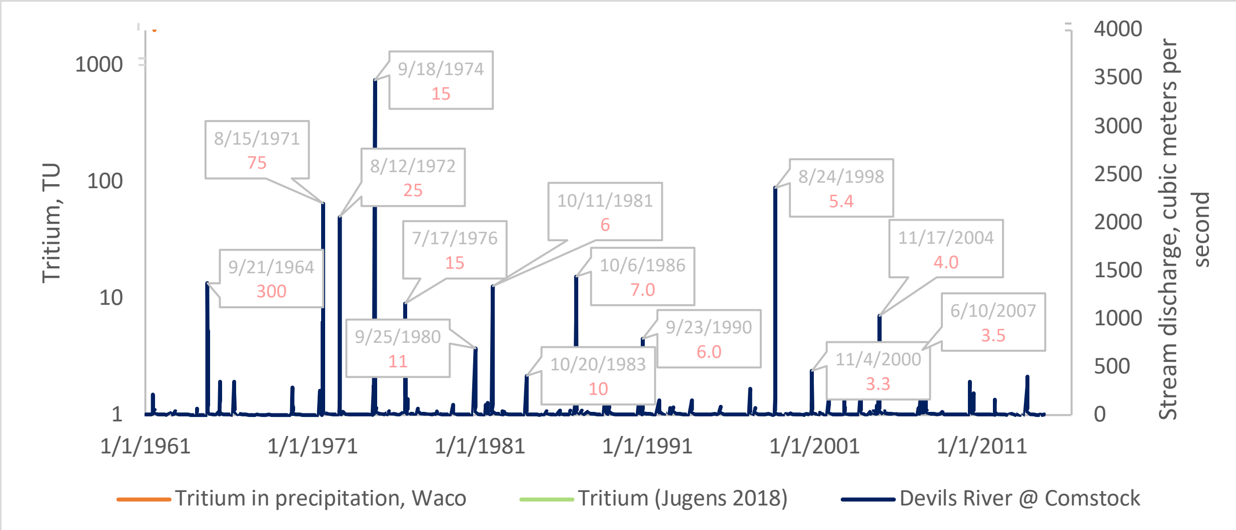

Figure B-2. Monthly tritium concentrations in precipitation in west Texas quadrangle and at Waco monitoring site and Devils River discharge at Comstock. Data from Jurgens, 2018, International Atomic Energy Agency, 2018, and International Boundary and Water Commission, 2018.

A close-up view of the decay curves covering the times when spring water samples were collected from San Felipe and Goodenough Springs (Figure B-4) shows that only the decay curve for 1981 recharge matches the observed tritium activity. A set of decay curves for recharge ranging from 1976 to 2000 lies slightly above the observed spring values, while both earlier and more recent recharge contains higher tritium activities. These decay curves suggest a range of residence times from 2 to 34 years as recharge from different flood events and inlet locations mix along their flow paths. The geographic distribution of tritium in groundwater (Figure B-5) shows higher activities near stream drainages and lower activities in groundwater under plateau areas between drainages, consistent with the model of focused recharge from surface water sources in the more hydraulically conductive drainage areas.

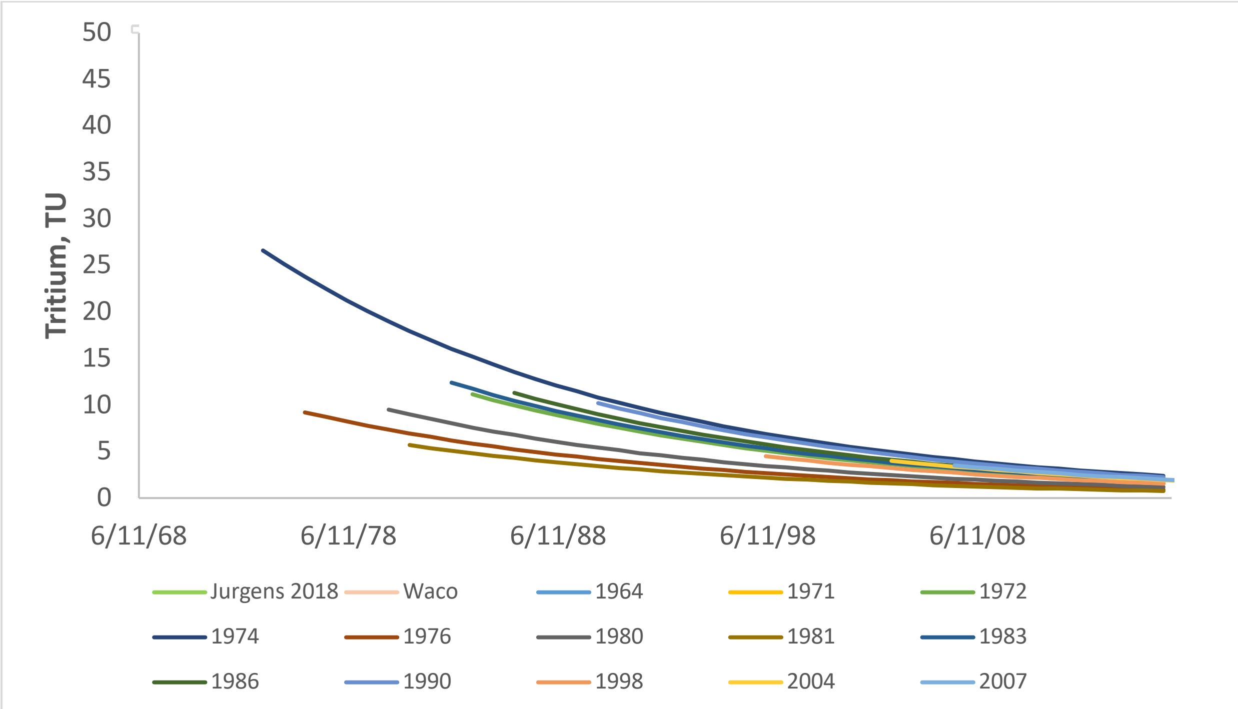

Figure B-3. Tritium input function and decay curves for potential recharge events occurring between 1964 and 2007.

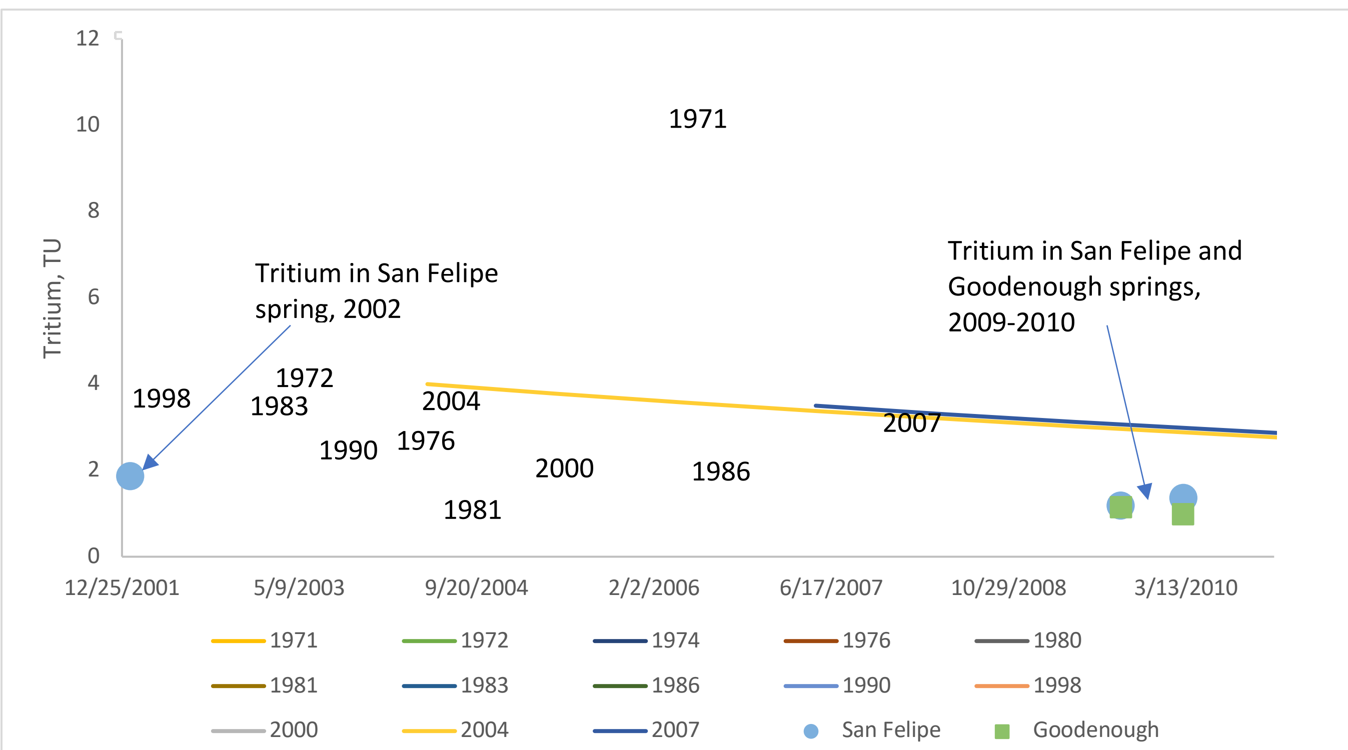

Figure B-4. Closeup of graph above, showing tritium decay curves relative to measured tritium concentrations in San Felipe and Goodenough springs in 2002, 2009, and 2010.

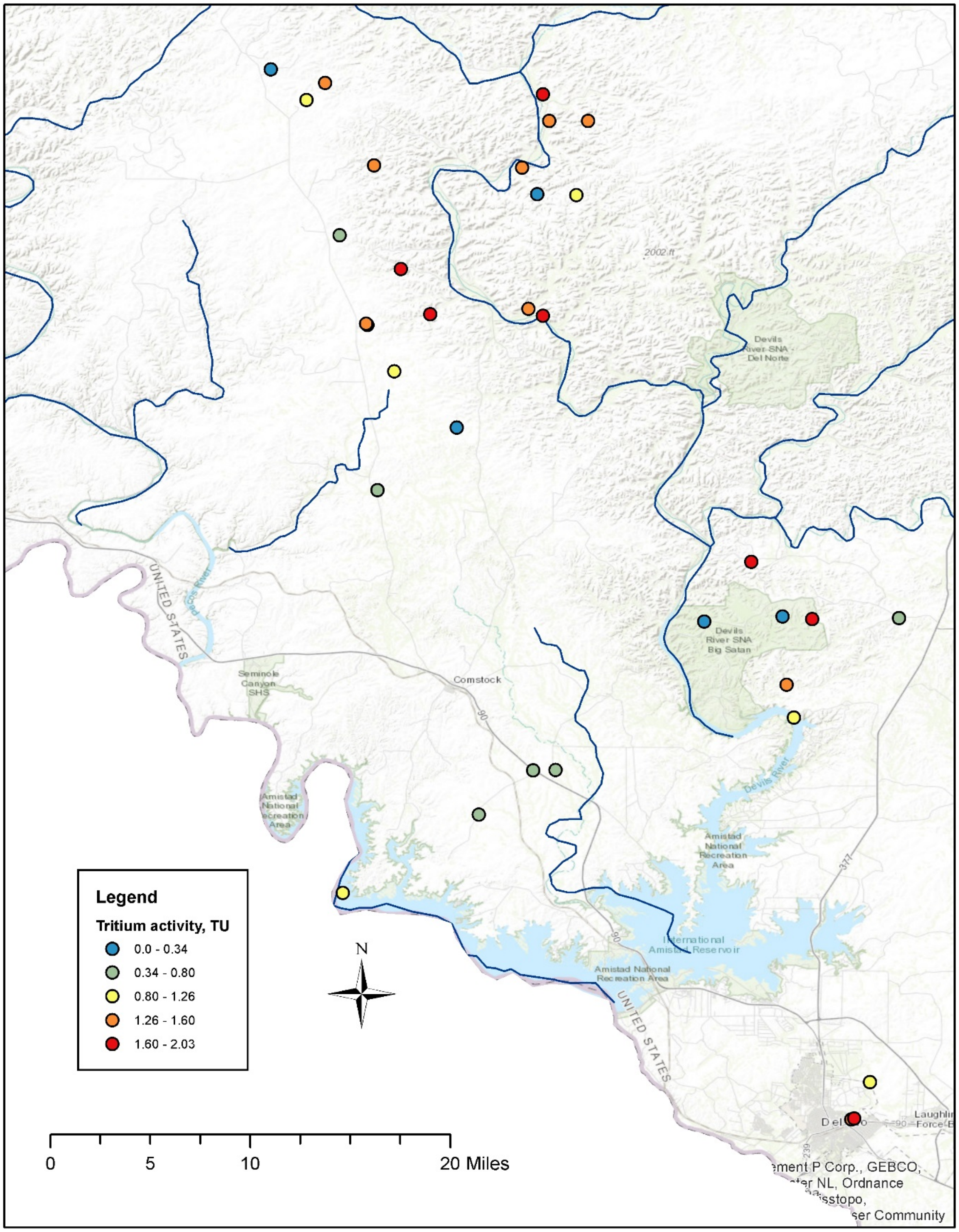

Figure B-5. Geographic distribution of tritium in the groundwater in the Devils River basin.

The major ion chemistry of the groundwater supports a model of conduit flow feeding the major springs largely separate from the aquifer matrix. On the Piper diagram of major ion concentrations in spring discharge and groundwater from Val Verde, Crockett, and Sutton counties (Figure B-6), the springs and Val Verde groundwater plot in a relatively tight cluster close to the calcium bicarbonate corner, while groundwater in Sutton and Crockett counties has a broader dispersion toward higher magnesium, chloride and sulfate contents.

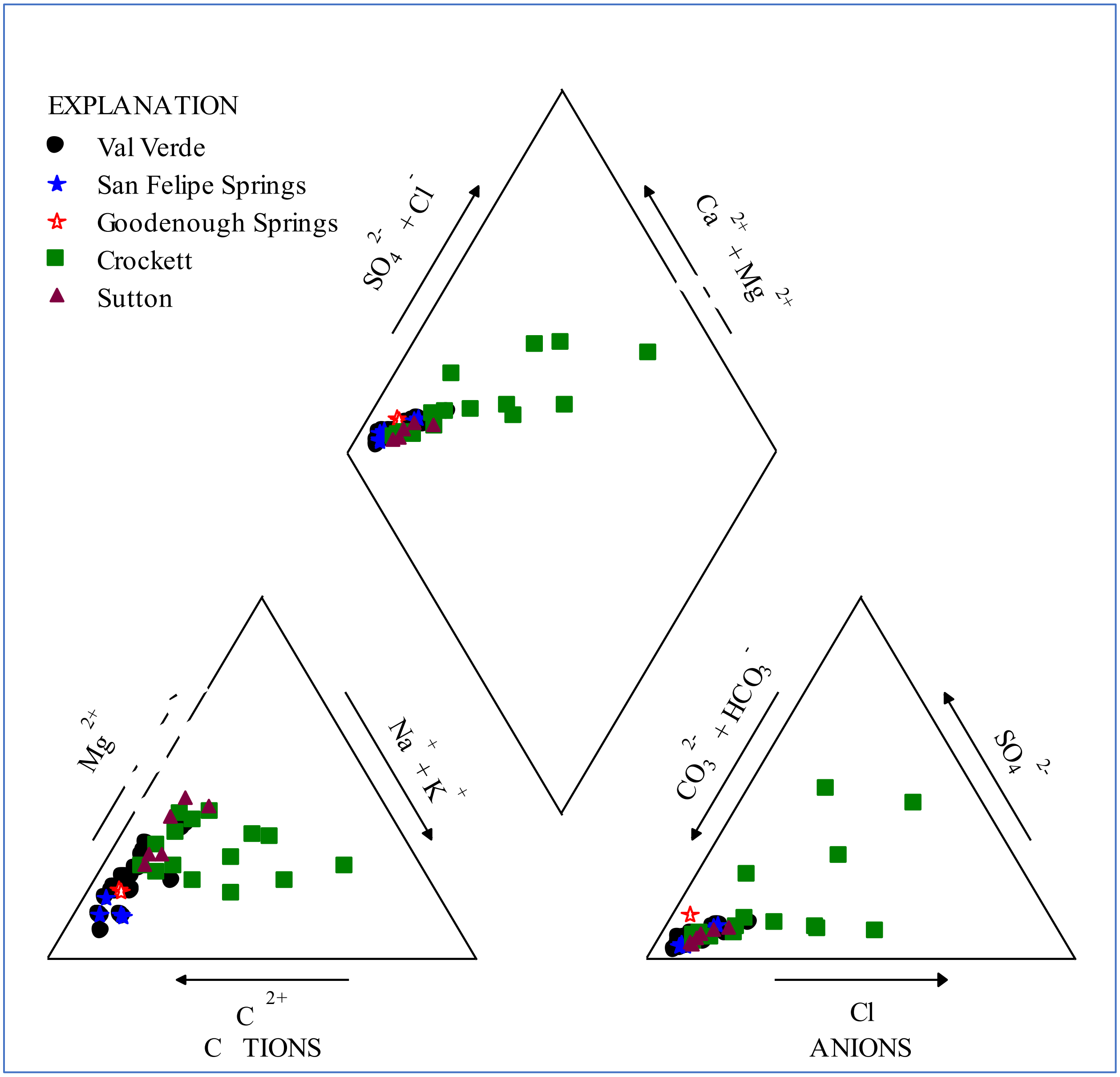

Figure B-6. Piper diagram comparing fresh Edwards Aquifer groundwater in Val Verde, Crockett, and Sutton counties with discharge from Goodenough and San Felipe springs.

Groundwater typically acquires magnesium, chloride, and sulfate during water-rock interactions, and the concentrations of these ions increase along flow-paths between recharge and discharge areas. Although groundwater in Crockett and Sutton counties is hydraulically upgradient from

Val Verde groundwater, the chemical data demonstrate that only a limited fraction of this upgradient groundwater can mix with Val Verde groundwater and still produce a composition consistent with the discharge from the major springs. Work by Nunu and others (2017) shows that these Crockett and Sutton county locations represent low recharge zones away from stream courses, while calcium-bicarbonate type groundwater extends into Crockett and Sutton counties along major drainages as part of a larger, regional flow system.

Other isotope and chemical indicators suggest that Goodenough and San Felipe discharge represent end-member compositions rather than integrating flow from the surrounding groundwater matrix. Nance (2010) uses the magnesium-to-calcium ratio (Mg/Ca) as a proxy for groundwater relative age and as an indicator of relative recharge efficiency, based on the correlations between the Mg/Ca ratio and radiocarbon content in groundwater from Crockett, Sutton, and Schleicher counties where the Mg/Ca ratio increased with apparent radiocarbon age. Musgrove and Banner (2004) use groundwater strontium isotope ratios ($^{87}Sr/^{86}Sr$) as an indicator of reaction with soil and aquifer materials, with the typical strontium isotope composition of soil leachates ranging from 0.7084 to 0.7094, while Edwards carbonate rocks cluster around values of 0.7076 to 0.7078. Goodenough Springs discharge falls along the trend for groundwater reaction with calcite at a moderate water-rock ratio (Figure B-7), with a lower $^{87}Sr/^{86}Sr$ ratio than all groundwater samples and a lower Mg/Ca ratio than all but two samples. San Felipe Springs discharge has a strontium isotope ratio midway between the Edwards carbonate sediments and soil leachates, suggesting it retains more of the signature of soils in its recharge area. Both springs lie along a calcite reaction path in contrast to many of the groundwater samples, which have higher Mg/Ca ratios typical of reaction with dolomites.

These results suggest that much of the flow from these major springs moves along flow-paths distinct from the groundwater found in the aquifer matrix rather than integrating flow from the entire contributing area upgradient from the point of discharge. This is possible in a karstic system where flow along major conduits is several orders of magnitude faster than groundwater flow in the aquifer matrix. Furthermore, it suggests that the conduit system does not simply aggregate diffuse flow from the matrix, but instead has a separate source of recharge. The obvious candidate for conduit recharge is captured surface water runoff that enters sinkholes or major fractures in the upper, intermittent reaches of the alluvial system. This conduit flow moves through the aquifer rapidly and remains distinct from more slowly moving groundwater that originates as diffuse recharge across the majority of the aquifer area. More work is needed to understand how conduit and matrix systems interact under varying aquifer conditions.

The deuterium and oxygen-18 isotope composition of groundwater and spring water provides some additional clues about recharge sources and processes. While the isotopic composition of San Felipe Springs is consistent with groundwater in its drainage basin, the isotopic composition of Goodenough Springs differs from groundwater in Val Verde, Crockett, and Sutton counties, potentially indicating a significant contribution from recharge areas in Mexico.

Deuterium and oxygen-18 are stable isotopes of hydrogen and oxygen that are found in water. The isotopic composition of precipitation varies regionally as a function of fractionation processes in the air masses that produce precipitation, with more negative values relative to standard mean ocean water typically found with increasing distance from the coast and increasing altitude (Kendall, Snyder, and Caldwell, 2004). The isotopic composition of individual precipitation events varies widely but forms a trend known as the local meteoric water line. Groundwater samples typically plot as a cluster along the local meteoric water line, reflecting the average properties of the more intense rain events responsible for most recharge.

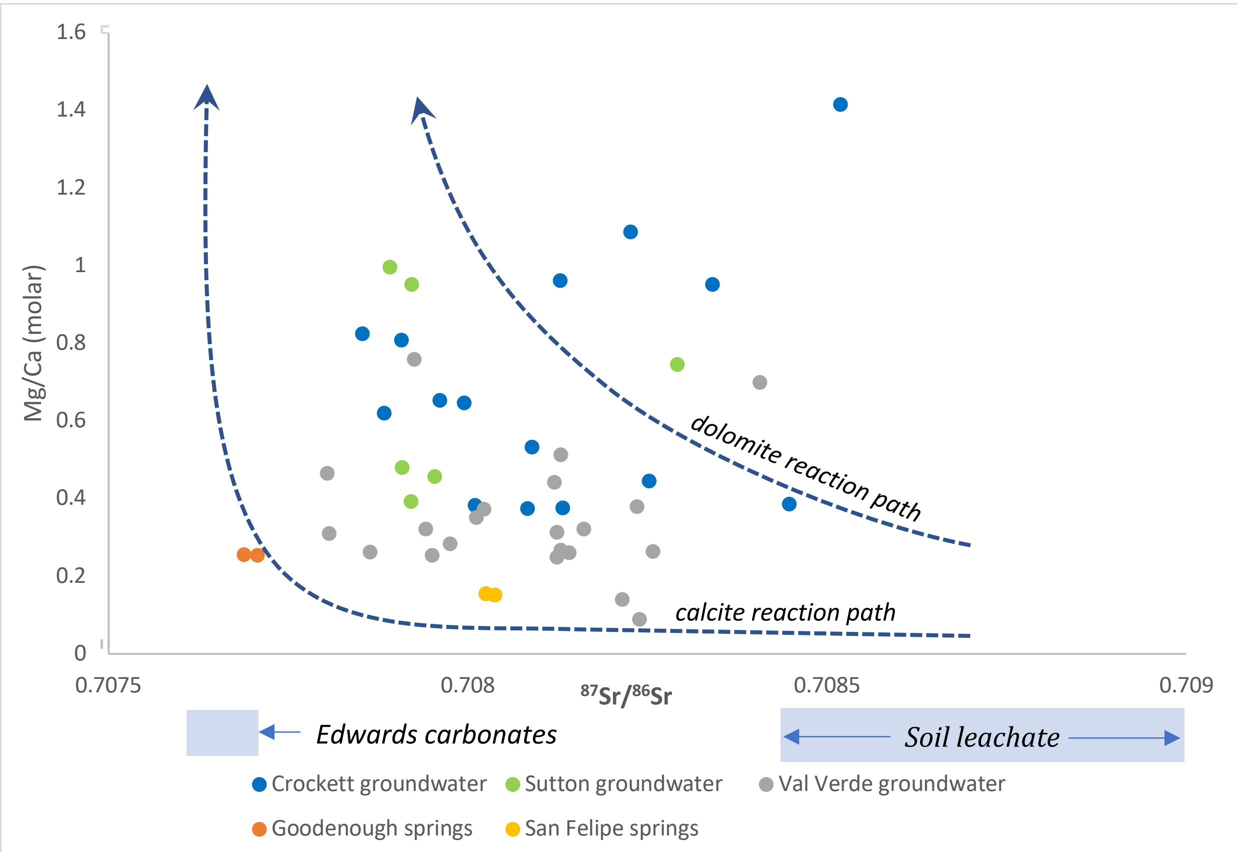

Figure B-7. Strontium isotope ratio and magnesium - calcium ratio for spring and groundwater samples from Val Verde and neighboring counties. Blue boxes show the typical strontium isotope composition of Edwards carbonate rocks and of soil leachates from Musgrove and Banner (2004). Arrows show schematic compositional changes as soil leachates evolve through reactions with calcite and dolomite along groundwater flow-path. Goodenough Springs discharge retains minimal influence from soil leachates, while San Felipe Springs discharge has more of a soil signature.

Deuterium and oxygen-18 results for groundwater in Val Verde, Crockett, and Sutton counties and Goodenough and San Felipe springs water (Figure B-8) generally plot close to the local meteoric water line defined here by GNIP data for Waco, Texas, precipitation (IAEA, 2018), but exhibit some significant geographic differences. The isotopic composition of Val Verde and Sutton County groundwater is tightly clustered and is consistent with San Felipe Springs composition. Crockett County groundwater is more variable, with a large spread between the Pecos and Devils River drainages. The isotopic composition of Goodenough Springs is distinct from Val Verde County groundwater. While the isotopic composition of groundwater in the Pecos River drainage is similar to Goodenough Springs, the chemical composition of the two differ. While Val Verde County groundwater plots along the local meteoric water line, data for Sutton and Crockett counties plots progressively further below the line, reflecting changes in local rainfall patterns with distance from the dominant regional source of moisture in the Gulf of Mexico. San Felipe Springs discharge plots between values for Val Verde and Sutton County groundwater, consistent with the geographic location of the drainage basins of San Felipe and Sycamore creeks, which includes portions of Val Verde and Edwards counties immediately south of Sutton County. In contrast, Goodenough Springs discharge has significantly more negative deuterium and oxygen-18 values than any local groundwater samples, except for a few Crockett County wells in the Pecos River drainage. The major ion chemistry rules out the Pecos basin as a significant source for Goodenough Springs; the Pecos area wells have very different chemical composition than Goodenough Springs discharge, with higher sodium, chloride, and sulfate contents.

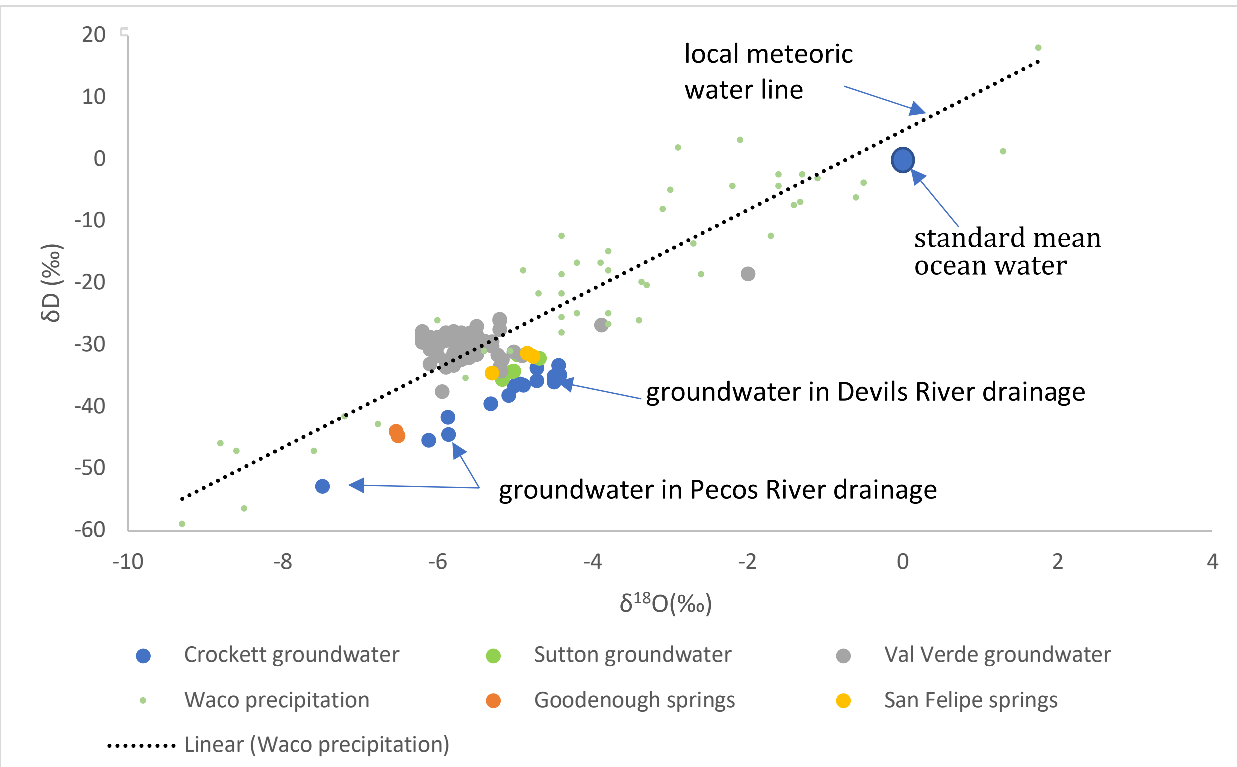

Figure B-8. Deuterium and oxygen-18 isotope values for groundwater and spring samples from Val Verde and adjoining counties, with local meteoric water line based on Waco, Texas, data from Global Network of Isotopes in Precipitation.

The geochemical evidence suggests that a significant component of recharge to Goodenough Springs originates at a higher altitude than is found in Val Verde, Crockett, and Sutton counties. The $\delta^{18}O$ and δD values of precipitation typically decrease with increasing altitude, with a gradient ranging from -0.45 to -1.5 ‰ per 1,000 feet for ^{18}O, and -4.5 to -12 ‰ per 1,000 feet for deuterium (Kendall, Snyder, and Caldwell, 2004). This gradient implies that the average recharge elevation of Goodenough Springs recharge is approximately 1,000 feet higher than the average recharge elevation of Val Verde, Crockett and Sutton County groundwater. The only area that fits these criteria is in Mexico, southwest of Amistad Reservoir, where Tertiary volcanic intrude the Salmon Peak limestone at elevations of 4,000 to 5,000 feet near the contact between the Salmon Peak and Austin Chalk formations (Figures B-9 and B-10). The rise in elevation likely increases precipitation locally, and intense fracturing around the intrusive volcanic provides ready conduits for runoff to infiltrate the Cretaceous carbonates.

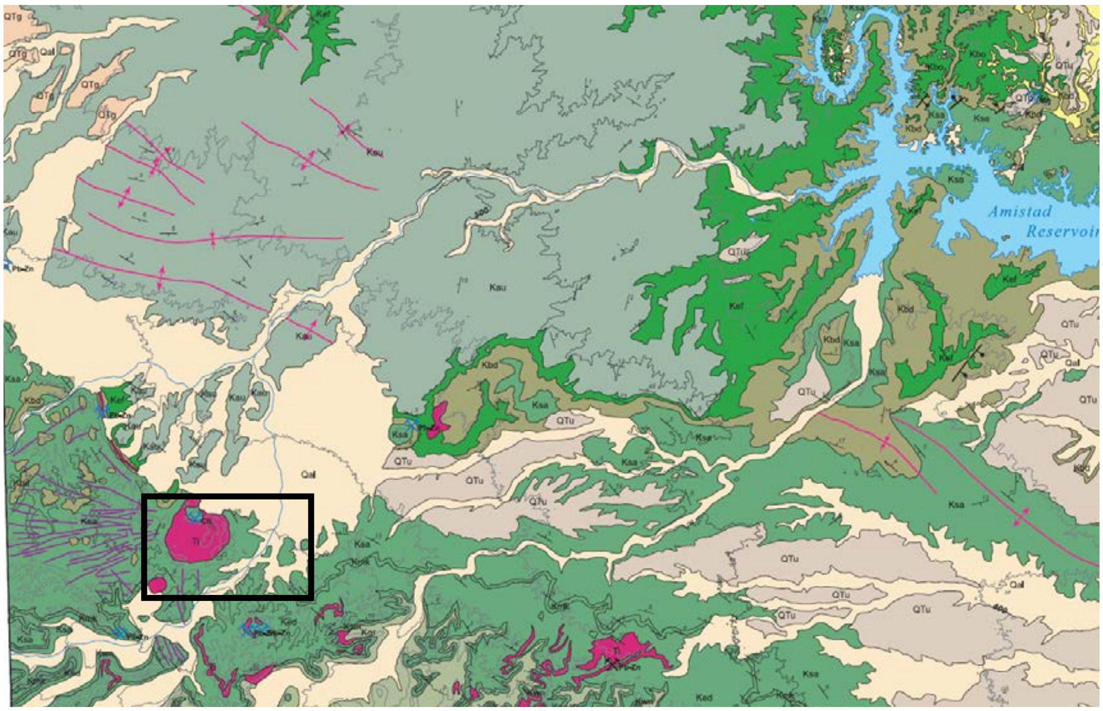

Figure B-9. Geologic map of Coahuila, Mexico, southwest of Amistad Reservoir. Box shows area of aerial image, below.

Figure B-10. Drainage and fracture patterns around Tertiary volcanic intrusions southwest of Amistad Reservoir in Coahuila, Mexico.

Appendix C

Water quality data

Table C-1. Surface water analyses.

Location ID	Location description	Source	Date	Ca	Mg	Na	K	HCO3	Cl	SO4	TDS
13835	Amistad above dam	TCEQ-CRP	4/23/2014	74.2	17.8	92.2	4.58	164.7	77	209	640
15892	Amistad above dam	EPA-STORET	3/1/2005	73.9	17.4	86.7	4.8	168.4	105	161	540
8450900	RG below Amistad	IBWC	2/6/2005	72.4	17.4	79.5	4	159.8	96.6	145.7	526
8450900	RG below Amistad	IBWC	3/7/2005	83.1	20	114	4.6	162.3	142.8	197.6	687
8450900	RG below Amistad	IBWC	4/4/2005	77.9	18.9	89.6	4.3	157.4	104.3	156.8	553
8450900	RG below Amistad	IBWC	8/1/2005	75.1	18	90	4.1	169.6	113.6	159.8	585
13223	RG above Langtry	EPA-STORET	1/28/2004	138	17.9	103	4.77	145.2	77.3	356	813
13223	RG above Langtry	EPA-STORET	2/24/2004	83.3	23.4	94.2	4.81	170.8	84.3	239	655
13223	RG above Langtry	EPA-STORET	4/14/2004	68.7	9.21	82.3	4.04	169.6	54.5	163	501
13223	RG above Langtry	EPA-STORET	7/14/2004	77.7	15.8	81.1	5.42	205.0	53.7	185	553
13223	RG above Langtry	EPA-STORET	8/4/2004	103	10.1	49.9	4.72	134.2	19.8	243	534
8377200	RG at Foster Ranch	USGS	2/14/2007	115	32	259	7.13	209.8	292	428	1290
8377201	RG at Foster Ranch	USGS	3/14/2007	77.6	18.4	115	5.55	145.2	123	229	715
8377202	RG at Foster Ranch	USGS	4/25/2007	96.5	25.8	161	6.5	176.9	142	363	957
8377203	RG at Foster Ranch	USGS	5/23/2007	74.8	7.67	76.1	4.66	128.1	34	224	527
8377204	RG at Foster Ranch	USGS	7/18/2007	92.8	8.84	86.7	5.62	124.4	33.8	276	611
8377205	RG at Foster Ranch	USGS	8/15/2007	99.5	12	129	6.97	185.4	88.9	319	825
8377206	RG at Foster Ranch	USGS	9/6/2007	88.8	21.7	140	6.24	167.1	107	328	865
18801	CAMS 729	TCEQ SWQMIS	10/4/2012	132	56.7	343	9.69	228.1	539	368	1677
18801	CAMS 729	TCEQ SWQMIS	4/25/2013	196	103	644	9.21	206.2	1020	641	2819
18801	CAMS 729	TCEQ SWQMIS	7/10/2013	136	71.2	422	9.65	190.3	801	480	2110
18801	CAMS 729	TCEQ SWQMIS	11/18/2013	172	85.4	517	11.1	226.9	906	519	2437
18801	CAMS 729	TCEQ SWQMIS	4/9/2014	189	97.1	594	11.7	226.9	1030	608	2757
18801	CAMS 729	TCEQ SWQMIS	10/21/2014	529	183	1140	30.1	170.8	2050	1720	5823
18801	CAMS 729	TCEQ SWQMIS	4/14/2015	345	128	805	20.6	192.8	1580	1250	4321
18801	CAMS 729	TCEQ SWQMIS	7/28/2015	271	120	774	14.9	185.4	1340	886	3591
Goodenough	Goodenough Springs	Kamps et al	6/25/2005	50.9	10.2	3.4	1.5	253.8	10	17	263
Goodenough	Goodenough Springs	USGS, 2005	1967-68 median	72	13	9.9	1.6	248.3	10	25	278
Devils River	at Pafford Crossing	Mast and Turk	1978 –95 median	53.1	13.6	8.3	1.3	199	15	9.1	299

Table C-2. Groundwater analyses.

State well number	Source	Date	Ca	Mg	Na	K	HCO3	Cl	SO4	TDS
5452605	TWDB	4/1/2003	88.1	15	21.4	1.99	294.1	44.1	16	371
5454302	TWDB	10/21/2004	78.5	11.4	6.87	1.8	270.9	11.6	7.36	280
5454502	TWDB	4/1/2003	72.5	13.8	14.8	1.19	256.3	24.6	12.6	307
5454804	TWDB	8/20/2007	49.9	21.2	14.8	0.7	219.7	24	15	256
5455904	TWDB	10/21/2004	70.9	14.8	9.08	1.21	266.0	12.9	9.85	278
5462302	TWDB	8/20/2007	77.4	15.1	9.6	1.4	279.5	14	14	297
5462603	TWDB	8/20/2007	77.1	16.8	24.9	2.8	250.2	39	28	344
5462902	TWDB	8/20/2007	55.3	17.2	6.7	1	224.5	10	9	231
5463403	TWDB	8/20/2007	71.6	16.2	8.8	1.4	270.9	12	12	281
5463802	TWDB	10/19/2004	73	12.9	7.02	1.36	267.3	10.1	8.84	269
5463803	TWDB	10/19/2004	72	13.1	8.83	1.32	262.4	12.8	9.85	274
5463901	TWDB	10/19/2004	72.3	15.2	8.06	1.41	275.8	12.1	8.89	280
5464102	TWDB	8/23/2007	78.8	15.2	7.9	1.7	289.2	11	12	295
5464103	TWDB	8/23/2007	81.4	15.9	8.2	1.7	296.5	12	12	303
5464702	TWDB	8/23/2007	68	10.9	5.4	0.8	222.1	7	11	230
5541706	TWDB	10/21/2004	78.1	16.5	7.88	2.01	279.5	12.8	19.4	308
5557801	TWDB	10/25/2004	73.3	11	6.69	1.34	250.2	12.8	6.19	263
5558803	TWDB	3/19/2003	35.5	21.9	6.39	0.63	205.0	10.7	8.36	203
7002602	TWDB	10/22/2004	37.3	20.4	4.75	0.75	197.7	7.65	6.13	193
7009803	TWDB	8/22/2007	68.5	13	6.4	1.3	259.9	10	8	258
7010803	TWDB	3/19/2003	41.5	14.1	5.86	0.73	195.3	8.95	4.76	188
7011402	TWDB	3/12/2003	51	10.9	10.2	0.61	179.4	15.6	7.58	211
7017102	TWDB	4/28/2003	49.5	22.8	15.3	1.27	234.3	21.6	21.3	265
7017201	TWDB	7/15/2015	54.5	17.4	6.39	1.03	240.4	9.64	6.06	235
7017203	TWDB	8/22/2007	56.2	15.1	7.4	0.9	222.1	11	7	229

State well number	Source	Date	Ca	Mg	Na	K	HCO3	Cl	SO4	TDS
7017302	TWDB	8/17/2010	65.2	10.3	5.06	1.02	230.6	8.33	5.33	230
7017402	TWDB	4/28/2003	52.1	16.9	9.39	0.68	212.3	15.2	21.9	246
7017402	TWDB	7/15/2015	59.7	14.6	12.9	0.68	214.8	23.1	25.7	274
7017403	TWDB	7/15/2015	56.2	10.6	8.15	0.94	214.8	13.3	7.61	222
7017502	TWDB	8/17/2010	81.5	4.38	9.77	0.7	235.5	18	10.4	272
7017502	TWDB	6/17/2015	88.2	3.04	13.5	0.88	245.3	24.6	11.7	304
7017601	TWDB	8/17/2010	61.9	7.78	6.23	0.69	207.4	10.7	6.73	216
7017601	TWDB	6/17/2015	58.9	8.8	5.62	0.87	212.3	8.88	5.23	213
7018102	TWDB	8/22/2007	59.7	9.2	5.1	0.9	207.5	7	8	210
7018303	TWDB	9/30/2004	80.4	3.33	4.97	0.94	216	5.28	36.9	254
7025101	TWDB	9/30/2004	57.5	9.31	5.46	0.72	205.0	7.75	4.73	208
7025204	TWDB	9/30/2004	76.4	2.54	14.1	0.6	206.2	21.2	11.5	260
7025601	TWDB	3/12/2003	77.1	8.46	10.1	1.25	240.4	19	9.49	273
7033501	TWDB	6/4/1969	78	7.3	41	0.8	241.1	59	19	358
7033501	TWDB	5/29/1976	137	6	107	0.8	268.5	141	160	729
7033501	TWDB	6/12/1979	145	10	119	0.8	266.0	144	218	814
7033501	TWDB	4/29/1985	132	6.6	116	1	278.2	156	137	739
7033503	TWDB	10/26/2004	90.4	13.5	64.1	2.71	223.3	74.8	120	497
7033504	TWDB	10/26/2004	107	8.78	20.5	1.49	313.6	45.7	36.7	404
7033604	TWDB	7/22/1968	74	8	9	1.2	238	20	6.7	253
7033604	TWDB	5/20/1976	80	7	41	0.8	219.7	53	59	363
7033604	TWDB	10/17/1984	85	10	60	2	217.2	72	97	449
7033604	TWDB	10/22/2004	88.5	11.5	79.9	2.08	207.5	90.3	129	519
7033605	TWDB	5/25/1976	99	9	68	0.8	220.9	86	131	520
7033605	TWDB	6/12/1979	100	14	77	0.8	217.2	89	161	567
7033605	TWDB	4/29/1985	106	7	87	3	218.4	94	169	594
7033605	TWDB	6/8/1993	100	16	107	3.9	222.1	110	191	661
7033605	TWDB	9/16/1997	100.9	16.5	83.5	3.14	222.1	101	145	587
7033605	TWDB	3/12/2003	91.4	12.1	51	2.38	239.2	64.4	85.1	450

State well number	Source	Date	Ca	Mg	Na	K	HCO3	Cl	SO4	TDS
7033904	TWDB	3/10/2003	88.5	10.7	43.3	2.01	241.6	57.8	74.2	422
7034703	TWDB	3/12/2003	105	21.9	16.9	1.35	275.8	63	53.5	434
7034704	TWDB	8/18/2010	81.4	6.9	7.4	0.73	253.8	12.6	8.27	262
7041301	TWDB	2/4/1966	76	6.9	5.8	0.8	250	12	5.8	246
7041301	TWDB	5/25/1966	74	6.1	5.5	2.3	241.0	10	4.3	237
7041301	TWDB	9/21/1966	72	5.5	4.4	0.8	206.0	9.6	7.2	219
7041301	TWDB	10/11/1972	80	7.2	5.8	1.3	253	8.9	7	249
7041301	TWDB	2/20/1973	80	7.2	5.6	1	235	11	7.6	251
7041301	TWDB	10/31/1973	72	9.3	5.2	1	243	10	8.4	248
7041301	TWDB	7/9/1974	75	7.2	5.7	0.9	247	9.4	8.6	251
7041301	TWDB	1/16/1975	71	6.9	5.4	1.1	240.0	9.7	8.1	243
7041301	TWDB	1/16/1976	73	7.3	5.2	0.9	249	9.5	5.7	236
7041301	TWDB	6/12/1993	81	7.5	6.1	1.1	246.5	10	9	257
7041301	TWDB	4/1/1994	72	6.9	5.9	0.8	231.9	11	9.4	228
7041301	TWDB	9/15/1997	76.3	8.05	7.4	1.34	230.7	12.9	19.1	262
7041301	TWDB	3/11/1999	74.2	6.77	5.36	0.87	247.7	9.8	6.86	234
7041301	TWDB	3/13/2003	78.7	7.17	5.69	0.93	246.5	9.34	6.98	253
7041301	TWDB	3/13/2003	78.7	7.17	5.69	0.93	246.5	9.34	6.98	253
7041302	TWDB	6/16/2015	89.3	9.41	21.4	1.26	261.2	33.9	39.2	345
7103102	TWDB	3/20/2003	101	51	42.2	3.07	246.5	44.9	281	674
7104402	TWDB	10/23/2004	80.7	28.5	49.4	2.22	269.7	85.5	77.5	484
7104502	TWDB	3/20/2003	68.6	21.9	11.5	1.08	281.9	20.6	22.1	308
7107101	TWDB	8/21/2007	71.6	10.6	6.8	1.5	237.9	10	12	253
7107401	TWDB	10/20/2004	65.1	15.4	9.52	1.23	253.8	14.5	9.23	268
7107401	TWDB	8/21/2007	72	16.6	10.4	1.3	257.5	15	12	285
7107702	TWDB	8/21/2007	68.3	19.3	9.3	1.4	270.9	13	18	303
7108102	TWDB	8/23/2007	77.6	13.4	7.5	1.6	258.7	11	11	272
7108401	TWDB	8/23/2007	87.1	14.7	9.6	1.1	284.3	15	14	308
7112502	TWDB	3/11/2003	105	29.5	120	2.58	220.9	193	152	738

State well number	Source	Date	Ca	Mg	Na	K	HCO3	Cl	SO4	TDS
7112502	TWDB	6/16/2015	98.6	29.8	120	2.44	223.3	202	161	749
7113901	TWDB	3/19/2003	84.4	35.9	49.9	0.96	244.1	76.9	145	540
7115202	TWDB	8/21/2007	62.6	10.3	10	0.9	216	15	9	243
7115401	TWDB	3/13/2003	68.6	10.1	4.72	2.2	236.8	7.86	4.67	243
7122501	TWDB	3/11/2003	79.3	9.97	8.34	1.5	251.4	12.5	16.5	279
7122501	TWDB	6/16/2015	70.9	42.6	26.8	0.94	286.8	42.5	103	449
7122902	TWDB	3/19/2003	65.5	18.4	12.8	1.56	249	19.4	37.1	301
7123502	TWDB	9/3/1965	60	13	9	1.2	229.1	16	9	240
7123502	TWDB	8/27/1969	62	14	9.2	1.3	240.1	14	9	250
7123502	TWDB	6/10/1993	70	15	9.6	1.6	246.5	15	11	270
7123502	TWDB	3/11/2003	67.1	14.6	9.26	1.42	250.2	14.4	9.87	267
7123502	TWDB	6/16/2015	64.5	14.8	10.2	1.31	252.6	7.28	4.89	252
7123901	TWDB	3/30/1950	66	14	9.9	1.6	256.1	14	12	272
7123901	TWDB	5/27/1976	67	12	9	0.8	240.4	14	11	257
7123901	TWDB	6/12/1979	54	14	8	0.8	203.8	20	11	227
7123901	TWDB	5/17/1994	70	14	9.1	1.5	255.1	15	11	271
7123901	TWDB	10/22/2004	70.3	11.4	8.49	1.3	247.7	12.6	12.7	264
7123901	TWDB	10/22/2004	70.3	11.4	8.49	1.3	247.7	12.6	12.7	264
7124702	TWDB	8/16/2010	68.9	11	10.1	1.85	228.2	18.2	14	263
7131302	TWDB	8/16/2010	73.7	13.9	10.6	1.1	225.8	16.2	43.5	298
7131802	TWDB	3/20/2003	80.3	16.3	13.2	1.46	228.2	16.8	55.4	323
7131803	TWDB	9/29/2004	70.6	12.4	10.7	1.16	235.5	15.6	30.7	284
7131904	TWDB	9/29/2004	70.8	11.5	12.5	1.08	234.3	16.3	27.2	284
7132101	TWDB	8/16/2010	41.8	8.91	42.6	1.09	84.2	83.8	34.7	299
7132803	TWDB	3/20/2003	138	10.8	98	1.58	277.0	177	137	736
7140307	TWDB	3/19/2003	97	10.9	109	2.25	220.9	126	169	641

Table C-3. TWDB isotopic analyses – Val Verde County groundwater and spring discharge.

Well No.[1]	Latitude	Longitude	Sample date	^{14}C, pmc	$\delta^{13}C$, (‰)	δD (‰)	$\delta^{18}O$ (‰)	$\delta^{18}O$ SO4(‰)	$^{87}Sr/^{86}Sr$	Sr, uG/L	$\delta^{34}S$ SO_4 (‰)	Tritium (TU)
5454804	30.131943	-101.30528	8/1/2006	0.3079	-6.1	-29.6	-5.8	2.7	0.708406	241.5	8.4	0.34
5454804	30.131943	-101.30528	8/20/2007	0.3083	-6.8	-32.4	-5.7					0.02
5455906	30.132221	-101.15889	8/2/2006	0.701	-10.2	-28.4	-5.5		0.708059	574.5	8.3	
5462301	30.109722	-101.27944	8/1/2006	0.6236	-12.3	-29.4	-5.4		0.708255	291.7	8.5	1.19
5462302	30.122221	-101.26583	8/1/2006	0.6579	-9.7	-29.9	-5.6	3	0.708161	405.2	7.6	1.37
5462302	30.122221	-101.26583	8/20/2007	0.7414	-8.6	-30.7	-5.7					
5462603	30.056111	-101.26972	8/20/2007	0.5065	-6.4	-27.5	-5.2					
5462902	30.011944	-101.25528	8/1/2006	0.5304	-8.5	-30.7	-6.1	4.9	0.708129	279.6	7	0.55
5462902	30.011944	-101.25528	8/20/2007	0.554	-7.8	-32.6	-5.9					
5463301	30.124166	-101.14111	8/2/2006	0.6915	-9.9	-28.1	-5.6	3.4	0.707936	1305	7.9	
5463403	30.0625	-101.23055	8/1/2006	0.6554	-9	-30	-5.5	2.8	0.708022	709.4	8.1	1.41
5463403	30.0625	-101.23055	8/20/2007	0.7054	-8.7	-30.2	-6					1.56
5464102	30.113888	-101.10833	8/2/2006			-28	-5.9		0.707929	949.8	7.8	1.76
5464102	30.113888	-101.10833	8/23/2007	0.815	-9.9	-30.2	-5.3					2.01
5464103	30.094721	-101.10361	8/2/2006	0.7223	-10.4	-28.6	-5.8		0.707941	875.7	12.9	1.59
5464103	30.094721	-101.10361	8/23/2007	0.7764	-9.6	-31.5	-5.5					

Well No.[1]	Latitude	Longitude	Sample date	^{14}C, pmc	$\delta^{13}C$, (‰)	δD (‰)	$\delta^{18}O$ (‰)	$\delta^{18}O$ SO4(‰)	$^{87}Sr/^{86}Sr$	Sr, uG/L	$\delta^{34}S$ SO_4 (‰)	Tritium (TU)
5464205	30.094721	-101.07555	8/2/2006	0.6778	-9.3	-29.3	-5.9	2.9	0.707952	785.1	8.4	1.44
5464401	30.073054	-101.1175	8/2/2006	0.7341	-10.4	-27.8	-5.8		0.7079455	866.5	9.5	
5464402	30.060833	-101.12333	8/2/2006	0.7232	-10.3	-28.7	-6		0.7079535	713.8	8.7	1.6
5464404	30.041666	-101.1125	8/2/2006	0.2551	-9.4	-29.1	-5.9	5.1	0.708166	136.3	4.1	0.04
5464702	30.04111	-101.08417	8/3/2006	0.6498	-8.4	-28	-5.7		0.708257	182.6	16	1.21
5464702	30.04111	-101.08417	8/23/2007	0.7979	-9.6	-26.1	-5.2					
7009803	29.775832	-100.9575	7/31/2006	0.7304	-10.3	-29.3	-6		0.708124	247.1	9.1	1.69
7009803	29.775832	-100.9575	8/22/2007	0.7841	-4.5	-33.3	-5.8					
7017102	29.732777	-100.99167	8/3/2006	0.1533	-7.5	-25.8	-5.2	8.2	0.707925	589.6	7.1	0.07
7017102	29.732777	-100.99167	4/28/2003									
7017203	29.736388	-100.935	8/3/2006	0.4637	-8.8	-28.9	-6.2		0.7081205	189.8	8.8	0.13
7017203	29.736388	-100.935	8/22/2007	0.5078	-7.4	-31.3	-5.8					
7017302	29.734444	-100.91333	7/31/2006	0.7451	-10.1	-30	-6	2.3	0.70814	181.1	9.3	1.86
7017302	29.734444	-100.91333	8/17/2010	0.7464	-11.7	-31.6	-5.23	3.7	0.708141		8.6	1.37
7017502	29.686944	-100.93194	8/17/2010	0.7923	-13	-26.8	-3.89	2.6	0.708239		4.8	1.58
7017801	29.663333	-100.92667	9/12/2009	0.7205	-11.5	-33.6	-5.2	5.9	0.708129		9.2	1.23
7017801	29.663333	-100.92667	3/5/2010	0.7408	-11.8	-34.2	-5.19	2.8	0.708124		8.2	1.26

Well No.[1]	Latitude	Longitude	Sample date	^{14}C, pmc	$\delta^{13}C$, (‰)	δD (‰)	$\delta^{18}O$ (‰)	$\delta^{18}O$ SO4(‰)	$^{87}Sr/^{86}Sr$	Sr, uG/L	$\delta^{34}S$ SO_4 (‰)	Tritium (TU)
7018102	29.735277	-100.85056	7/31/2006	0.4772	-8.6	-28.4	-6.2		0.70795	226	8.8	0.67
7018102	29.735277	-100.85056	8/22/2007	0.7773	-10.1	-27	-5.5					
7034704	29.399721	-100.87167	8/18/2010	0.7417	-12.5	-31.7	-4.91	5.9	0.708215		5.5	1.2
7107101	29.987499	-101.21111	8/1/2006	0.6686	-9.1	-29	-5.9	2.3	0.708033	652.2	8.3	1.37
7107101	29.987499	-101.21111	8/21/2007	0.791	-13.4	-33.1	-6.1					2.03
7107401	29.947221	-101.23528	8/1/2006	0.2992	-6.2	-28.7	-6.1	2.1	0.708235	406.8	5.7	0.29
7107401	29.947221	-101.23528	8/21/2007	0.6052	-7.9	-31.7	-6					
7107402	29.948055	-101.23611	8/1/2006	0.5773	-8.3	-29.6	-6.2	2.5	0.708022	333.3	8.3	1.4
7107503	29.955	-101.18972	8/3/2006	0.6728	-10.1	-28.9	-5.5		0.708061	491.4	3.8	1.71
7107702	29.913611	-101.21583	8/3/2006	0.5513	-8.4	-29.9	-5.7		0.707804	5876	16.5	1.18
7107702	29.913611	-101.21583	8/21/2007	0.5547	-7.2	-33.6	-5.9					
7108102	29.958888	-101.11889	8/3/2006	0.7196	-10.2	-28.5	-5.5		0.707975	738.2	8.4	1.49
7108102	29.958888	-101.11889	8/23/2007	0.8019	-10.3	-32.3	-5.8					
7108401	29.953888	-101.10833	8/3/2006	0.708	-9.9	-29	-5.8	2.7	0.707993	616.8	7.5	1.87
7108401	29.953888	-101.10833	8/23/2007	0.8502	-9.7	-29.5	-5.3					1.82
7115201	29.873054	-101.17055	8/3/2006	0.3949	-8.1	-27.8	-6.2		0.708065	633.8	10.2	0.28
7115202	29.856388	-101.18722	8/21/2007	0.3418	-7	-32	-5.6					

Well No.[1]	Latitude	Longitude	Sample date	^{14}C, pmc	$\delta^{13}C$, (‰)	δD (‰)	$\delta^{18}O$ (‰)	$\delta^{18}O$ SO4(‰)	$^{87}Sr/^{86}Sr$	Sr, uG/L	$\delta^{34}S$ SO_4 (‰)	Tritium (TU)
7115401	29.827777	-101.22805	1/17/2002	0.363	-9.6	-37.5	-5.95					0.79
7115401	29.827777	-101.22805	3/13/2003									
7124702	29.625277	-101.09917	8/16/2010	0.4599	-9.6	-31.1	-5.02	4.2	0.707864		2.5	0.74
7131302	29.593055	-101.15472	8/16/2010	0.4548	-9.3	-32.4	-5.17	7.3	0.707807		-5.8	0.8
7132101	29.624999	-101.11528	8/16/2010	0.2785	-15.1	-18.5	-2	5.5	0.708012		-1.9	0.56
7130901	29.536388	-101.25306	9/12/2009	0.5411	-10.3	-44.7	-6.52	5.8	0.707688		-4.2	1.13
7130901	29.536388	-101.25306	3/6/2010	0.5131	-10.2	-43.9	-6.54	6.1	0.707707		-3.5	0.96
7041301	29.373332	-100.88305	1/18/2002	0.741	-11.8	-34.5	-5.3					1.85
7041301	29.373332	-100.88305	3/13/2003									
7041302	29.372777	-100.885	9/11/2009	0.7054	-12	-31.8	-4.77	5.4	0.708025		2.5	1.17
7041302	29.372777	-100.885	3/6/2010	0.7022	-12.3	-31.3	-4.85	9.6	0.708037		2.3	1.35

[1] Well numbers in bold represent spring water samples

[2] Estimated distance to nearest drainage; minimum of 100 meters. Spring samples listed as 500m to enhance visibility on plots.

Table C-4. Isotope data for Crockett and Sutton County Edwards groundwater samples, from Nance, 2010.

Well No.	County	Latitude	Longitude	$^{87}Sr/^{86}Sr$	$\delta^{18}O$, (‰)	δD (‰)	$\delta^{13}C$ (‰)	^{14}C, pmc	Tritium (TU)
5403506	Crockett	30.9511	-101.6948	0.708083	-5.87	-41.7	-6	0.703	3.28
5405406	Crockett	30.9413	-101.4636	0.708518	-6.12	-45.4	-6.6	0.071	0.09
5411306	Crockett	30.8705	-101.6461	0.708226	-7.49	-52.8	-6	0.113	0.02
5411512	Crockett	30.8201	-101.6778	0.707995	-5.86	-44.4	-9.8	0.541	1.93
5414503	Crockett	30.8038	-101.302	0.707883	-4.72	-35.8	-6.6	0.328	0.83
5422901	Crockett	30.6441	-101.2706	0.707853	-4.5	-35	-6	0.237	0.03
5423204	Crockett	30.7127	-101.1978	0.70801	-4.9	-36.5	-8	0.427	1.04
5431602	Crockett	30.5579	-101.1659	0.708252	-4.94	-36.3	-6	0.449	1.14
5432206	Crockett	30.6244	-101.0697	0.708128	-4.43	-34.8	-5.4	0.155	0.01
5432503	Crockett	30.549	-101.0747	0.708089	-4.44	-33.3	-7.3	0.353	0.39
5438903	Crockett	30.4726	-101.0829	0.708447	-5.01	-36.6	-7.8	0.507	0.9
5440201	Crockett	30.3986	-101.2795	0.707961	-4.72	-33.7	-7	0.332	0.11
5444401	Crockett	30.3126	-101.6085	0.70834	-4.5	-36	-5.4	0.159	0.18
5445201	Crockett	30.3758	-101.4532	0.708132	-5.32	-39.5	-9.5	0.586	1.62
5446502	Crockett	30.3021	-101.317	0.707907	-5.09	-38.1	-7	0.342	0.6
5522901	Sutton	30.6426	-100.2509	0.707891	-4.69	-32.1	-7	0.216	0.12
5525901	Sutton	30.512	-100.9003	0.707908	-5.05	-34.3	-11.1	0.548	0.99
5527603	Sutton	30.5749	-100.6424	0.707954	-5.17	-35.6	-9.3	0.611	1.14
5530402	Sutton	30.5622	-100.347	0.707922	-5.02	-34.2	-8.1	0.333	0
5541202	Sutton	30.3511	-100.9436	0.707921	-4.98	-31.7	-9.6	0.6	1.06
5545307	Sutton	30.3592	-100.3981	0.708291	-5.36	NA	-10.2	0.41	0.5

NA= not available

Table C-5. Water quality data for Crockett and Sutton County Edwards groundwater samples, from Nance, 2010.

Well No.	Si	Ca	Mg	Na	K	Sr	HCO3	SO4	Cl	F	NO3	pH	TDS
5403506	28	97	22	22	4.5	1.78	281	80	30	0.4	8.85	7	433
5405406	9	134	115	478	15.9	4.06	351	723	512	2.6	0.22	7.2	2166
5411306	11	91	60	116	5.7	2.65	288	304	89	1.9	0.22	7	823
5411512	27	130	51	100	4.4	3.73	349	190	152	1	8.85	6.8	839
5414503	17	77	29	113	3.2	1.43	271	36	183	1.1	8.85	7.1	603
5422901	20	56	28	20	1.5	1.44	247	22	32	2.3	15.94	7.4	320
5423204	18	86	20	40	2.4	1.09	278	33	61	0.9	12.84	6.7	412
5431602	22	85	23	27	2.1	0.64	308	22	40	0.6	12.84	6.9	386
5432206	18	60	35	59	2	0.74	256	31	92	1.3	14.17	7.4	439
5432503	15	65	21	12	0.9	0.44	250	14	14	0.4	15.49	7.4	280
5440201	17	63	25	17	0.8	0.73	268	15	22	0.6	4.87	7.1	297
5438903	21	77	18	12	0.9	0.27	281	12	16	0.4	11.51	6.9	306
5444401	16	45	26	21	1	4.08	211	25	30	2.4	12.4	7.4	287
5445201	21	92	21	74	2.3	1	303	35	112	0.6	10.18	7.2	518
5446502	15	55	27	13	1.2	6.14	261	17	16	1.6	5.76	6.9	286
5522901	17	48	29	21	1.3	4.43	238	20	27	0.9	9.3	7.4	295
5525901	17	72	21	16	1.8	2.26	276	20	24	0.6	11.95	7.1	322
5527603	15	72	20	11	1.5	1.37	298	11	15	0.3	7.08	7.2	300
5530402	13	45	26	11	0.9	1.44	239	12	14	0.7	3.54	7.4	245
5541202	17	84	20	14	1.8	1.84	308	18	20	0.5	10.18	7	338
5545307	14	53	24	10	1.3	0.24	261	8	15	0.3	3.54	7.2	258

Appendix D

Public comments

Comments to: Hydrogeology of Val Verde County with emphasis on the Devils River Watershed and San Felipe Springs

Ronald T. Green, Ph.D., P.G.
Southwest Research Institute®
January 24, 2018
Del Rio, Texas

1) The cretaceous-age carbonate Edwards-Trinity Aquifer is dominated by karstic preferential flow paths (i.e., conduits) aligned with major and minor tributaries. These preferential flow features appear to be restricted to within 120-150 ft of ground surface.

2) The upper reaches of the major watersheds in Val Verde County (i.e., lower Pecos River, Devils River, Sycamore Creek) are hydraulically separate. The lowest reaches of these watersheds, where the aquifers are confined or semi-confined, may be in hydraulic communication. The result is that most of these watersheds act separately hydraulically. For example, pumping in the upper reach of one watershed will not draw water from adjoining watersheds.

3) Each of the three watersheds should be assigned a separate drought trigger. Again, this is because pumping from the upper reach of one watershed will not draw water from adjoining watersheds. Triggers could be in terms of river flow or groundwater elevation, which are correlated. Complications are encountered when pumping from the lower reach of any of the watersheds. This is because: (1) Pumping from near Amistad Reservoir will extract surface water from the Reservoir and limit the amount of groundwater pulled from the watershed. (2) Pumping from regions where the aquifers are confined or semi-confined can result in extraction from adjoining watersheds.

4) The extents and boundaries of the springshed for San Felipe Springs and the watershed for Sycamore Creek are not fully defined. Additional work is needed to define these watersheds and to better define the hydraulic relationship among the lower Devils River, San Felipe Springs capture area, Sycamore Creek watershed, Amistad Reservoir, and Rio Grande. These

hydraulic relationships are complicated by the facts that the lower reaches of the aquifers may be confined or semi-confined and the close proximity of a surface-water boundary condition in Amistad Reservoir and the Rio Grande. One important limiting factor is that the discharge from either San Felipe Springs and in Sycamore Creek is limited due to the relatively modest sizes of their respective capture areas.

5) The upper reaches of all watershed aquifers, particularly the Devils River watershed, are relatively thin and unconfined. [Note the Edwards portion of the Edwards-Trinity Aquifer is treated hydraulically separately.] Detailed coupled surface-water/groundwater modeling has shown that relatively modest pumping in the upper reach of the Devils Rivers (i.e., 4,000-6,000 acre-ft/yr) has resulted in the cessation of live water between Pecan Springs and Beaver Lake, a distance of about 10 miles. It should be noted that the time during which this live water was lost (i.e., post 1960) corresponds with a period of increased spring and stream flow in the Edwards Plateau due to improved land management practices. The acute sensitivity of live flow to pumping is due to the fact that the permeable portion of the aquifer is relatively thin and that surface-water flow in the river and groundwater flow in the conduits are intricately linked with topography.

Woody plant encroachment paradox: Rivers rebound as degraded grasslands convert to woodlands

Wilcox, B. P., and Y. Huang (2010), Woody plant encroachment paradox: Rivers rebound as degraded grasslands convert to woodlands, Geophys. Res. Lett., 37, L07402.

Abstract
The related phenomena of degradation and woody plant encroachment have transformed huge tracts of rangelands. Woody encroachment is assumed to reduce groundwater recharge and streamflow. We analyzed the long-term (85 years) trends of four major river basins in the Edwards Plateau region of Texas. This region, in which springs are abundant because of the karst geology, has undergone degradation and woody encroachment. We found that, contrary to widespread perceptions, streamflows have not been declining. The contribution of baseflow has doubled—even though woody cover has expanded and rainfall amounts have remained constant. We attribute this increase in springflow to a landscape recovery that has taken place concurrently with woody expansion—a recovery brought about by lower grazing pressure. Our results indicate that for drylands where the geology supports springs, it is degradation and not woody encroachment that leads to regional-scale declines in groundwater recharge and streamflows.

References:

Green, R.T., F.P. Bertetti, and M.S. Miller. 2014. Focused Groundwater Flow in a Carbonate Aquifer in a Semi-Arid Environment. *Journal of Hydrology*. 517:284–297. doi: 10.1016/j.jhydrol.2014.05.015

Green, R.T., N. Toll, and F.P. Bertetti. 2016. Develop a Groundwater Flow Model to Understand the Groundwater Resources of the Lower Pecos River Watershed. Contract Report for the City of Laredo. Final Report.

Toll, N., S.B. Fratesi, R.T. Green, F.P. Bertetti, and R. Nunu. 2017. Water-Resource Management of the Devils River Watershed Final Report. Contract Report for the Devils River Conservancy.

TEXAS
FOUNDATION *for* CONSERVATION

Ensuring the wildlife of Texas
for the people of Texas

RECEIVED

MAR 26 2018

Texas Water Development Board

March 23, 2018

Mr. Larry French
Texas Water Development Board
PO Box 13231, 1700 N Congress Ave
Austin TX 78711-3231

Dear Mr. French,

I appreciate the opportunity to comment on the Priority Groundwater Management Area process that your agency is undertaking in conjunction with the Texas Commission on Environmental Quality and the Texas Parks and Wildlife Department with regards to the Devils River area.

I understand your current timeline includes a second stakeholder meeting in September; if at all possible, I encourage you to accelerate the schedule. As you're aware, TCEQ Commissioners vote to establish a PGMA, and there may not be time to give the necessary public notice, hold a hearing, etc. prior to the start of the Legislative Session if they don't receive TWDB recommendations sooner.

There is more to this issue that hydrological models and groundwater pumping. The Devils River is the most pristine river in the state, and it should stay that way forever.

The people of Texas have a vested interest in the health and vitality of the Devils River, as we collectively own about 37,000 acres managed by the Texas Parks and Wildlife Department. These State Natural Areas provide camping, hiking, hunting, paddling, swimming, and wildlife watching opportunities unlike anywhere else in the state. For many Texans, our state parks and natural areas are the gateway to the outdoors, as the vast majority of land in our state is privately owned.

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Furthermore, the Devils River is home to several Endangered Species including the Devils River minnow and the newly listed Texas Hornshell freshwater mussel. To quote the US Fish and Wildlife Federal Register notice:

> "Under the Endangered Species Act, we can determine that a species is an endangered or threatened species based on any of the following factors: **(A) The present or threatened destruction, modification, or curtailment of its habitat or range;** (B) Overutilization for commercial, recreational, scientific, or educational purposes; (C) Disease or predation; (D) The inadequacy of existing regulatory mechanisms; or **(E) Other natural or manmade factors affecting its continued existence.**
>
> The Texas hornshell is an endangered species based on impairment of water quality, **loss of flowing water**, and accumulation of fine sediment (Factor A), predation (Factor C), and barriers to host fish movement and the effects of climate change (Factor E)." [emphasis added]

It is also important to note the Devils River accounts for about 42% of the US-based freshwater inflows to the Lake Amistad Reservoir. Lake Amistad sends water to the Rio Grande River, which serves as the primary water source for numerous downstream users, including the City of Laredo, population 260,000. Laredo has no other source of drinking water.

Lake Amistad is one of the finest bass fishing lakes in the state and will host more than 100 fishing tournaments this year. The influx of out of town fishermen is an important source of revenue for the City of Del Rio and the surrounding communities. Birdwatching, boating, hiking, scuba diving and camping in the Lake Amistad National Recreation Area brought more than 1.1 million visitors to the area last year.

In addition to the outdoor recreation attractions, there are hundreds of ancient rock art pictographs, some dating back more than 4,000 years. The Lower Pecos style is unique and thought to have evolved with little outside influence. One expert described the area as a "prehistoric open-air art gallery" because the pictographs are so numerous.

Some people believe there is "excess" groundwater that could be pumped and sold. But the water is everything. It binds the mysterious and beautiful elements of this unique area and casts a spell across the entire state.

People who come to see the pictographs, or fish, or scuba dive, or birdwatch are changed when they return home. Kayak and canoe stores all over Texas have photos of the Devils River on the walls, and the salespeople regale customers with tales of adventures in Val Verde County. People who float the Devils talk about the experience in wistful tones and share clear and vibrant memories. The presence of the river changes all of us, and we are better people because of its existence. The clear water in the Devils River has sustained the bodies and souls of humans for thousands of years, and we have a moral obligation to ensure that will not change.

On August 6, 1912, Teddy Roosevelt gave a speech in Chicago during which he said, "We do not intend that our natural resources shall be exploited by the few against the interests of the many…"

The river is absolutely unique in terms of its historical, cultural, economic, and ecological importance. If we are going to err in taking water from the Devils River watershed, we must err in favor of the resource, rather than short-term economic gain for a few people.

Respectfully,

John D. Shepperd
Executive Director, Texas Foundation for Conservation

Cc: Carter Smith, Texas Parks and Wildlife Department
Richard A. Hyde, Texas Commission on Environmental Quality
Representative Pancho Nevarez

February 2, 2018

Larry French
P.G. Division Director
Texas Water Development Board
1700 North Congress Avenue
Austin, Texas 78701

Dear Mr. French,

Devils River Conservancy (DRC) is a 501(c)3 non-profit organization made-up of Val Verde County landowners. The DRC's mission is to protect the Devils River and the lands within its watershed, the natural flora, fauna, and historical heritage, the maintenance of the region's natural ecosystem, and education of the public about the benefits of the same for themselves and future generations.

The Devils River Watershed in Val Verde County is the vibrant biological crossroads of the Texas Hill Country, Chihuahuan Desert, and Tamaulipan Brush Country landscapes. The springs of the Devils River provide a substantial quantity of freshwater flows to Amistad Reservoir and downstream stakeholders on the Rio Grande. The consistent spring flows support a diverse and delicate ecosystem from their origin, near Juno, Texas, to Amistad Reservoir and beyond.

The Devils River Conservancy supports the use of hydrologically related triggers in managing the groundwater of each unique watershed in Val Verde County. We stress the need to consult available science and provide consideration for protection of all native aquatic species and their habitat when making recommendations or establishing flow triggers. In addition, DRC encourages Texas Water Development Board to utilize Southwest Research Institute's 2017 study '*Water-Resource Management of the Devils River Watershed*' in identifying an appropriate hydrologic trigger for the Devils River Basin.

Sincerely,

Randy Nunns
President

CC Representative Poncho Nevarez

Comments on draft TWDB report:

"Overview of Groundwater Conditions in Val Verde County, Texas"

Thank you for the opportunity to provide comment.

The report provides a thorough review of available information related to the hydrologic system in Val Verde County. The findings and discussion in Chapter 8.0, Groundwater Management and Feasibility of Hydrologic Triggers, draw the technical information together in a coherent manner and make reasonable recommendations. I especially agree with the groundwater zone concept and identification of the zones described in the report.

Other parts of the report have errors or other issues that should be addressed by the authors prior to final publication. Below, I have identified several items that I believe are problematic.

1. Factual error on page 37, 3rd paragraph (*emphasis added*)

> "The current evaluation considers spring discharges to streams and rivers separately from wells, while Green, Bertetti and Miller (2014) ***apparently grouped spring flow rates and well production rates together***. The 22 springs in Val Verde County for which there are discharge estimates included in the TWDB groundwater database have an aggregate total average discharge of nearly 7,000 gallons per minute and a median discharge of approximately 500 gallons per minute; by definition, these large spring discharges are close to surface water features. While the presence of large springs is clear evidence of the karst nature of the aquifer, these spring flows are not directly comparable to well yields or specific capacities under pumping conditions."

The highlighted statement in Paragraph 3 above is factually incorrect. I'm not sure why it seems "apparent" that spring data were used, but that is an incorrect assumption and is made without merit. The analysis in Green et al. (2014) only included data from wells. These data were derived from the TWDB Groundwater Database, Submitted Driller's Report Database, and independent well tests (some of which are included in this draft report). No springs were included at any time. Please correct the paragraph to remove the implication that springs were included, and as a result, biased the analyses of Green et al. (2014)

2. There appear to be some misconceptions regarding the findings of Green et al. (2104). Additionally, there seems to be some confusion regarding the reporting of correlation calculations produced by quantitative statistical analyses versus "eye-balling" limited data in a map figure.

Page 32, last paragraph (***emphasis added***)

> "***Based on a review of groundwater wells, well capacities, and well locations, SWRI concluded that there is a high correlation between high capacity wells and proximity to river channels*** that points to the occurrence of preferential groundwater flowpaths that coincide with river channels." …"This pattern is also incorporated in the Val Verde County model, which assigns higher hydraulic conductivity values in stream channels. However, ***our review of available well capacity data indicates a possible, but not strong correlation between well capacity and stream channels*** (Figure 4-10)."

Page 37, 2nd paragraph (***emphasis added***)

> "The pattern of increased groundwater productivity near stream drainages noted by Toll and others (2017) is ***not apparent from the TWDB data***. The distribution of wells with higher specific capacity (Figure 4-10) shows several high-capacity wells along the upper Devils River, above Juno, and along the Rio Grande, especially in the Del Rio area. Several moderate-capacity wells are also located near the Pecos River in the northwestern part of the county. But low capacity wells are also found along drainages."

The conclusions of Green et al. (2014) do not indicate there should be no low capacity wells found along drainages. The Edwards system in Val Verde County is a karst system and should be expected to have significant hydraulic variability, especially where conduits are not present. Essentially, higher capacity wells are more likely to be found nearer to drainages, but they shouldn't be expected to be found exclusively near drainages.

Part of the analysis described in Green et al. (2014) was designed to quantitatively evaluate the conceptual model originally proposed by Woodruff and Abbott (Abbott, 1975; Woodruff and Abbott, 1979, 1986) that conduit development might be preferentially co-located along drainage features. Although our initial visual observations of maps suggested a pattern or correlation of larger capacity wells with drainage channels, visual interpretation of data can often be skewed or biased by trivial things, such as use of certain colors or dark contrast to plot wells on the map. Additionally, it was difficult to determine adequate criteria to identify a particular drainage or draw as a feature substantial enough to warrant inclusion in the analysis. We arbitrarily chose to include drainage features with stream order values of at least 3 (meaning that more than two drainages would have had to have merged to form the channel to be analyzed, see the figure below).

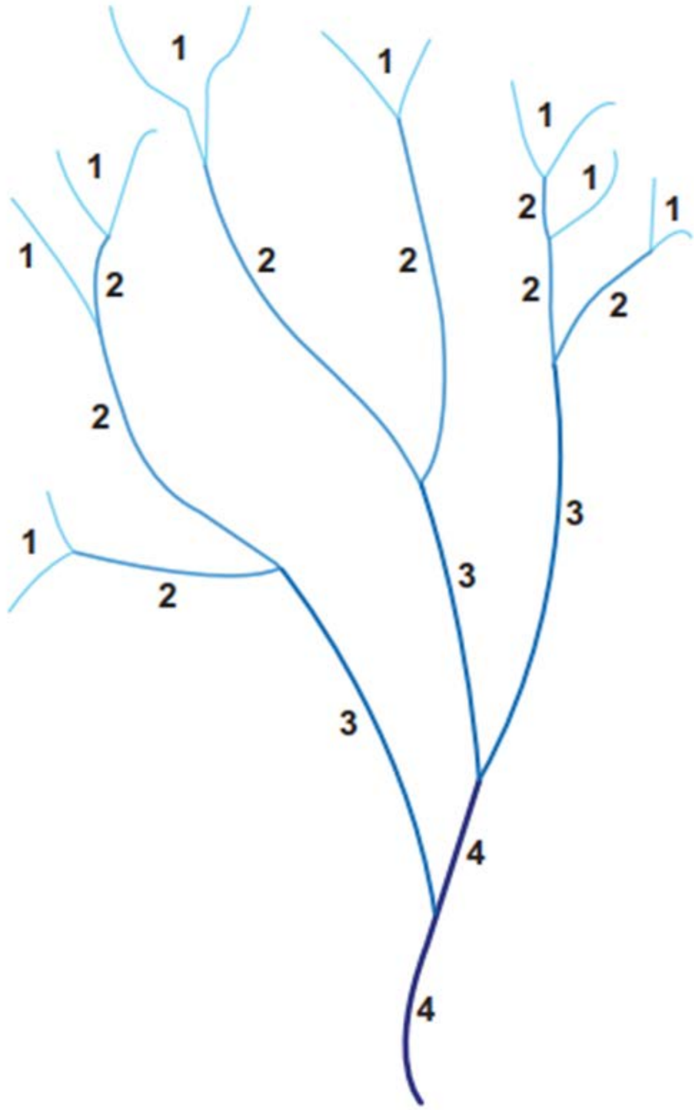
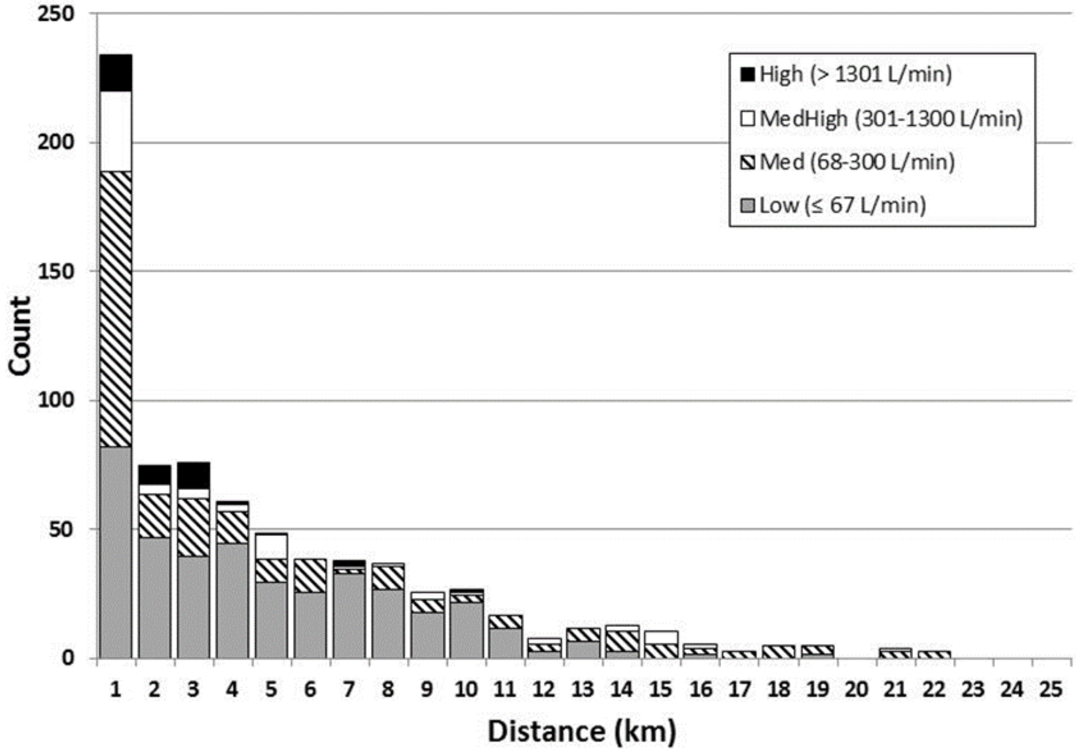
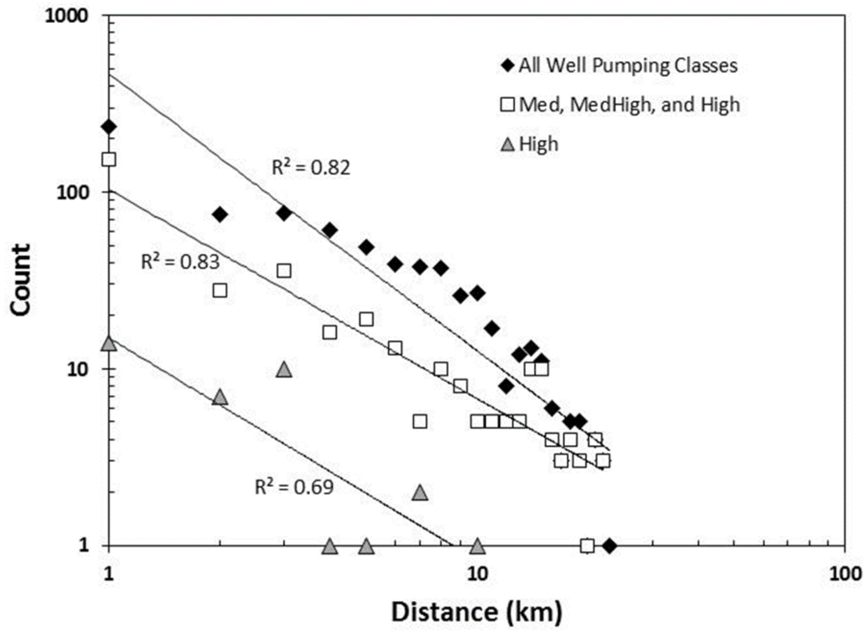


Figure 2. *Stream ordering using the Strahler stream ordering system.*

The analysis was conducted by calculating distance from wells to the nearest 3rd order drainage using the "NEAR" function in ArcGIS. We then conducted a statistical analysis to bin the wells by reported pumping capacity. The binning utilized parameters from a normal distribution fit to log-transformed data. Results are shown below.



Using the binned data, we calculated the correlation between distance and well capacity. The coefficient of determination (or R^2) values from the correlation were 0.69 and 0.83 for high capacity (>1300 L/min) and medium to high capacity (all >68 L/min) wells. These values were statistically significant and are reasonably stated as "highly correlative."



In contrast, the text of the draft report indicates the correlation is not strong based on "our review," but no meaningful quantitative evidence is provided to support such a statement. Instead, it appears as though the authors visually inspected Figure 4-10 and drew conclusions accordingly. If some quantitative data were used, there appear to be discrepancies in them as well. A review of "Distance to Drainage" data in Table C-3 indicates an inconsistent method of assigning the distance values was employed, and there is no discussion of how those values are determined. An example can be seen with wells 54-54-804 and 54-62-302. Regardless of the stream data set employed, 54-62-302 is closer to drainage features than 54-54-804, and the distance from 54-62-302 to a nearby main drainage feature, Johnson Draw, is closer to 7 km than the 10-km value listed in Table C-3. Finally, it appears that some well data included in Table 4-1 is not plotted in Figure 4-10. For instance:

Page 35, 5th paragraph

> "Wet Rock Environmental conducted pumping tests on three wells on the Weston Ranch property, in southeastern Val Verde County."

It seems obvious that even the limited available data are not all included in the "review." Thus, incorrect, non-technically defensible conclusions exemplified by those stated on pages 32 and 37 are more likely to be reached. I recommend the authors revise their review strategy or modify the text accordingly.

3. The analyses and conclusions in *Appendix B – Geochemical assessment of groundwater flow paths, mixing, and residence time* suffer from several inconsistent or inadequately defended arguments.

A. Discussion of tritium and GNIP data.

Page 121, 2nd paragraph

> From 1961 to 2004 there were a total of 12 potential recharge events, defined by storms that resulted in peak flows greater than about 15,000 cubic feet per second (425 cubic meters per second) in the Devils River at the Comstock gage (Figure B-2).

What is the basis for establishing this flow value as a threshold for recharge in the Val Verde system? I am unaware of any data that correlate only high flow events to recharge. In fact, data from Table C-3, Well 54-62-302, show that over two successive sampling events in 2006 and 2007 the measured fraction of modern carbon (C-14) in the well increased from 0.66 to 0.74 (younger), indicating recharge of the system occurred. Not only does this indicate recharge without a large flow event, but recharge along a smaller order drainage feature. Thus, the initial premise that some minimum value of flow in the Devils River is correlated with or required for recharge in the system is incorrect. As an aside, data such as this (recharge along drainages) are consistent with the inclusion of small order drainage features as recharge and flow paths in Toll et al. (2107).

Page 121, 2nd paragraph

> GNIP data show that tritium concentrations in precipitation during these storm events varied widely, depending on the direction the storm was traveling relative to nuclear test sites, timing relative to nuclear tests, how much rain had already fallen from the air mass, and other factors, resulting in unique decay curves for each recharge event (Figure B-3).

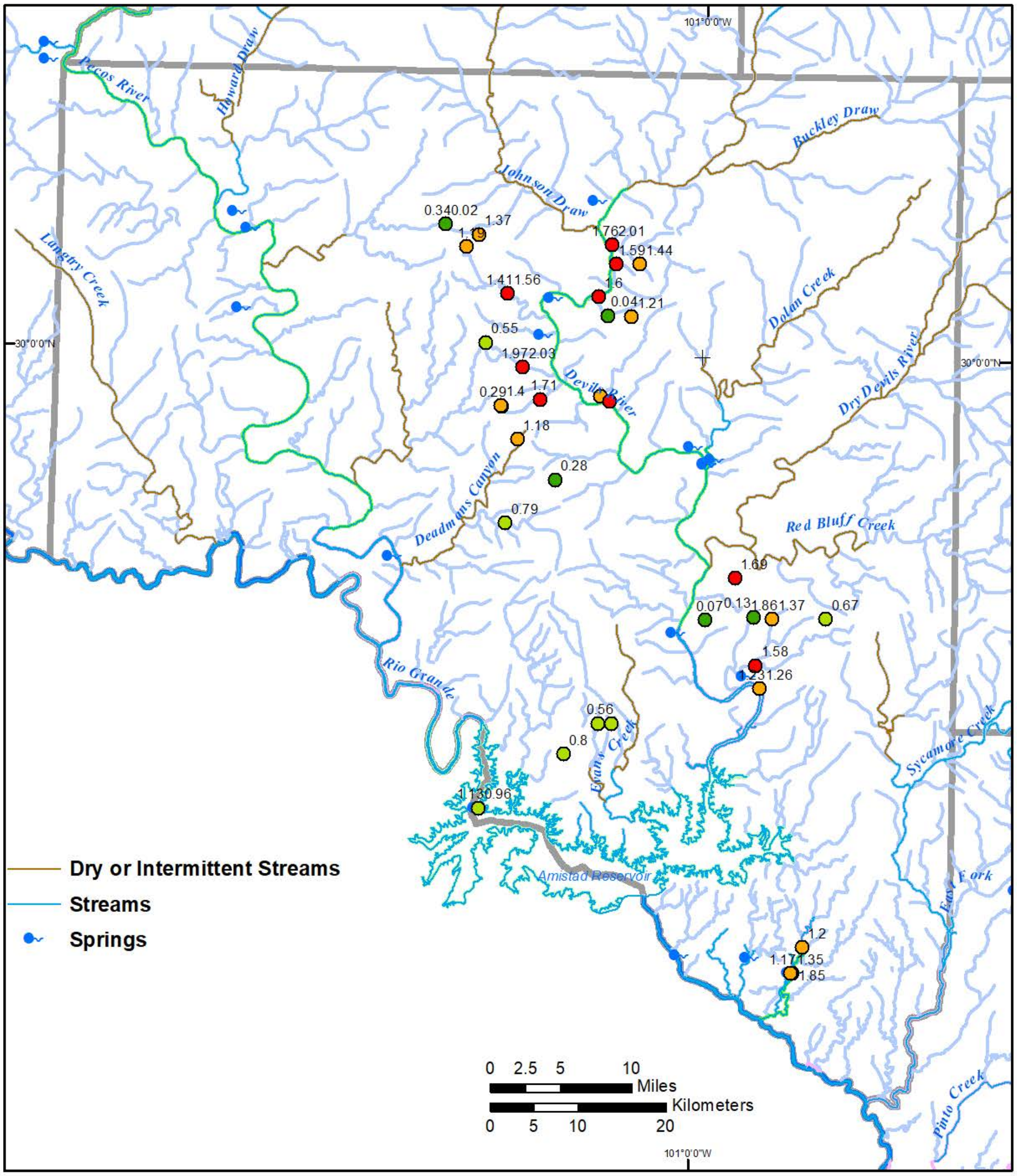
The GNIP data are not corrected or calibrated for storm source or rainout. They may vary because of these factors but the data do not account for this. Thus, use of data recorded at Waco may be completely inconsistent with expected tritium deposition in Val Verde County. Other calibrations have attempted to estimate tritium deposition on a sub-regional scale (e.g., Michel et al., 2018).

Page 122 (***emphasis added***)

> ***These tritium decay curves indicate a mean residence times of 21 to 34 years for Goodenough and San Felipe Springs discharge***. A close-up view of the decay curves covering the times when spring water samples were collected from San Felipe and Goodenough Springs (Figure 4-29) shows that only two of the decay curves, for 1976 and 1981 recharge, match the observed tritium concentrations, with the 1980 decay curve slightly above observed values.

> These decay curves match observed tritium concentrations, giving a mean residence time of 21 to 34 years.

The figure to which the paragraph refers is B-3 and not 4-29. Nonetheless, the conclusion that residence time can be discerned from these plots is incorrect. One could argue that residence time is much longer or much shorter based on the data shown. As mentioned previously, there is no basis for the assumption that recharge has occurred only during the selected time periods (in fact, it is clearly shown that this is an incorrect assumption). First, potential mixing is not included the assessment. Obviously, water discharging from the springs should be a composite of many recharge events. If the mean residence time is reasonable, the discharge should be a composite of many events including the 1971, 1972, 1974, and 1983 events in addition to the ones mentioned. The combination of each of these events indicates that, if anything, measured tritium at the springs should be much higher for the suggested residence time. The low values could just as well indicate that despite the predicted higher tritium content, there is a longer residence time. Second, there is some suggestion in Appendix B that San Felipe and Good Enough Springs have very different source areas, yet Figure B-3 treats both as having similar source terms. Finally, and perhaps most importantly, the data included in the draft report aren't consistent with this conceptualization. A rough map of the data in Table C-3 is shown below.



Despite predictions that recharge events should produce at least some samples with tritium concentrations greater than 2 TU (based on the information in Figure B-3), none are found. In fact, the data suggest that all water near the drainages in Val Verde county is approximately the same age, with older water found away from these drainages. This is consistent with recharge preferentially occurring in the more hydraulically conductive drainage areas and less so in the plateau regions away from drainages. Using this information and the measured values at the springs, it seems that residence time is reasonably less than 12 years.

B. Connection to Sutton and Crockett counties

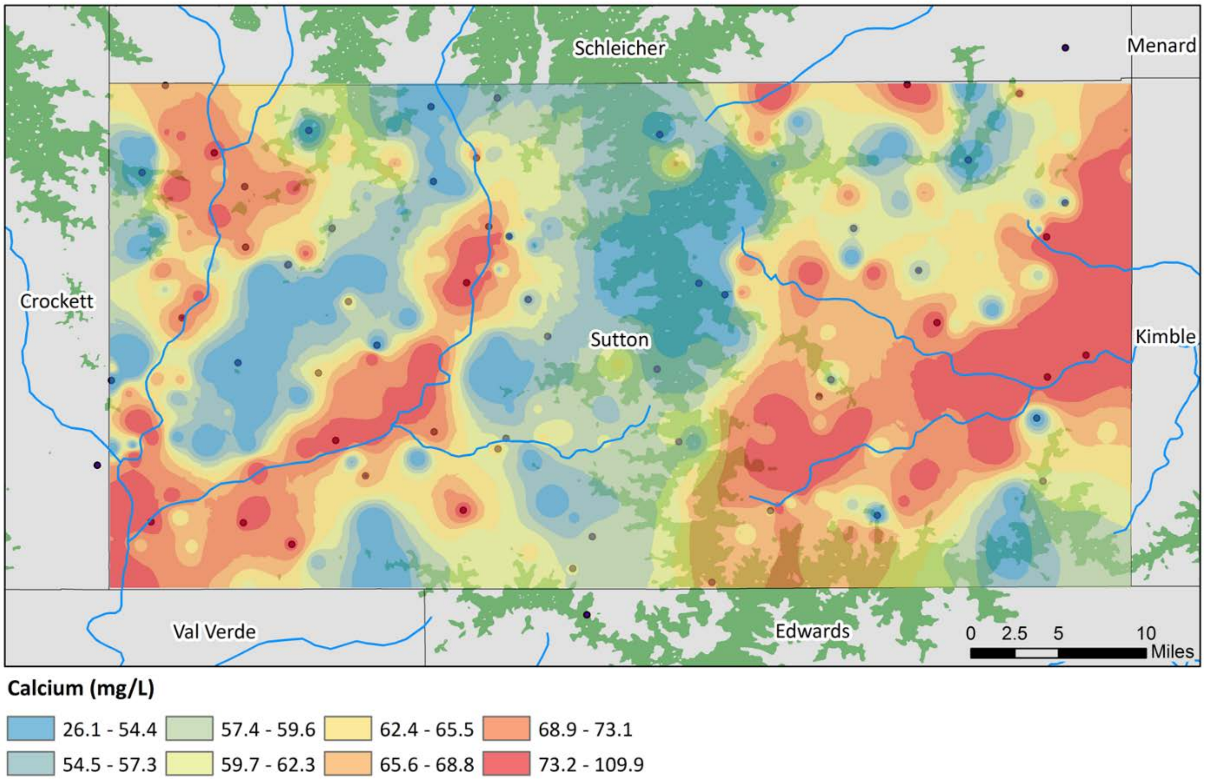
Pages 124 and 125

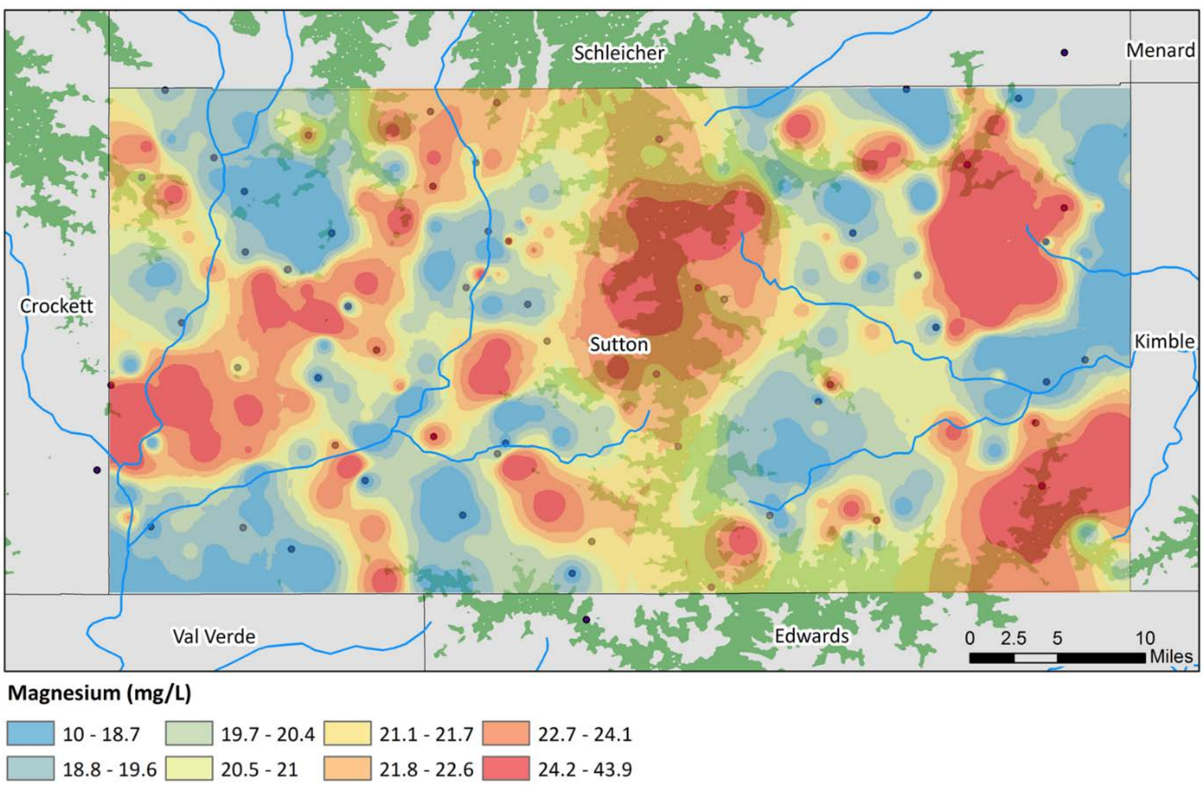
> Groundwater typically acquires magnesium, chloride and sulfate during water-rock interactions, and the concentrations of these ions increase along flow-paths between recharge and discharge areas. Although groundwater in Crockett and Sutton counties is hydraulically upgradient from Val Verde groundwater, the chemical data demonstrate that only a limited fraction of this upgradient groundwater can mix with Val Verde groundwater and still produce a composition consistent with the discharge from the major springs. These results suggest that most discharge from Goodenough and San Felipe springs originates within or near Val Verde County and is not part of a larger, regional flow system.

Water chemistry data for Sutton County in Figures B-5 and B-6 is biased by use of a limited data set and failure to accommodate the spatial and hydraulic characteristics of the groundwater system.

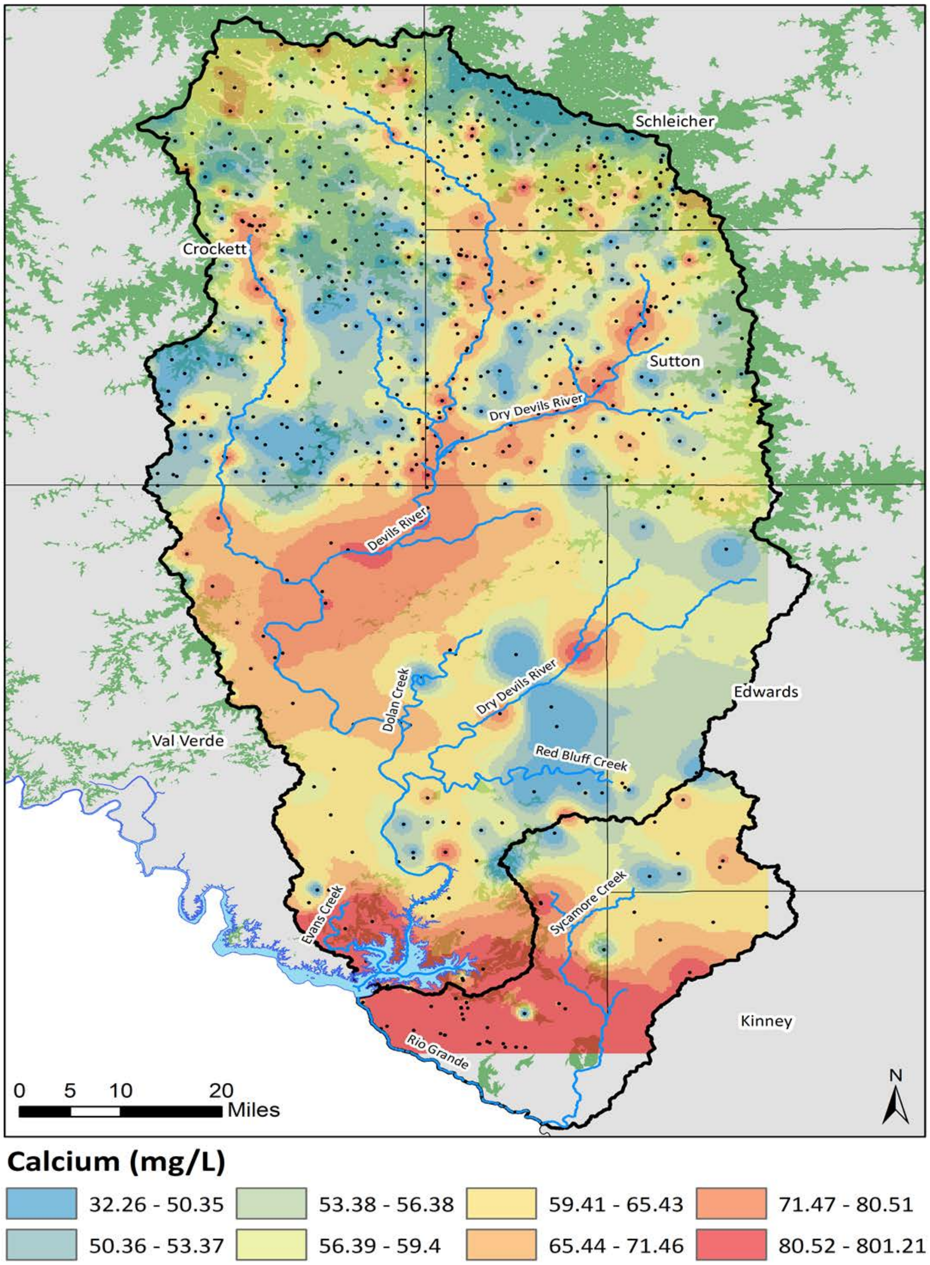
San Felipe Springs may discharge water from a limited system in Val Verde County, but the data presented in Figure B-5 do not fully support that because there is no tie to the locations or characteristics of the wells whose data are plotted. For example, most of the Val Verde well data appear to have compositions with a greater contribution from Mg than samples from San Felipe Springs. This low Mg signal is typical of Edwards waters in Kinney County (and wells east of San Felipe Springs). In short, the conclusion may be correct, but it does not follow from what is presented in the report.

The disconnect between Sutton County well data is a function of the limited number of samples considered in the report. Edwards waters in Sutton County are influenced by recharge in drainages and longer residence times in areas capped by Buda Limestone (as reported by Nance, 2010). A couple of figures below (from Nunu et al., 2017) clearly show the high concentrations of Ca associated with active recharge areas and zones of higher Mg concentrations associated with greater residence times below the Buda capped regions. These figures were generated using data collected by Sutton County from 2013 to 2016 and known to be in the TWDB database. Other data (not shown) confirm some of the results of Nance (2010) and others and indicate higher Mg/Ca ratios are associated with longer residence time.


Schleicher
Menard
Crockett
Sutton
Kimble
Val Verde
Edwards
0 2.5 5 10
Miles
Calcium (mg/L)
26.1 - 54.4
54.5 - 57.3
57.4 - 59.6
59.7 - 62.3
62.4 - 65.5
65.6 - 68.8
68.9 - 73.1
73.2 - 109.9


Schleicher
Menard
Crockett
Sutton
Kimble
Val Verde
Edwards
0 2.5 5 10
Miles
Magnesium (mg/L)
10 - 18.7
18.8 - 19.6
19.7 - 20.4
20.5 - 21
21.1 - 21.7
21.8 - 22.6
22.7 - 24.1
24.2 - 43.9

The trends Sutton County can be extended into Val Verde County to show the "active" flow and recharge areas associated with drainages (below). Thus, the chemical "disconnect" suggested in the report is really a function of the varying components of the hydrologic system and not really indicative of separation of the system from north to south (although I agree that Crockett County mostly affects the western (or Pecos) portion of Val Verde County.



In summary, I think the draft report is valuable and incorporates a great deal of work. I do believe it would be much improved if some attention was paid to addressing the items to which I refer in these comments. Should you have any questions or require additional information, please do not hesitate to contact me by email or phone.

Thank you.

Paul Bertetti, P.G.
Director -- Aquifer Science
Edwards Aquifer Authority

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From:	leebee@stx.rr.com
To:	Larry French
Cc:	canalcompany@yahoo.com
Subject:	Apache Fault
Date:	Tuesday, September 18, 2018 7:27:36 AM

In 1988 Chemical Waste Management was trying to put in a hazardous waste site just west Dryden Texas. Mr. Pat Boland from Midland, Texas, a geologist, identified the Apache fault running under this site. It runs from Baloreaha Springs to San Felipe springs thru Goodenough springs down to Los Mossis springs. The Apache fault was also found by seismograph at Spofford, Texas. This was done by a Mexican congressman, Jesus Maria Ramon from Acuna, Mexico as Mexico was heavily involved in this fight. The fault is visible from the air at Dryden. Just east of Dryden is an underground river called the Cimarron river. The river can be seen in a cave that is 400 feet deep. How do I know this? I was a Del Rio city councilman during that time and spent lots of time with Pat investigating this fault. Del Rio was successful in getting the Chem Waste application rejected, by the then TNRCC, because of this fault and underlying aquifers. I have read your report and find it fatality flawed as it does not mention anything that I have described to you. There is clear evidence that San Felipe Springs water comes from the Apache fault. Therefore your report must be rejected. I strongly urge a more complete investigation to be done on this matter. The city should have all the information to back up what I have just told you.

Lee Weathersbee
Del Rio, Texas
830-734-6604

Comments on "Overview of Groundwater Conditions in Val Verde County, Texas" (Weinberg, 2018)

The Texas Legislature instructed the Texas Water Development Board to complete an overview of the hydrogeology of Val Verde County, similar to what would be required for a Priority Groundwater Management Area (PGMA) evaluation, and to assess the feasibility of employing hydrologic triggers to manage the aquifer. Following are comments on the report prepared by Ronald T. Green, Ph.D., P.G., Southwest Research Institute@. October 17, 2018.

The charge to complete an overview of the hydrology of Val Verde County, as defined by the Texas Legislature, has inherent difficulties. The lower Pecos River and the lower Devils River watersheds, which comprise most of Val Verde County, extend a significant distance outside of Val Verde County (Figure 1). By not designating natural hydraulic boundaries when conducting hydrogeological evaluations, increased uncertainty in the evaluation is introduced compared with an evaluation for a study area bounded by natural hydraulic boundaries. The Val Verde County hydrologic overview evaluation is made particularly challenging by: (i) the extension of the headwaters of the watersheds beyond the county lines, (ii) the inclusion of multiple groundwater and surface-water regimes included within the study area, and (iii) the hydrogeological complexity of the county.

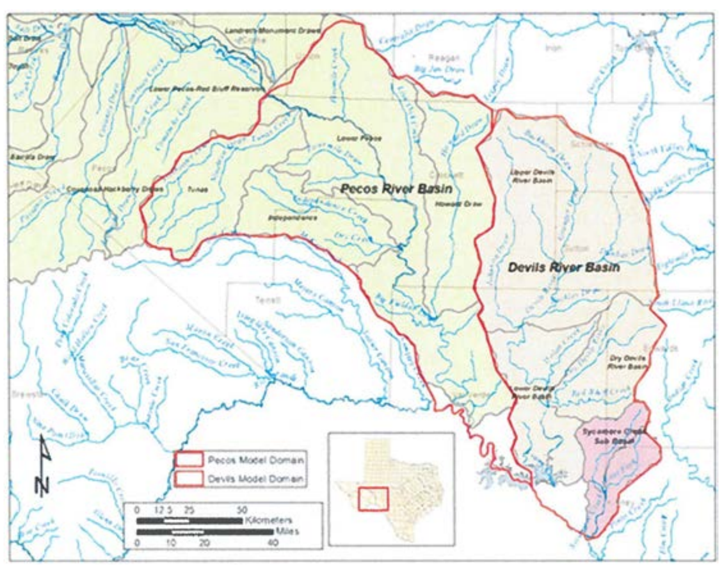

Figure 1. Major watersheds in and proximal to Val Verde County

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The water budget of Val Verde County is fairly well constrained in terms of discharge (*i.e.*, the sum of pumping plus discharge via the Rio Grande). Calculating how much water is recharged to Val Verde County from each of the watersheds (*e.g.*, Pecos River, Devils River, Sycamore Creek) is not well constrained even though the contributions from each of the major springs (*e.g.*, Goodenough, San Felipe, Cienegas) is known.

Additional documentation is available to frame the following statement from Weinberg (2018) in the context of Val Verde County's water resources. Weinberg (2018) stated the following:

Baseflow in the upper Devils River, which is entirely from groundwater discharge, has remained essentially the same for at least the last 100 years. Available evidence indicates that starting point of perennial flow has historically occurred near Pecan Spring and has not changed in response to pumping from irrigation wells near Juno.

Our research has resulted in evidence that partially contradicts this statement. The now-dry Beaver Lake, located adjacent to the Devils River near Juno, is a critical case exhibiting how ical status of the Devils River watershed. There is ample evidence that the springs to Beaver Lake were sufficient to sustain Beaver Lake as a persistent surface water body in a semi-arid environment even during periods of drought. It is unknown, although with limited observations, that spring flow at Beaver Lake was previously sufficient (i.e., prior to the early 20th century) to provide continuous outflow from Beaver Lake to Pecan Springs where current continuous surface flow (i.e., live water) is currently observed.

Absent in Wienberg (2018) are TWDB documents summarizing the history of water-well development in four of the counties that cover the Devils River watershed, namely Crockett County (Iglehart, 1967), Schleicher County (Muller and Crouch, 1971), Sutton County (Muller and Pool, 1972), and Val Verde County (George, 1950). These and other publications include documentation to substantiate the premise that Beaver Lake was a persistent surface-water pool prior to development and attendant increases in pumping in the upper half of the Devils River watershed. A number of historical accounts that describe Beaver Lake were assimilated into a 2011 publication by Patrick Dearen, *Devils River: Treacherous Twin to the Pecos, 1535-1900* (Dearen, 2011). The historical accounts are mostly from records by the U.S. Cavalry, cattle drives, and wagon trains that ventured across south-central Texas in the mid to late 19th century. The consensus of these observations is that prior to the 20th century, Beaver Lake was a persistent source of water prior to development for those who ventured across the upper Devils River watershed. Following are the salient comments from Dearen (2011) with relevance to the hydrology of Devils River and Beaver Lake.

Beaver lake features prominently in the report of the 1849 expedition led by Thomas B. Eastland through Texas to California:

> Where the [Devils] river widened into a small, natural reservoir that would become known as Beaver Lake, twenty-two miles upstream from Second Crossing, Eastland and his companions camped July 27 [1849] and waited for the engineers to complete a trail out across the divide between the Devils and Pecos. The pool, fringed by line oaks, willows, and mesquites, was an exquisite site, even for a river of singular characteristics.
>
> 'We are encamped in a beautiful Valley surrounded by an hundred Hills rich in fine Grass, enough for thousands of Animals' described Eastland. 'In the midst of the Valley

is a beautiful lake of pure water fed by many springs running out of the neighboring hills'. (Dearen 2011, p. 31-33)

Beaver Lake also appears in the account of Blake's 1854 geological mapping expedition from the Red River to the Rio Grande:

Although Blake's [camp's] exact location is debatable, evidence points to the vicinity of Beaver Lake, a coveted oasis that long had nurtured passing military parties. Not only was the lake generally considered the river's head, thus echoing the description in Camp Blake's post return for April but on June 6 [1854] a traveler would delineate a 'Devils River Station' (presumably Blake) at the final watering point before the road struck out for Howard's Spring—an accurate characterization of the Beaver Lake area. (Dearen 2011, p. 50)

Dearen (2011) pg 41. The drought that plagued the Devils in 1850 spread like a blight throughout West Texas and wreaked a toll."

Brune (1975), in his survey *Springs of Texas*, stated that: "The Devil's River at this point {Juno, Headwater, or Stein Springs} was described in 1916 as a beautiful stream with large live oaks. The springs, Beaver Lake upstream, and the perennial flow of the Devil's River in this area have all disappeared." Brune (1975) did not provide attribution for the observation made in 1916.

An additional recollection of Beaver Lake from prior to 1953 is provided in the *Amarillo Sunday News Globe*, December 13, 1953, edition, published in Amarillo, Texas, in a byline by Laura V. Hamner. In the article, Laura V. Hamner interviewed the wife of the owner of Beaver Lake Ranch at the time, whom she mistakenly identified as "Mrs. Earl Williams." In the following discussion, the interviewee will be referred to by her actual name, "Mrs. Byron Earl Wilson."

In the days of [Mr. Wilson's] youth, Beaver Lake was a deep pool of water. Mrs. [Wilson] recalls their early married life, when they had a motor boat on that lake which now is a dry depression.

Beaver Lake played a part in cattle history in those early days. In winter, cattle from the Concho country drifted southward and a general roundup on the Rio Grande was held annually. 'The cattlemen gathered up all the strays they could find and drove them north. Naturally, there would be local cattle caught in the herd. The men halted the cattle at Beaver Lake because it was the last water hole before they reached the Concho. Sometimes, 50,000 head would be held there for a day or two, sometimes four days, while cattle were being cut out. Then the cattle would be trailed northward, a string 15 miles long, and cattlemen would follow, cutting out their cattle as they located them. (Hamner, 1953)

Note that Mr. Byron Earl Wilson was born in 1882. His "early married life" was likely the late 1900s into the 1910s and possibly the 1920s. Based on the recollection of Mrs. Byron Earl Wilson, Beaver Lake was a "deep pool of water" into the 1910s and possibly later. The first Evinrude outboard motor was manufactured in 1907, thus the timeline that Beaver Lake was a deep pool in the early 20th century and completely dry by the 1950s is reasonable.

Water-well information for Sutton County (Muller and Pool, 1972), Schleicher County (Muller and Crouch, 1971), Val Verde County (George, 1950), and Crockett County (Iglehart, 1967) was reviewed to establish the timeline of the influx of groundwater pumping in those portions or the Devils River watershed in each respective county. The number of well completions by decade for Devils River watershed within each county is plotted in Figure 2. The dates of all well completions in the databases are not known. Because the completion dates of newer wells are more likely known than older wells, it is likely that these data are biased to suggest that fewer wells in the first half of the 20th century were completed than actually occurred. Nonetheless, Figure 1 clearly illustrates that a marked increase in water-well construction began in the 1920s and continued for several decades.

The 2011 alternative Edwards-Trinity (Plateau) Aquifer Groundwater Availability Model (Hutchison et al., 2011), prepared for the Texas Water Development Board, included estimates for annual pumping from 1930 to 2006 in Crockett, Schleicher, Sutton, and Val Verde counties. Those estimates are included here as Figure 3. The origin of these pumping volumes is not documented and appear to be best guesses. For example, correspondence with the Sutton County Underground Water Conservation District suggests that the marked increase in pumping in Sutton County that began in 1960 (Hutchison et al., 2011) is not supported by data at the District. It is likely that the onset of increased pumping began earlier than 1960. Supporting this assertion are the estimates of annual pumping for Schleicher and Crockett counties, which together with Sutton County comprise the upper watershed of the Devils River (Hutchison et al., 2011). The pumping estimates for both Schleicher and Crockett counties indicate that the increase in annual pumping in this area likely began several decades earlier than 1960, thereby agreeing with the marked increase in water-well construction in Sutton County (Muller and Power, 1972).

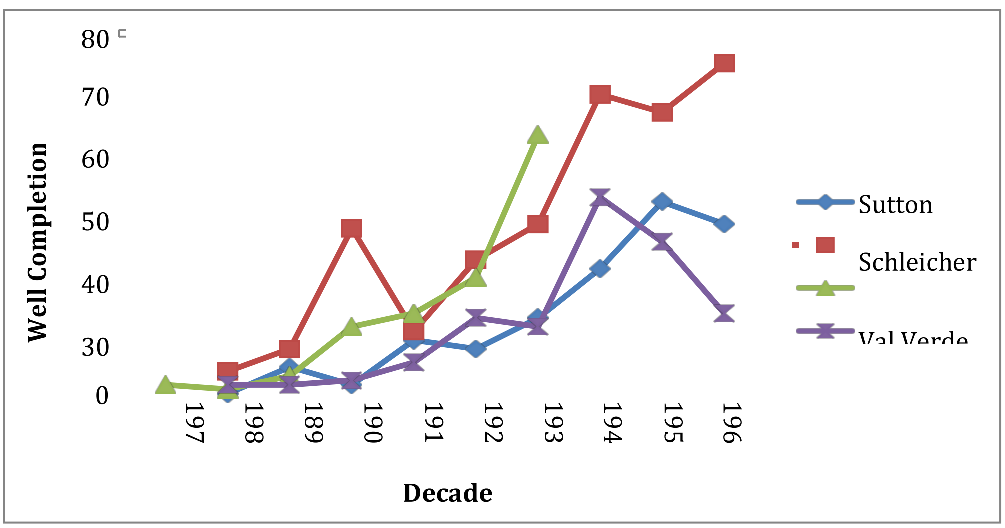

Figure 2. Number of new water wells per decade in Sutton County (blue line) (Muller and Pool, 1972); Schleicher County (red line) (Muller and Crouch, 1971); Val Verde County (green line) (George, 1950); and Crockett County (purple line) (Iglehart, 1967)

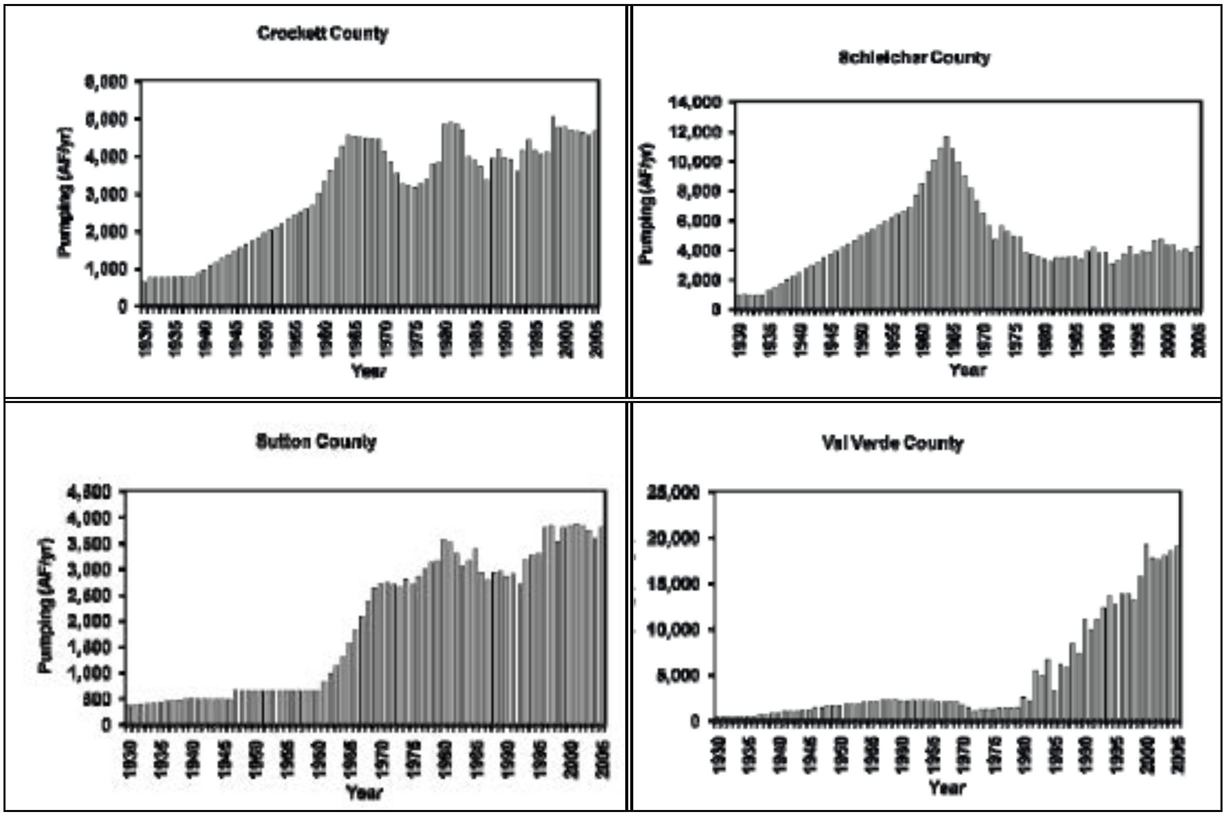

Figure 2. Estimated annual pumping in Crockett, Schleicher, Sutton, and Val Verde counties for the period 1930-2005 (Hutchison et al., 2011)

The consensus of the historical accounts mentioned earlier is that Beaver Lake was historically a persistent surface-water body that could provide adequate water to thousands of cattle, was sufficiently extensive (surface area and depth) to allow for a power boat, and was sufficiently resilient even during periods of drought (*e.g.*, the 1850 drought) such that it did not go dry. Based on well completion documentation, it appears that the marked increase in well completions and associated pumping in the upper Devils River watershed occurred contemporaneously with the drying of Beaver Lake and lends credence to the role of groundwater depletion in drying the springs that sustained Beaver Lake. Drying of Beaver Lake, which occurred in the early 20th century, is in approximate agreement with the TWDB Val Verde Report (Weinberg, 2018) which stated "Baseflow in the upper Devils River…has remained essentially the same for at least the past 100 years."

The statement in Weinberg (2018) that "Available evidence indicates that starting point of perennial flow has historically occurred near Pecan Spring and has not changed in response to pumping from irrigation wells near Juno" warrants additional discussion.

Spring locations in the Devils River watershed in Val Verde County are plotted on a map in Figure 4. Included are springs mapped during a field survey conducted in the late 1930s (George, 1950) and from data published by Ashworth and Stein (2005). Ashworth and Stein (2005) relied on spring locations and names obtained from U.S. Geological Survey (USGS) topographic maps and spring database, Texas Water Development Board (TWDB) and their predecessor agencies, the International Boundary and

Water Commission (IBWC), and in Springs of Texas by Brune (1975, 1981). Tables 1 and 2 list the springs from George (1950) and Ashworth and Stein (2005), respectively. Spring locations mapped in the late 1930s (denoted by green dots) are significantly more prevalent than locations from Ashworth and Stein (2005). This may be attributed to loss of springs due to pumping or simply that those additional springs mapped in the 1930s were not included in subsequent surveys.

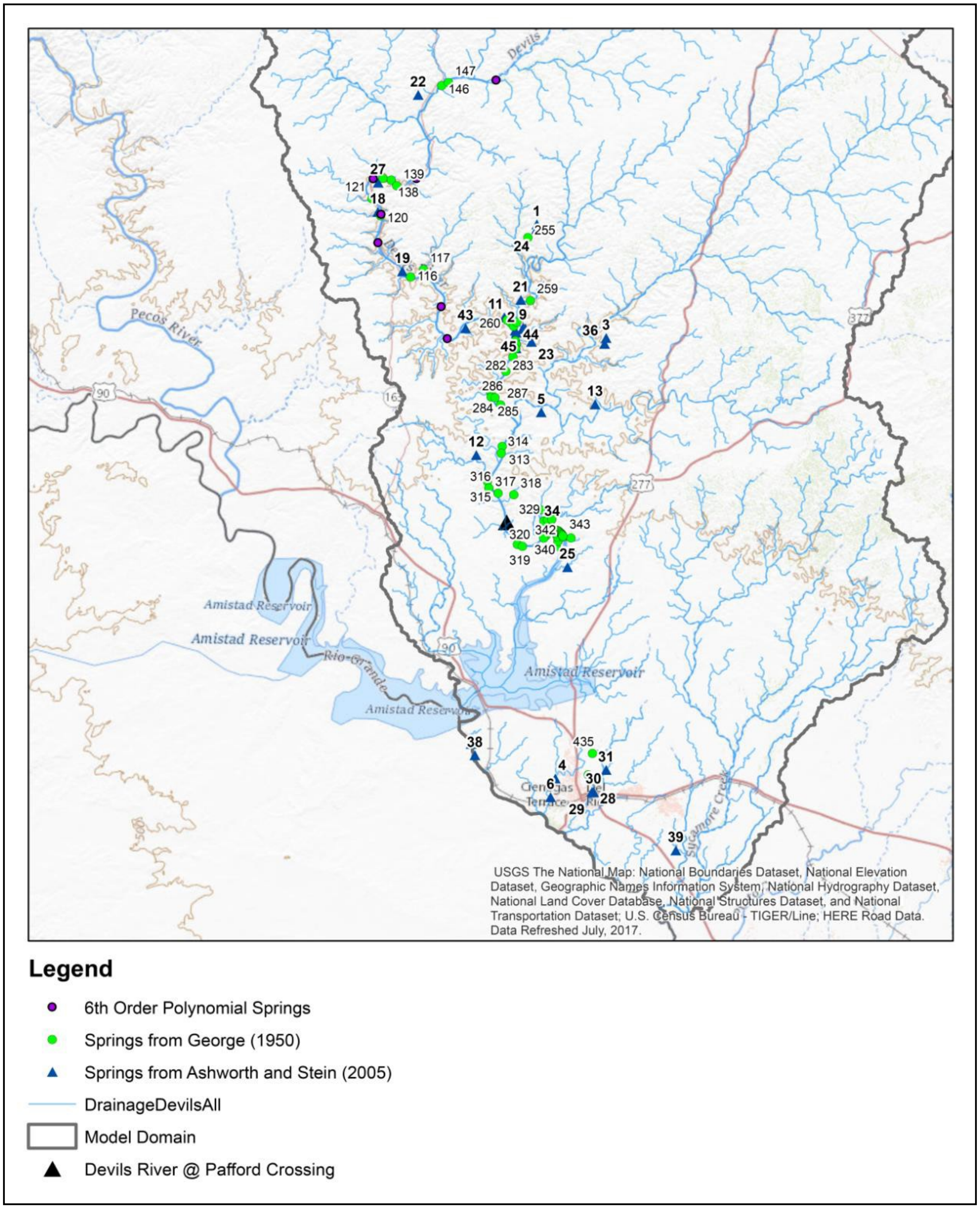

Figure 4. Spring locations in the Devils River watershed in Val Verde County

Table 1. Springs from George (1950)

Spring_No	Name	Owner	Pumping Rate (gpm)
116		W.T. Baker	500
117	Huffstutter Spring	S.E. Hallam	275
120		C.B. Hudspeth	1000
121		C.B. Hudspeth	20
137		C.B. Hudspeth	700
138	Pecan Spring Two	C.B. Hudspeth	125
139	Pecan Spring	C.B. Hudspeth	2000
146	Stein Springs	R.G. Nance	5
147	Beaver Lake Springs	B.E. Wilson	6
255		W. Fawcett	1
259		E.K. Fawcett	1500
260		E.K. Fawcett	2000
261		E.K. Fawcett	8000
262		E.K. Fawcett	2000
263		E.K. Fawcett	115
277		E.K. Fawcett	10
278		E.K. Fawcett	60
279		E.K. Fawcett	1
282	Dolan Springs	E.K. Fawcett	125
283	Dolan Springs	E.K. Fawcett	200
284		A. Madison	200
285		A. Madison	500
286		A. Madison	50
287		A. Madison	5
313		Tom Bright	6
314		Tom Bright	1
315		R. Gillis	5000
316		R. Gillis	80
317		L.L. Hinds	1
318	Little Satan Spring	L.L. Hinds	3
319		J.C. Mayfield	25
320		J.C. Mayfield	55
322		J.C. Mayfield	3
323		J.C. Mayfield	20
324		J.C. Mayfield	120
325		J.C. Mayfield	160
326		J.C. Mayfield	46
327		J.C. Mayfield	20
328	Big Satan Spring	L.L. Hines	5
329		R. Cauthorn	80
330		R. Cauthorn	675
331		R. Cauthorn	4
332		R. Cauthorn	55
344		R. Cauthorn	155
345		Sam Smith	260
346		Sam Smith	125
333		R. Cauthorn	135
334		R. Cauthorn	35
335		R. Cauthorn	1700
336		R. Cauthorn	220
337		R. Cauthorn	540
338		R. Cauthorn	340

339		R. Cauthorn	70
340		R. Cauthorn	275
341		R. Cauthorn	490
342		R. Cauthorn	2500
343		R. Cauthorn	40
431		F. Cantu	105
433	San Felipe Spring	City of Del Rio	55000
435	San Felipe Spring	Jap Lowe	60

Table 2. Springs from Ashworth and Stein (2005)

ID_No	State Well Number	Name	Latitude	Longitude	Elev_ft
1		Big Norris Spring	30.0141	-100.968	1959
2	7001704	Blue Spring	29.8936	-100.9938	1480
3		Camp Spring	29.8869	-100.8755	1667
4	7033801	Cantu Springs	29.3875	-100.9322	979
5		Carlos Camp Spring	29.8016	-100.9583	1373
6		Cienegas Creek Spring	29.3662	-100.9379	938
7	5460804	Cox Springs	30.0416	-101.5416	1763
8		Dead Man Springs	29.7916	-101.3583	1378
9	7001702	Dolan Springs	29.8969	-100.9836	1340
10		Everett Springs	30.0083	-101.5083	1683
11	7108901	Finegan Springs	29.9083	-101.0083	1607
12	7124301	Gillis Springs	29.752	-101.0416	1180
13		Glenn Spring	29.8116	-100.8886	1449
14	7130901	Goodenough Springs	29.5363	-101.2531	1122
15		Grass Patch Springs	29.8736	-100.9922	1331
16	7112504	Guy Skiles Springs	29.8166	-101.5579	1320
17	5452801	Howard Springs	30.1583	-101.5417	1661
18	5463801	Hudspeth Springs	30.025	-101.175	1618
19	7107603	Huffstutler Springs	29.9583	-101.1416	1506
20		Indian Springs	29.665	-101.9263	1220
21		Jose Maria Spring	29.9283	-100.9872	1451
22	5455905	Juno Springs	30.1583	-101.1254	2007
23		Leon Spring	29.8811	-100.9725	1492
24		Little Norris Spring	30.0091	-100.9683	2010
25		Lowry Springs	29.6269	-100.9208	1196
26	7140903	McKee Springs	29.425	-101.0416	970
27		Pecan Springs	30.0583	-101.1751	1844
28	7041301	San Felipe Spring E	29.3725	-100.883	975
29	7041302	San Felipe Spring W	29.3728	-100.8847	960
30	7041303	San Felipe Spring S	29.373	-100.8825	975
31		San Felipe Creek Spring	29.3981	-100.8666	1015
32		Scott Spring	30.0166	-101.5189	1447
33		Seep Springs	29.8233	-101.5116	1422
34	7017501	Slaughter Bend Springs	29.6751	-100.9416	1345
35		Snake Springs	29.8961	-100.9808	1385
36		Spotted Oak Spring	29.8802	-100.8775	1671
37		Tardy Spring	30.1239	-101.5378	1563
38	7140905	US No. 3 Spring	29.4122	-101.0365	921
39	7042601	Yoas Springs	29.3083	-100.7751	980
40	7112501		29.8099	-101.5732	1260
41	5460301		30.1233	-101.534	1537
42	5460302		30.1235	-101.5335	1537
43	7108801		29.8952	-101.0582	1472

44	7001703		29.8913	-100.9923	1520
45	7001701		29.8955	-100.9829	1360

Also included in Figure 3 are locations designated as potential springs based on the small-scale deviations of the stream bed from the overall stream gradient. Preferential flow paths often follow bedding plane partings that, when they intersect with a stream, often cause localized spots of increased stream incision. It is likely, therefore, that where the preferential flow paths intersect the stream valley, there exist small-scale depressions relative to the overall stream gradient. These depressions are more likely to intersect the water table and form springs than the stream reaches not located in one of these depressions.

To ascertain locations where the river bed cut down into the preferential flow paths, the basal elevation of the river channel was determined using a digital elevation map (DEM). Several orders of a polynomial were fit to these data. The thought behind this exercise is that pronounced deviations in the riverbed that are below the polynomial would indicate the likely locations of springs and pools of water that would form in the river bed where the elevation of groundwater is above ground level. Springs would form at these low points when the groundwater elevation was sufficiently high. Conversely, these same springs and pools would go dry when groundwater elevations went down. Deviations between actual river bed elevations and a 6th-order polynomial are plotted in Figure 5. Hypothetical spring/pool locations are noted in Figure 5 where the differences between measured and modeled elevations have the greatest negative values.

Noteworthy is that there are no springs or pools associated with the northern most dips in the river bed. This is reasonable. The water table at these locations is well below the river bed. Springs would only discharge at these locations if the water table were to significantly rise. This scenario is unlikely unless the watershed were to enter a pluvial period, something that would be expected during a glacial epoch. Also noteworthy is that location B in Figures 4 and 5 is aligned with Beaver Lake. The fact that Beaver Lake is a depression in the river bed is logical. The groundwater elevation at the springs Beaver Lake is interpreted to have been sufficiently high prior to the early 20th century that there was perennial discharge during those times. The lowering of the water table at Beaver Lake is interpreted to been modest, particularly since the aquifer is phreatic in this area, however this lowering has been sufficient that Beaver Lake springs no longer are perennial and rarely flow. Analyses and evaluations at SwRI support the premise that springs that sustained Beaver Lake have been depleted by pumping upgradient of Beaver Lake (Toll et al., 2017).

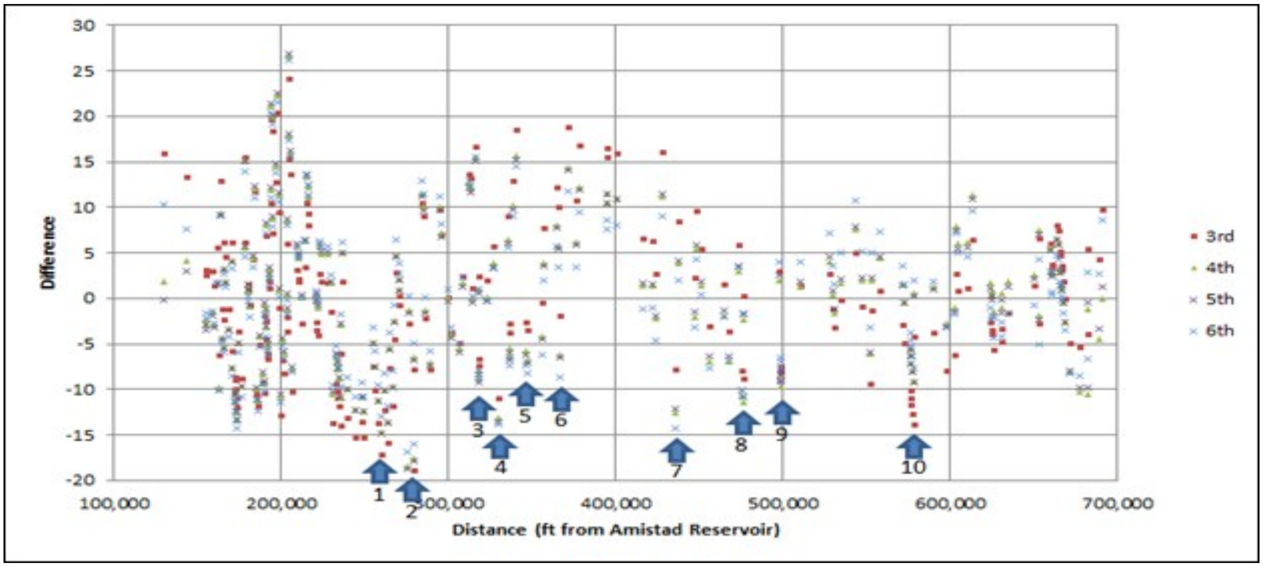

Figure 5. Difference between measured and modeled riverbed elevations

Limited documentation is available to ascertain whether there was consistent flow from Beaver Lake to Pecan Springs prior to the early 20th century. A gain-loss survey from August 1925 (Texas Board of Water Engineers, 1960) noted there was no flow in the Devils River at a point 0.2 miles below Beaver Lake.

Significant flow in the Devils River was not observed upstream of Juno Springs. Beaver Lake was cited in the survey, but neither the status of the lake nor discharge at the springs that sustained Beaver Lake was noted in report.

In summary, Beaver Lake is viewed as a bell weather for the hydrogeological status of the Devils River watershed. There is ample evidence that the springs to Beaver Lake were sufficient to sustain Beaver Lake as a persistent surface water body in a semi-arid environment even during periods of drought. It is known, although with limited observations, that before the early 20th century spring flow at Beaver Lake was previously sufficient to provide continuous outflow from Beaver Lake to Pecan Springs where current continuous surface flow is currently observed.

Effects of pumping on recharge, streamflow, and surface water/groundwater interactions described in Weinberg (2018) are generally consistent with other recent similar discussions (Fratesi et al., 2014; presentations by R.T. Green to the Texas Legislature Natural Resources Committee, 2018). In summary, Weinberg (2018) notes :

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> Pumping may affect the lateral movement of groundwater in Val Verde County and surrounding areas. Large-scale pumping over an extended period may produce a cone of depression in the potentiometric surface sufficient to induce lateral groundwater flow into the county from surrounding areas. This is especially likely in the southern portion of Val Verde County where the Edwards aquifer unit is thicker and larger volumes of groundwater can be produced. Confined groundwater conditions in the southern part of the county will also tend to create a wider cone of depression because the smaller confined aquifer storage coefficient results in greater drawdown for a given pumping volume. Groundwater flow in the thinner Edwards aquifer unit north of the Maverick Basin appears to be separated into distinct groundwater basins coincident with the

surface water drainages. Pumping in the upstream portion of one basin is unlikely to affect adjacent basins, even if the aquifer is locally dewatered, because the gradient created by the pumping will probably not be sufficient to induce flow across the divide between the surface water basins. (Weinberg, 2018)

Weinberg (2018) provides Figure 6 with groundwater elevations measured at two wells, 5463401 and 7001707. The relatively flat response in measured groundwater is clearly indicative of a phreatic aquifer. Well 5463401 is located near Juno and well 7001707 is located near the confluence of Dolan Creek and Devils River. As discussed in the Numerical Model section of these comments, the Val Verde County Model does not honor this important tendency for the phreatic parts of adjoining watersheds in Val Verde County to act hydraulically separately.

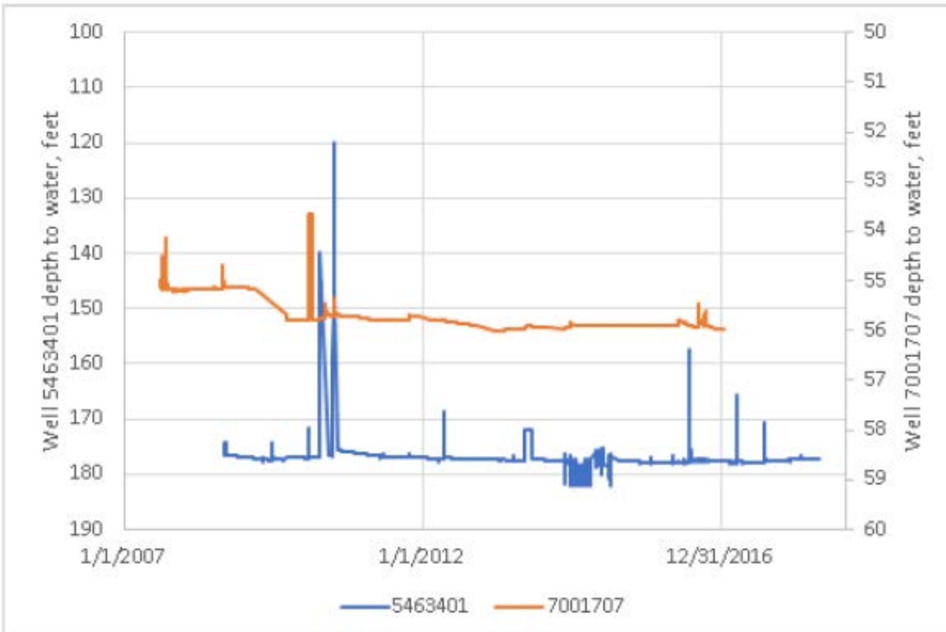

Figure 6. Hydrographs of TWDB Recorder Wells in the Devils River Watershed showing little overall variation in water levels over a 10-year period. (Figure 8-2 in Weinberg, 2018)

Weinberg (2018) states that:

Available data suggest that the groundwater flow system in conduits is poorly connected to the limestone rock matrix. The conduit system is recharged separately from the aquifer matrix and there is limited mixing between the two systems. Conduits are primarily recharged by runoff that is concentrated along the surface drainage system and enters the aquifer through large openings, such as sinkholes and solution-enlarged fractures. The matrix is recharged by precipitation percolating through soils. Because the amount of recharge to the rock matrix is much smaller than that to the conduit system, groundwater originating from the rock matrix represents a small fraction of the overall volume of groundwater discharged from the major springs. (Weinberg, 2018)

Parts of this premise are problematic and are not aligned with current concepts on karst aquifers, which posit that the matrix and conduits (as well as fractures) are usually in direct communication with each other. Speleogenesis, the evolution of karst aquifers, is the technical basis of the integral hydraulic relationship between karst features and rock matrix. Seminal texts by Klimchouk et al. (2000) and Gabrošek (2002) provide clear explanations how karst aquifers form and how rock matrix can provide the principal source of conduit water. The conduits account for most of the permeability within the aquifer, and the matrix accounts for most of its storage capacity. Water is transmitted back and forth between the conduits and matrix during high- and low-flow events. It is true that preferential flow paths likely account for a large fraction of the discharge in the streambed, but these conduits are themselves fed by matrix flow in between storm events. The conceptualization that rock matrix and conduits are separate dual systems is not consistent with the karstic Edwards-Trinity Aquifer in the Devils River watershed (Green et al., 2014).

The amount of recharge experienced in Val Verde County and environs is discussed in some detail in Weinberg (2018). The range in recharge values by a number of researchers varies from a fraction on an inch/year to several inches/year. This uncertainty in recharge in the semi-arid karst landscape in Val Verde County adds to the uncertainty in calculating its water budget.

Weinberg (2018) asserted “The current evaluation considers spring discharges to streams and rivers separately from wells, while Green et al. (2014) apparently grouped spring flow rates and well production rates together.” Green et al. (2014) did not group spring flow rates and well production together. Figure 7 and 8 from Green et al. (2014) and associated evidence reflect only wells, not wells and springs as noted by Weinberg (2010).

Weinberg (2018) relies solely on specific capacity data for wells located in Val Verde County in arriving at the conclusion that “The pattern of increased groundwater productivity near stream drainages noted by Toll and others (2017) is not apparent from the TWDB data.” This position by Weinberg (2018) is a clear example of how Weinberg (2018) was limited by the restriction that the hydrologic overview was restricted to Val Verde County. Weinberg (2018) limited his assessment of whether conduits are aligned with river channels to 59 wells in Val Verde County with reported well yield and drawdown values to form his opinion that the pattern of increased groundwater productivity near stream drainages noted by Toll et al. (2017) is not apparent from the TWDB data. As noted in Green et al. (2014), specific capacity data in the Devils River watershed are sparse. It is for this reason that well capacity data were used as a surrogate for specific capacity data. Toll et al. (2017) relied on Green et al. (2014) in which the entire Devils River watershed, spanning parts of five counties, was used to support their conceptualization that pathways with high preferential flow (i.e., conduits) are aligned with river channels. Green et al. (2014) relied on the TWDB database of 2,200 wells of which 750 wells had pumping capacity data. Clearly, low capacity wells are not an indication that the aquifer is limited in terms of hydraulic conductivity. What is useful in this analysis is that: (i) high capacity wells are found only proximal to river channels and (ii) no high capacity wells are found distal from river channels.

The conceptual model of preferential flow paths aligned with river channels in the karstic Edwards-Trinity Aquifer was not proposed by Green et al. (2014). It was first proposed by Abbott (1975) and Woodruff and Abbott (1979, 1986). In fact, correlation between karst development and river channels has been observed elsewhere (Allen et al., 1997; MacDonald and Allen, 2001; Mocochain et al., 2009).

Green et al. (2014) corroborated the conceptualization of Abbott (1975) and Woodruff and Abbott (1979, 1986) that conduits align with river channels in the Edwards Plateau using well capacity data, chemical data, surface geophysical imaging, and well hydraulics.

To refute the conceptualization of Abbott (1975), Woodruff and Abbott (1979, 1986), Green et al. (2014) and Toll et al. (2017) is not difficult. All one needs is to identify high capacity wells located distal from river channels (i.e., the presence of wells with capacity greater than 100 gpm in the tablelands of the Devils River watershed). To date, no such wells have been identified.

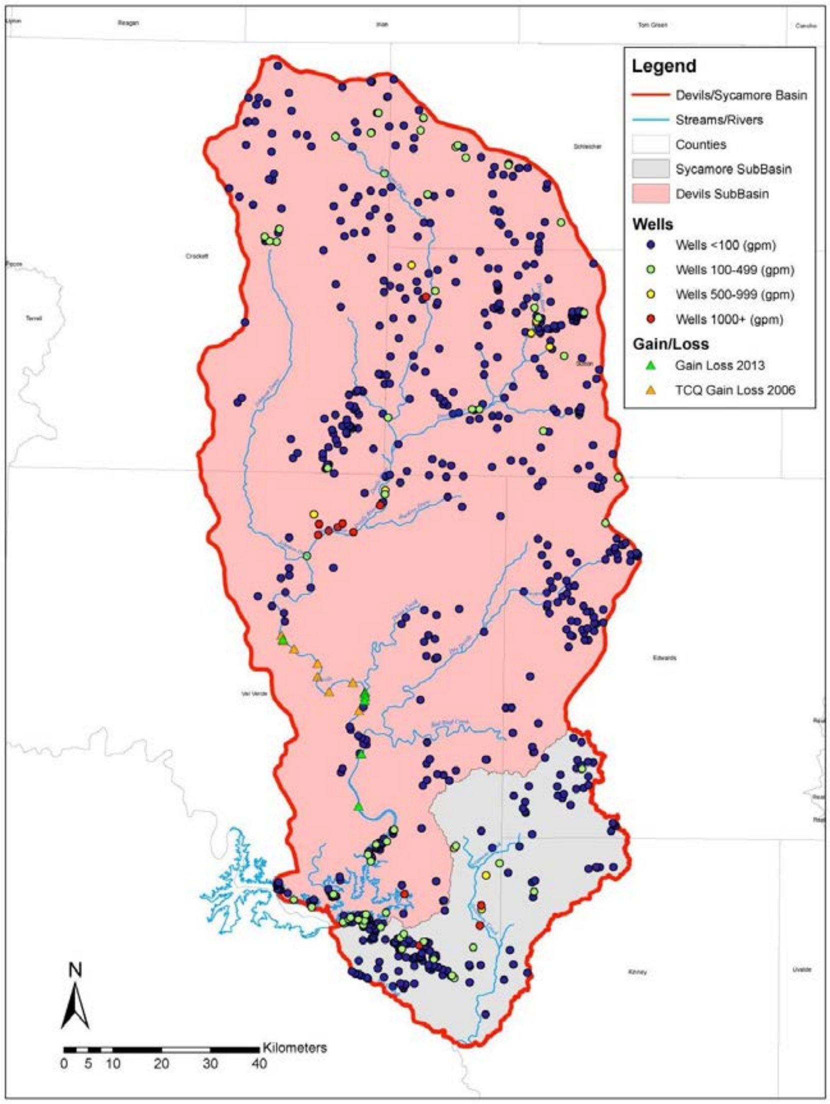

Figure 7. Map of the Devils River watershed with well locations. Highest capacity wells [> 3,785 684 L/min (1,000 gpm)] are denoted by a red dot, higher capacity wells [between 1,890 L/min (500 685 gpm) and 3,784 L/min (999 gpm)] are denoted by a yellow dot, lower capacity wells [between 686 378 L/min (100 gpm) and 1,889 L/min (499 gpm)] are denoted with green dots, and wells with 687 capacity less than 100 gpm are denoted with a purple dot. As illustrated, the majority of wells 688 have capacities less than 378 L/min (100 gpm).

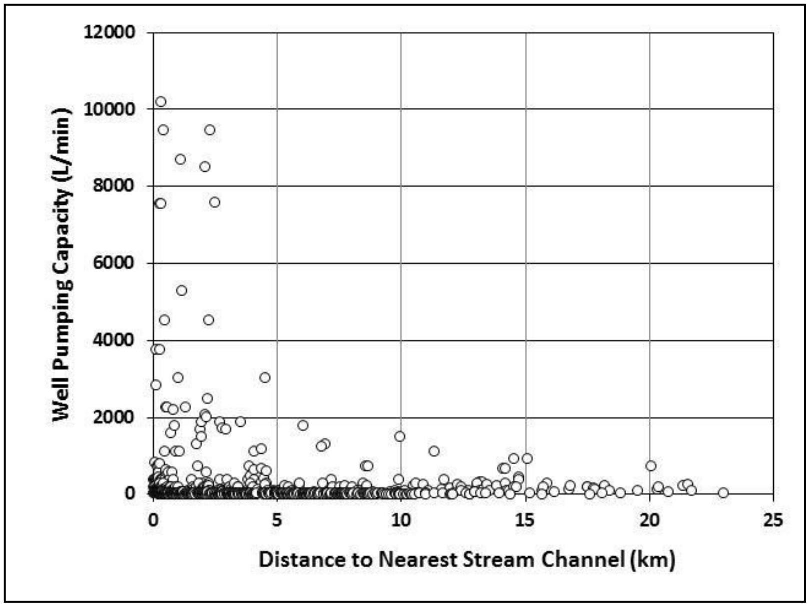

Figure 8. Graph of well capacity versus distance from closest river. The vertical red line indicates an approximate demarcation line that denotes the maximum probable distance that a well with capacity greater than 1,890 L/min (500 gpm) will be found from a river channel. One well with a capacity of 3,024 L/min (800 gpm) at a distance of 4.5 km from the closest river is the only known exception to this generalization.

Weinberg (2018) comments on the residence time of water discharged from Goodenough and San Felipe springs: “The mean residence time of groundwater discharged at Goodenough Springs and San Felipe Springs is estimated to be between 21 and 34 years.” This is predicated on an assumption that the Edwards-Trinity Aquifer in the Devils River watershed behaves as a porous medium. The Edwards-Trinity Aquifer in the Devils River watershed is a karstic carbonate aquifer.

The Devils River is recharged by groundwater issued from springs in the riverbed. Water samples collected from the Devils River are a mixture of matrix water and conduit water. In general, matrix water is older and conduit water is younger. The mix of matrix water and conduit water discharged to the river varies in time. The water mixture will tend to be younger if sampled during a period of active recharge (*i.e.,* during a wet year) due the higher proportion of conduit water. Conversely, the water mixture will tend to be older if sampled during a period of limited recharge (*i.e.,* during a drought) due to the higher proportion of matrix water. It is difficult to ascertain which portion of the water is derived from the rock matrix and which is derived from conduits.

If TWDB chooses to assert that the “age” of the water discharged from Goodenough Springs and San Felipe Springs is estimated to be between 21 and 34 years, it would be informative to have qualifying supporting discussion regarding what portion of the water is relatively young water representing conduit flow and what portion of the water is relatively old water representing matrix flow. If, as asserted elsewhere in the document, there is limited mixing between conduits and matrix, are the dates representative of conduit water? Groundwater flow in conduits is rapid, averaging a kilometer/day (0.6

miles/day) (Worthington, 2007). The draft document by Weinberg (2018) would benefit by a clarification of this discrepancy or ambiguity.

Weinberg (2018) states the following as an explanation of the impact of grazing and brush growth/control on recharge and surface runoff on the Edwards Plateau.

> Historical changes in vegetation on the Edwards Plateau are thought to have increased runoff and reduced infiltration in the aftermath of European settlement in the mid to late-19th century. Researchers are still debating the recent effects of ongoing changes in plant communities. Field studies in Central Texas find a modest, short-term decrease in evapotranspiration and runoff and an increase in recharge following brush removal, but areas with thin, karstic soils may not derive significant hydrological benefit from brush removal and poorly managed or poorly timed intervention can increase erosion and soil loss (Goodwin, 2010, Ball and Taylor, 2003, Afinowicz, Munster and Wilcox, 2005, Banta and Slattery, 2011, Saleh and others, 2009).

Weinberg (2010) correctly notes that the technical community continues to debate whether the increase in brush growth in the Edwards Plateau has resulted in a decrease in recharge. The Texas Hill Country has undergone two phases of land-use change over the past 130 years. First, severe overgrazing and tree cutting from 1890 to 1960 resulted in a degraded open landscape. Starting in about 1960, the decline in overgrazing resulted in a more heavily wooded landscape than any time in the recent past (Wilcox and Huang, 2010). Also starting in about 1960, stream baseflow increased and is now about double compared with the baseflow of streams during times of overgrazing (Wilcox and Huang, 2010). Conventional thought was that the pervasive growth of woody plants leads to decreased recharge, spring discharge, and stream flow (see for example the widely cited Zhang et al., 2001). This belief came under scrutiny with the publication of a seminal paper by Wilcox and Huang (2010). Wilcox and Huang (2010) investigated the correlation of the encroachment of woody plants with stream baseflow in four watersheds in the Texas Hill Country, namely the Guadalupe, Frio, Nueces, and Llano river watersheds. In this work, they noted that recharge in the Texas Hill Country has doubled concurrent with the expansion of woody plants. Increased recharge is reflected in increased spring discharge and increased stream baseflow. Wilcox and Huang (2010) assert that increased recharge is due to improved land- management practices that reduced grazing pressure. Although this premise is not embraced by all, a number of subsequent studies and peer-reviewed publications targeting the Texas Hill Country have substantiated the claims by Wilcox and Huang (2010) (Bazan et al., 2012).

Similar to elsewhere in the Texas Hill County, land use in the Devils River watershed has experienced improved management practices and land use over the past half century. Much of the improved land management is due to decreased grazing pressures. Similar to other watersheds on the Edwards Plateau, this improvement in land management has resulted in increased woody growth in the Devils River watershed. Based on the work by Wilcox and Huang (2010), spring flow and stream flow in the Devils River should have increased over the same time frame as land-use improvement. The fact that Beaver Lake has experienced continued dewatering during a period during which spring discharge and stream baseflow should have increased suggests that another factor was at play. This other factor is identified as the increased quantity of water pumped from the upper Devils River watershed over this time frame.

Numerical Models.

Weinberg (2018) posits “The Val Verde County Model is potentially better suited for evaluating groundwater management options than the regional Edwards-Trinity (Plateau) Aquifer GAM or the watershed-based Devil River Watershed model.” A major limitation in the Val Verde County Model is that it is predicated on a porous media conceptualization that assumes a confined aquifer that does not honor separation of watershed basins. As a consequence, pumping from the phreatic portion of the model (the upland areas in the northern portion of the model, covering 70-80% of Val Verde County) in one watershed will be hydraulically transmitted to adjoining watersheds. This tendency is clearly illustrated in Figures A-7 through A-27 in the Val Verde County Model report (EcoKai Environmental, Inc. and Hutchison, 2014). Figure A-21 from EcoKai Environmental, Inc. and Hutchison (2014) is included here as an example (Figure 9). The simulation by the Val Verde County Model in Figure 9 indicates that pumping from the Sycamore Creek watershed (*e.g.*, at the Weston Ranch) will impact not only the Edwards-Trinity Aquifer in the Devils River watershed, but also the Edwards-Trinity Aquifer in the Pecos River watershed and also into Mexico. This simulation is in conflict with the hydraulic conceptualization stated by Weinberg (2018): "Pumping in the upstream portion of one basin is unlikely to affect adjacent basins, even if the aquifer is locally dewatered, because the gradient created by the pumping will probably not be sufficient to induce flow across the divide between the surface water basins".

As a consequence, using the Val Verde County Model will predict that the hydraulic impact of pumping will be spread over a larger area than would actually occur if groundwater pumping were restricted to the watershed in which it is pumped. Also as a consequence, the predicted impact to the watershed in which the pumping is simulated will be less than what would otherwise be predicted if all pumped water were extracted only from the Edwards-Trinity Aquifer within that watershed.

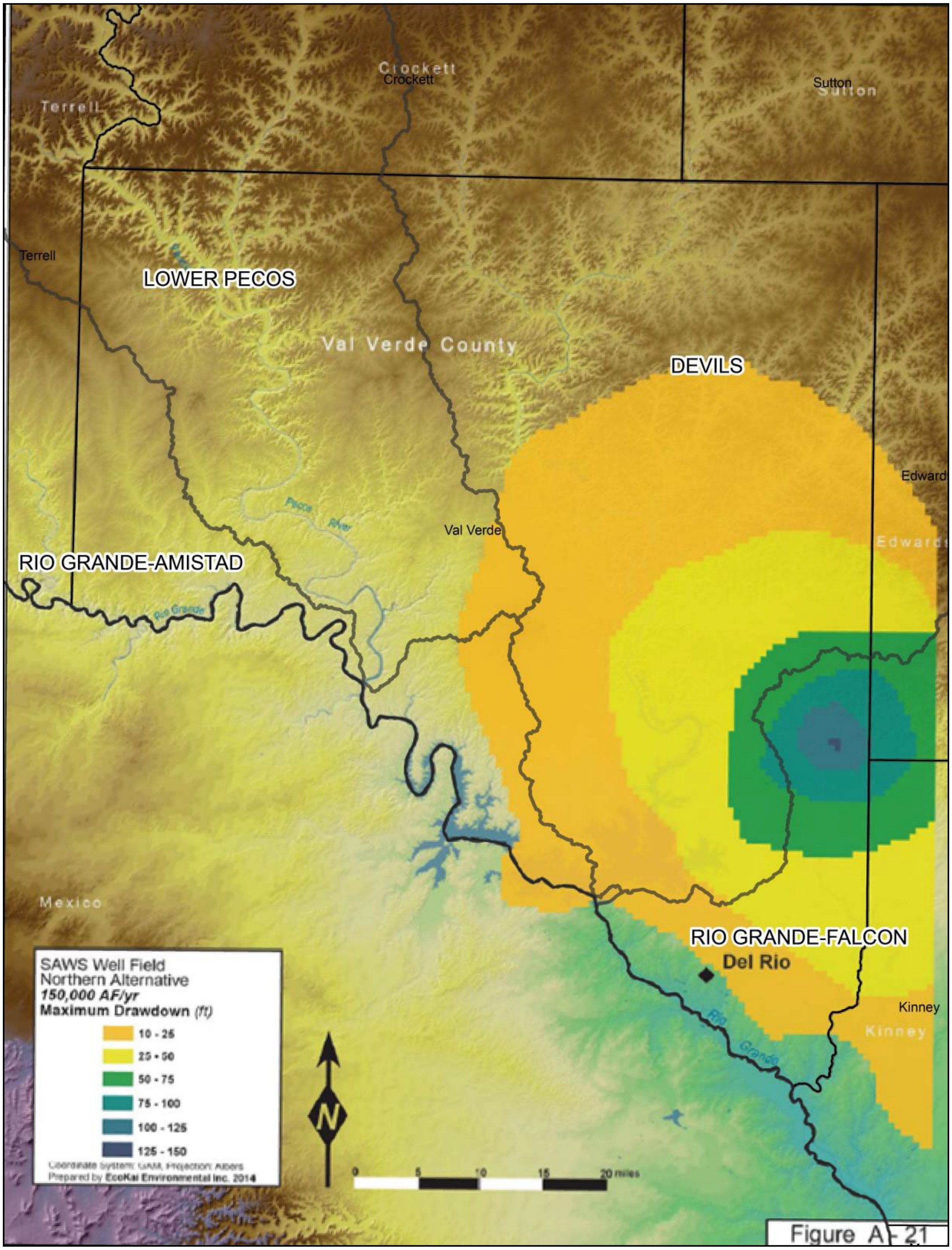

Figure 9. Simulated drawdown of pumping from the SAWS well field-northern alternative. Figure A-21 from EcoKai Environmental, Inc. and Hutchison (2014)

Groundwater Management Zones

Weinberg (2018) notes the following:

> “Based on our review of available data, Val Verde County has sufficient hydrogeologic variability to support the establishment of aquifer management zones in the event a groundwater conservation district is established. Four separate groundwater management zones, based on approximate watershed boundaries, could be defined in Val Verde County as shown in Figure 8-3. Groundwater contributing to flow in the Pecos River, Devils River, and Sycamore/San Felipe Creek drainages occupies generally separate flow systems.”

Figure 8-3 from Weinberg (2018) is reproduced here as Figure 10.

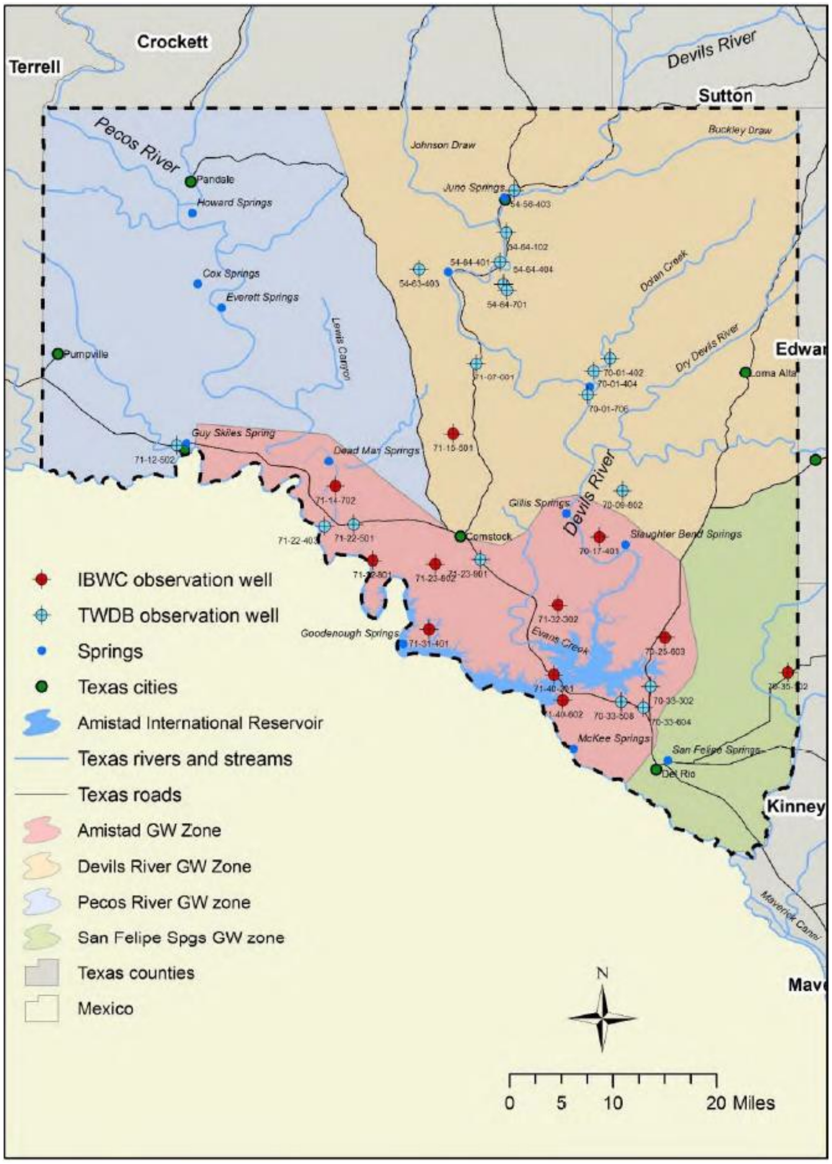

Figure 10. Map of possible groundwater management areas for Val Verde County. (Figure 8-3 in Weinberg, 2018)

Weinberg (2018) provides a convincing argument for the four groundwater management zones. Based on the recognition by Weinberg (2018) that phreatic aquifer watersheds are hydraulically separate, provides ample basis for the designation of each watershed as a separate groundwater management zone. Designation of the Pecos River and Devils River watersheds as separate groundwater management zones is clearly warranted. The zone proximal to Amistad Reservoir is a bit problematic. This zone is clearly impacted by Amistad Reservoir; however, excessive pumping in one part of the zone may not be hydraulically transmitted throughout the entire proposed zone. This is not a limitation in the zone designation, rather it is a consequence of Amistad Reservoir dominating the hydraulics of areas adjoining the reservoir.

The remaining zone to the southeast could be modified from what is proposed in Figure 10 (figure 8-3 in Weinberg, 2018). Analyses conducted by staff at SwRI suggest the designation of Sycamore Creek watershed as separate from the zone containing San Felipe Springs (Green et al., 2014; Toll et al., 2017). Sufficient evidence suggests parsing out Sycamore Creek watershed from San Felipe Springs.

One source of uncertainty in these zone designations is to identify the capture area that provides water for San Felipe Springs. The surface watershed that contains San Felipe Springs is only 53 mi^2. Weinberg (2018) and others correctly note that discharge at San Felipe Springs increased subsequent to construction and filling of Amistad Reservoir. Given that San Felipe Springs is located downdip in the Edwards-Trinity Aquifer and is likely sourced from the confined portion of the Edwards-Trinity Aquifer, discharge at San Felipe Springs is likely sourced from a comingled source of confined aquifers that underlie an area that extends well beyond the extent of the surface watershed coincident with San Felipe Springs. Additional investigation could clarify the extent of this source area; however, this added detail is not deemed necessary to go forward in establishing groundwater management zones.

This perspective that the source area for San Felipe Springs is greater than the 53 mi^2 watershed is supported by the observation that discharge at San Felipe Springs is augmented by Amistad Reservoir. Thus, if additional pumping were to occur in the capture zone of San Felipe Springs, some discharge to the springs would be offset by additional recharge from Amistad Reservoir. Understanding the intricacies of this hydraulic relationship is not critical to designating San Felipe Springs to be part of the Amistad Groundwater Zone and designating the area to the east to be part of the Sycamore Creek groundwater management zone.

Weinberg (2018) proposes the use of a combination of index wells and river gauges as hydrologic triggers. The designation of a river gauge would be appropriate for each of the three watershed management zones. San Felipe Springs discharge could be designated as the trigger for the Amistad groundwater management area, even though it is understood that the impact of pumping at the west end of this management zone would be muted or subdued in terms of its effect on discharge at San Felipe Springs.

Weinberg (2018) states that "Measured flow in the Devils River at Pafford Crossing is influenced by Amistad reservoir water levels and is not a good indicator of conditions in the upper, spring-fed reaches of the river." This is predicated on the premise that the Pafford Crossing gauge is sufficiently close to Amistad Reservoir that the hydraulic gradient at Pafford Crossing has been altered.

Weinberg (2018) cites groundwater elevation data at well 7017401 as evidence that the river gauge at Pafford Crossing is hydraulically impacted by Amistad Reservoir. Well 7017401 is located approximately 1.6 miles east of Pafford Crossing. There are limited data for well 7017401 at the time Amistad Reservoir was completed (Table 4). There are no groundwater elevation data available for the period 1969-2006; thus, whether the impact of Amistad Reservoir reaches Pafford Crossing and how much of an impact Amistad Reservoir has had at this distance from the reservoir is uncertain. Given the data available (Table 3), the magnitude of the impact on river flow at Pafford Crossing does not appear significant.

This assessment is supported by flow measured at Pafford Crossing (Figure 11) compared with annual precipitation measured at Del Rio International Airport (Figure 12). As illustrated in Figure 11, baseflow at Pafford Crossing increased after Amistad Reservoir was constructed and filled in 1969. This increase in baseflow is consistent with a general increase in annual precipitation observed during the late 1960s and into the 1970s. The fact that flow measured at Pafford Crossing demonstrated no significant change from the time prior to construction of Amistad Reservoir, suggests that the Pafford Crossing gauge could be a candidate trigger for the Devils River watershed.

Table 3. Data for well 70-17-401 accessed from TWDB on October 11, 2018

Date	Depth to Water	Groundwater Elevation (ft, msl)
11/9/1965	325.4	1135.6
7/1/1968	329.2	1131.8
7/1/1969	328.5	1132.5
11/20/1969	323	1138
1/9/2006	320.43	1140.57
7/17/2006	322.5	1138.5
10/27/2006	323.01	1137.99
1/22/2007	323.1	1137.9
4/2/2007	316.8	1144.2
7/16/2007	318.64	1142.36
10/15/2007	322.65	1138.35
1/7/2008	319.5	1141.5
4/21/2008	320.58	1140.42
7/7/2008	321.58	1139.42
3/16/2009	321.1	1139.9
9/20/2011	320	1141

The gauge at Pafford Crossing is recommended as a viable trigger gauge for Devils River watershed. Designation of this gauge as the trigger for the Devils River watershed can be reconsidered in the future by comparison with a new gauge located upstream for confirmation that the gauge is at a valid location. If justified, a new gauge location can be designated if appropriate. Nonetheless, the Pafford Crossing gauge is a viable gauge for this purpose.

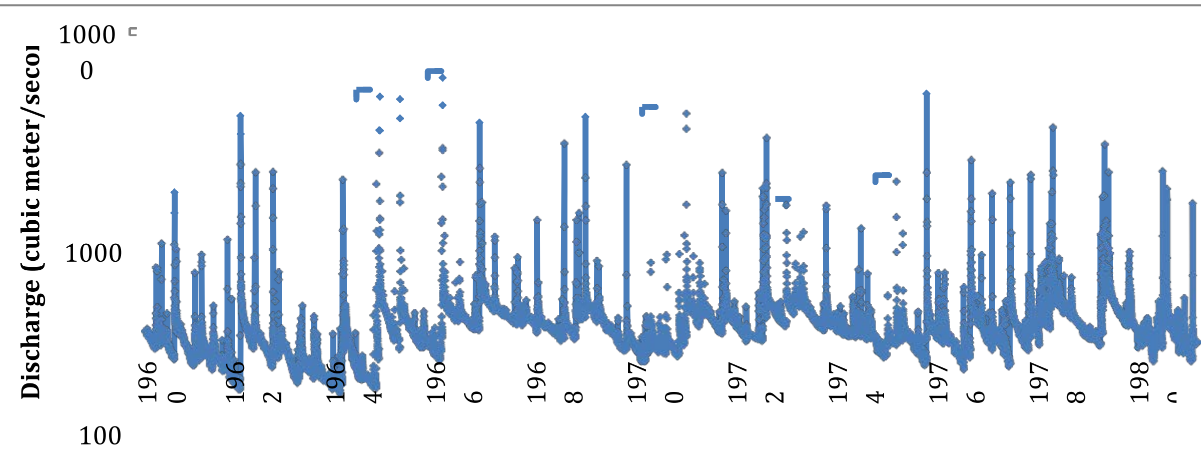

Figure 11. Discharge measured at Pafford Crossing gauge. (IBWC webpage accessed October 2018)

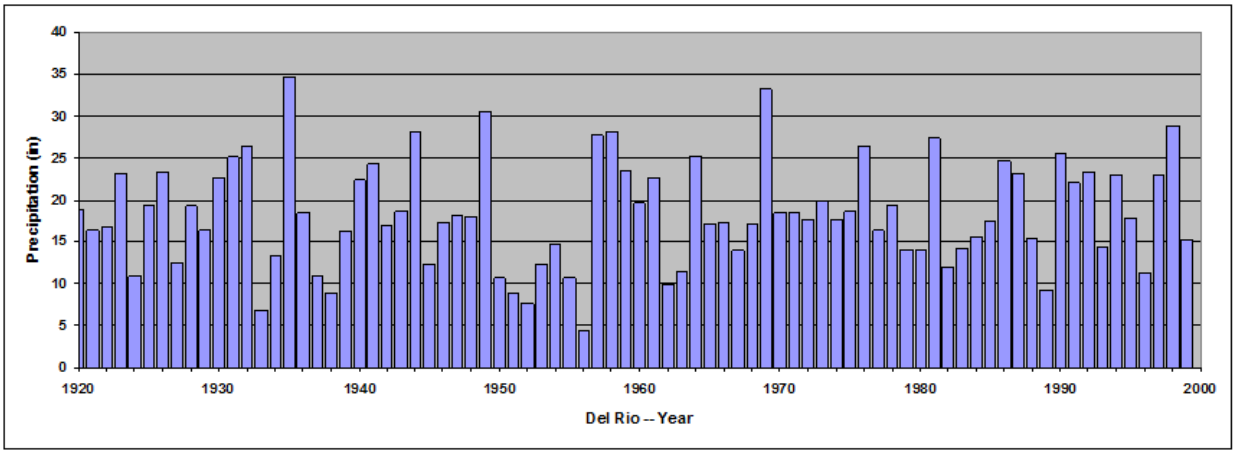

Figure 12. Precipitation measured at Del Rio International Airport 1920-2000

Because the Val Verde County Model is a porous media model which characterizes the Edwards-Trinity Aquifer as confined, it does not honor the hydraulic separation of the major watersheds in Val Verde County (*i.e.*, Pecos River, Devils River, and Sycamore Creek watersheds). The Val Verde County Model would not be an appropriate tool to simulate the designation of separate hydraulic triggers for each of the four proposed groundwater management zones.

The use of a model in which the hydraulic separation between adjoining watersheds is honored is recommended for use in water-resource management assessments. Watershed-scale models such as the Devils River watershed model by Toll et al. (2017) and the lower Pecos River watershed by Green et al. (2016) are possible candidates for this purpose; however, this is clearly the perspective of SwRI. If these models are not selected for future watershed-scale water-resource analyses, it is suggested that whatever model or models are used should honor the hydraulic separation between adjoining watersheds.

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September 10, 2018

Honorable Lyle Larson
Chairman, House Natural Resources Committee
Texas House of Representatives
Texas Capitol Extension, Room E2.406
Austin, Texas 78701

Honorable Poncho Nevárez
House Natural Resources Committee
Texas House of Representatives
Texas Capitol Extension, Room E1.508
Austin, Texas 78701

Dr. Larry French PhD.
Texas Water Development Board
1700 North Congress Ave.
Austin, Texas 78701

Re: Val Verde County Groundwater – Devils River Surface Water/Groundwater Interaction

Dear Chairman Larson, Representative Nevárez and Dr. French:

As you are aware, I represent a number of landowners with interest in the water issues in Val Verde County. Following the Committee's hearing in Del Rio during the prior Interim Session, and Representative Nevárez's request for a review of and report on the issues by the Texas Water Development Board (TWDB) at the end of the last Regular Session, these landowners have monitored activity related to the TWDB's anticipated report to the Legislature and, in particular the Natural Resources Committee when it meets in Del Rio this week.

Historically these landowners have provided the Committee with copies hydrogeologic reports prepared by various Texas based entities familiar with the hydrogeology and historic uses of water within Val Verde County, including a report they commissioned. For this reason, my group has been in a watch mode, reviewing information filed with the TWDB regarding Val Verde County groundwater, and anticipating the TWDB's upcoming report to the Committee. During this time frame, the Landowners received and studied a report entitled *Water-Resource Management of the Devils River Watershed (2017)* prepared Report by Drs. Toll and Green and their group with the Southwest Research Institute out of San Antonio ("SwRI Report"). As this report look as both groundwater hydrology or hydrogeology and surface water hydrology issues, the Landowners commissioned the LRE Water LLC, which has expertise in both disciples to review and provide them comments on the SwRI Report.

After reviewing the LRE analysis of the SwRI Report, my group asked me to share that analysis with the Committee and Dr. French at the TWDB. They are hopeful that the insights and recommendations in the LRE analysis will be useful in the continued development of our knowledge of the groundwater and surface water characteristics and interactive issues in Val Verde County. Once the TWDB has been made public at the upcoming Committee meeting in Del Rio, these interested Landowners anticipate reviewing the recommendations of TWDB and providing an updated analysis and comments for the Committee's consideration.

Thank you for your service to Texas. We look forward to continuing to work with the Committee and TWDB on this matter.

Best wishes.

Sincerely,

MCCARTHY & MCCARTHY, LLP

Edmond R. McCarthy, Jr.

ERM/tn

cc: Ms. Shannon Houston, Committee Director
House Natural Resource Committee
Texas Capitol Extension, Room E2.406

Val Verde County Landowner Interests

LREWater, LLC
a Leonard Rice Engineers Company

TECHNICAL MEMORANDUM

TO:	Mr. Ed McCarthy, Attorney for Val Verde County Landowner Interests
FROM:	Michael R. Keester, P.G. and Jordan Furnans, Ph.D., P.E., P.G.
SUBJECT:	Review of *Water-Resource Management of the Devils River Watershed* Report by Toll and others (2017)
DATE:	September 10, 2018

On August 29, 2017, Southwest Research Institute (2017) published a press release indicating they completed a study that "provides detailed models linking groundwater in a Texas aquifer to the surface flows in one of the state's most pristine rivers." The press release stated that the study provides the first means for water managers to evaluate the relationship between pumping and spring flows. While not identified in the press release, the study that it refers to is the *Water- Resource Management of the Devils River Watershed* report (Toll and others, 2017) which was presented the following day at the Texas Alliance of Groundwater Districts Groundwater Summit (Green and others, 2017).

As requested, LRE Water, LLC conducted a preliminary review of the work documented in the report. As part of our review, we also considered previous hydrogeologic investigations conducted within the Devils River watershed, Val Verde County, and the Edwards-Trinity (Plateau) Aquifer along with our professional experience in surface water and groundwater modeling. Based on the information reviewed, we developed professional opinions regarding the modeling and results reported by Toll and others (2017). Importantly, as a preliminary review it was beyond the scope of our work to fully investigate all aspects of the reported modeling and we focused on those issues that appeared most significant to the applicability and credibility of the model.

Toll and others (2017) state that the "Devils River watershed basin is being threatened by proposed large-scale groundwater export projects." To better understand the perceived threat, they conducted their study for the purpose of evaluating how pumping in the upper Devils River watershed would affect downstream discharge in the Devils River (Figure 1 is a location map for reference). To conduct the evaluation, the report authors developed what they called an integrated surface-water/groundwater model.

Conceptual Model

A conceptual model is simply a description the modeler's understanding of the flow system. This understanding will then guide the collection of data to define the model structure, parameters, boundary conditions, and calibration. It is an important step in developing the subsequent numerical model and should be guided by the model's purpose (Anderson and Woessner, 2002).

Toll and others (2017) do not discuss the structure or hydraulic properties of Edwards-Trinity (Plateau) Aquifer much in their report. However, they do adopt the conceptualization of Green and others (2014) that flow in the aquifer within the Devils River watershed is dominated by preferential flow paths aligned with the major river channels. We view this conceptualization as reasonable and one possibility for flow within the aquifer system. As discussed by Reeves and Small (1973), northeast trending faults are common in the southern part of Val Verde County and percolation of rainfall would have caused dissolution of the carbonate rocks. With many springs issuing from the northeast trending faults (Reeves and Small, 1973), it is likely that preferential flow along lines of weakness would consolidate into the drainage pattern observed today.

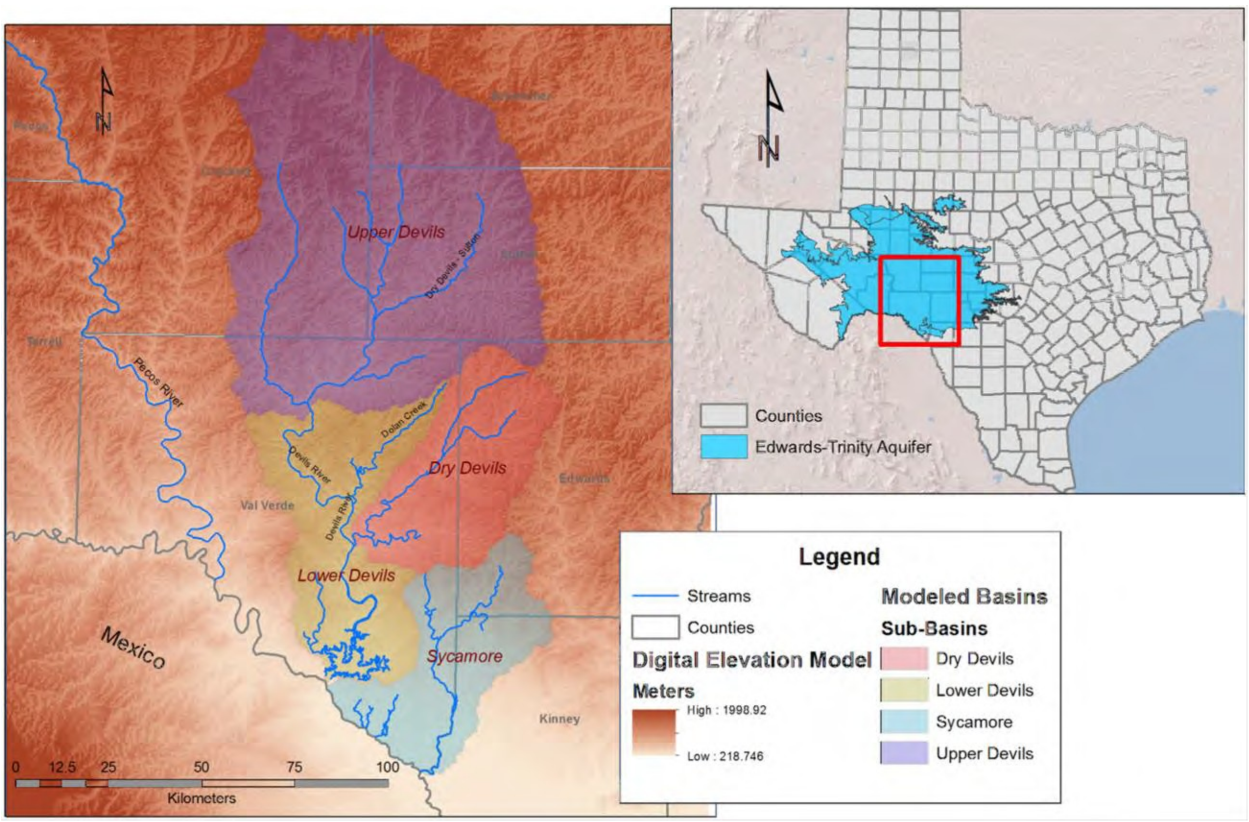

Figure 1. Location map from Toll and others (2017).

While some of the preferential flow paths may align with the river channels, it is also likely that the flow is normal to the channels in many cases. That is, rather than flow being parallel to the channels it may also be perpendicular or somewhere between the two extremes. While the report authors discuss preferential flow as "aligned" with the channels, they use a more complex example of preferential flow development, shown in Figure 2, to describe the conceptualized conduit network. We believe the conduit development shown in Figure 2 is a reasonable assumption for flow in the Edwards and associated limestones.

An important part of the conceptual model discussed by Toll and others (2017) is that Devils River is "gaining throughout virtually its entire reach" and that the "baseflow is entirely attributed to groundwater." To the first claim, the authors do not provide measured streamflows or other data to substantiate the claim, but it is likely a correct assumption. With regard to baseflow, we agree that it is likely all from groundwater.

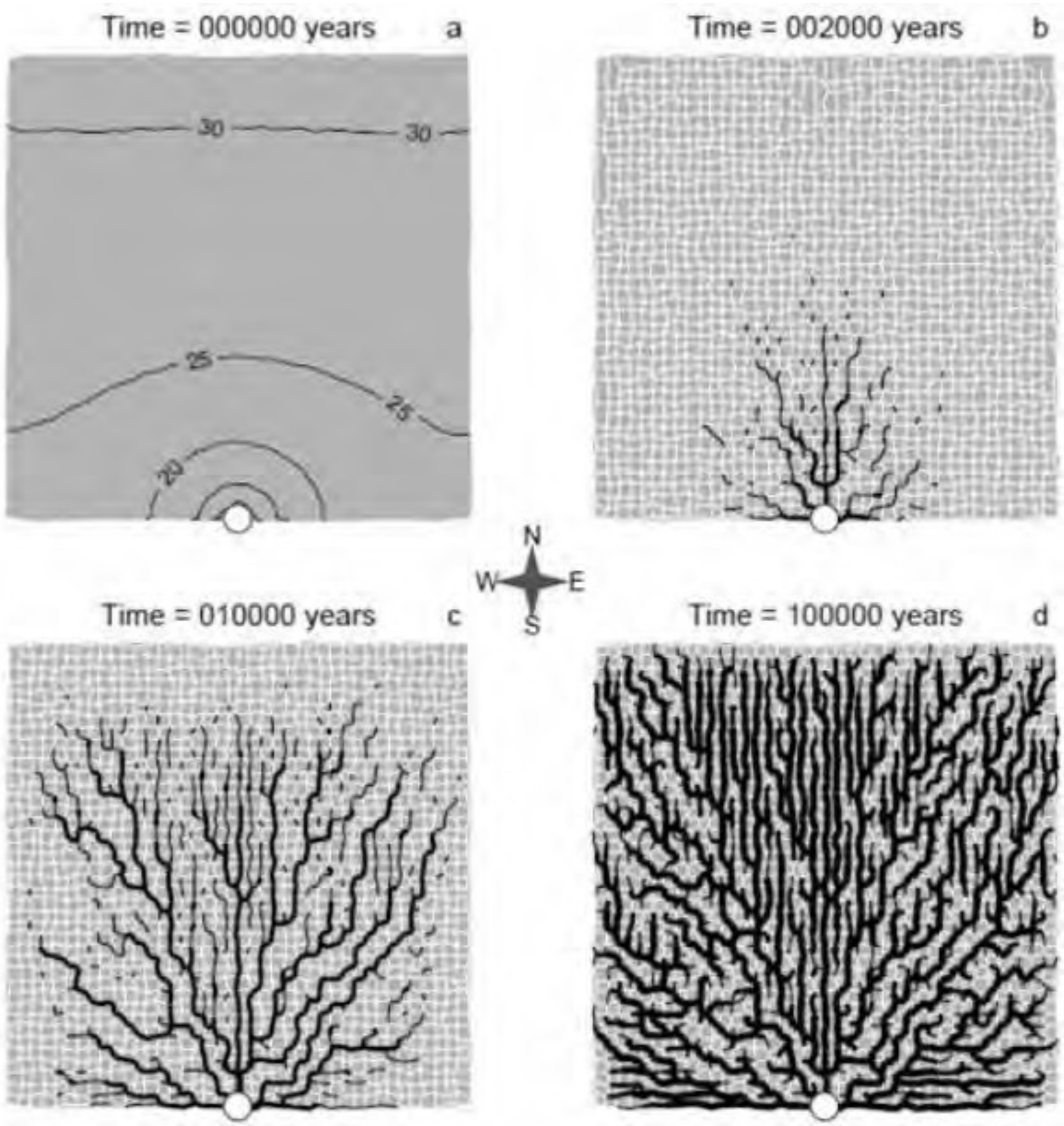

Figure 2. Example of conduit development used by Toll and others (2017). Shown as Figure 17 in their report.

For clarification, we understand baseflow to mean the portion of stream discharge attributable to groundwater seeping into the stream (Fetter, 1994). That is, baseflow is the portion of stream flow that would occur without precipitation runoff and may be attributed to groundwater discharge as springflow or seepage. We believe this clarification is important because Toll and others (2017) state that "[c]apturing the dynamic response of baseflow in the river is a prime objective" of their project. While we understand streamflows are dynamic, their statement suggests that they believe the groundwater discharge to the streams is as dynamic as streamflow changes are to runoff events. We feel this apparent view of groundwater discharge being highly dynamic is an incorrect conceptualization of the flow system and is contrary to accepted hydrogeological definition.

Regarding the flow features, Toll and others (2017) state that they are located within one mile of streams and rivers at depths less than 150 feet. The defined proximity to the streams is based on analysis of reported well yields compared to distance from the river (Green and others, 2014). Reeves and Small (1973) also stated that, based on available data, large capacity wells should be located near major rivers. Due to the likely development pattern of karst features, it is reasonable that there would be greater connectivity between conduits and one would be more likely to intersect a karst feature near the rivers. Regarding the depth, there is ample evidence that karst features can occur at greater depths. For example, a cursory review of the well data from 1973 shows many wells completed to depths greater than 150 feet (Reeves and Small, 1973), which would likely not occur if supplies were available from shallower depths.

As mentioned above, Toll and others (2017) do not discuss analysis of data to develop estimates of the hydraulic properties for the aquifers. For example, there is no discussion of using pumping test data to help constrain estimates of aquifer hydraulic conductivity, transmissivity, or storage coefficient. They reference the conceptual model of Green and others (2014) as the basis for their conceptual model, but the referenced article relates to well yields in relation to the major river channels and does not discuss distribution of aquifer hydraulic properties.

The lack of data analysis to determine a starting point and calibration constraint for the aquifer hydraulic characteristics is a significant concern. The apparent lack of analysis of aquifer properties may indicate that the modelers intended to set the properties in the model to meet their preconceived notion of how groundwater flows through the system rather than letting the data determine how the numerical model would be developed. Also, it prohibits potential users from being informed of the differences between modeled parameters and the measured values at specific locations. Perhaps most importantly, the lack of analysis does not provide constraint on aquifer hydraulic parameters during the model calibration process. The constraints during model calibration are very significant because they will inform the numerical model regarding the spatial distribution of the hydraulic parameters along with the aquifer heterogenity and anisotropy.

Other items that we believe are missing from the conceptual model discussion by Toll and others (2017), but are beyond the scope of this preliminary review, include:

- Aquifer structure such as formation contact elevations and faulting
- Vertical flow within the Edwards and associated limestones

- The effect of Lake Amistad on the groundwater conditions in the Devils River basin, including the rise in aquifer water levels documented after completion of Amistad Dam (HDR, 2001; Anaya and Jones, 2009; EcoKai, 2014)
- Aquifer water budget analyses, such as that of William F. Guyton and Associates (1964) or Reeves and Small (1973)

Overall, Toll and others (2017) focus their discussion on features and preferential groundwater flow in the aquifer aligned with rivers. While this conceptualization is partially valid, it does not capture the full complexity of flow within the aquifer. In addition, the focus is to the detriment of considering other important factors within the hydrogeologic system.

Surface Water Model

Toll and others (2017) state that they developed the surface-water model using HEC-HMS "to capture river-flow conditions and model land-surface processes, providing recharge to the groundwater model." While they state that measured discharge was the target for calibration of the surface-water model, they also state that recharge to the groundwater model was "calibrated via the groundwater model" and was a more critical calibration target than measured discharge. However, the surface water model itself is not described very well and it is unclear as to how they calibrated to recharge. In addition, calibration results in the form of statistics that describe how well the model matches observed data were not reported.

To determine recharge to the groundwater system, the model authors used the initial losses and abstractions from the rainfall data used in the surface water model. Toll and others (2017) discuss these calculations in their report, but they do not document how much water the initial losses and abstractions contribute to the groundwater system nor do they document if the amounts are reasonable. To determine reasonability, the authors suggested that surface water discharges resulted from some storm events but not others, implying that the abstractions from the small storm events were accurate, thus providing reasonable assertions that the model accurately determines the portion of precipitation that becomes recharge. However, the report figures showing comparisons between the observed and modeled streamflow suggest uncertainity with regard to model validity. For example, the figures presented by Toll and others (2017), like their Figure 15, focus on the comparison between the modeled and measured discharges after the larger storm events, which appear to be decent, but the figures do not really focus on the comparisons between modeled and observed discharge after the minor storm events that have a greater effect on recharge.

The documentation of the surface water model is poor. Without documentation of how much water the initial losses and abstractions contribute to the groundwater system, it is not possible to evaluate the reasonability of the results. Based on their statement that recharge was a critical calibration target, it is not clear if the physical properties assigned in the model were based on measured or realistic values to determine potential recharge or if the property values were assigned to match a preconceived recharge amount regardless of whether they were realistic for the physical conditions.

Groundwater Model

Toll and others (2017) used MODFLOW-USG (Panday and others, 2013) as the numerical code to simulate the aquifer system. Unlike the model grid in previous versions of MODFLOW, the selected code allows for grid refinement at specific areas where greater resolution in the model results is desired. We believe the code selected is appropriate for providing the additional detail along streams; however, it is important to remember that like the rest of the MODFLOW family, the code uses equations based on porous media flow, not fractures or conduits. While the use of MODFLOW to represent a karst system is common and accepted, extra care must be taken to ensure the aquifer if represent appropriately.

Model Grid and Boundary Conditions

Beyond describing the numerical model as having two layers with layer one representing the Edwards and associated limestones and layer two representing the Trinity, there is little discussion regarding the model grid. That is, grid dimensions are not provided nor is the level of refinement along the streams. Upon visual inspection of the figures provided in the report, we estimate the largest grid cells are 1,500 meters (4,921 feet) on each side (assuming map units are consistent with units used elsewhere in the report). There also appear to be two levels of refinement withthe cells proximal to the stream being 375 meters (1,230 feet) on each side and cells a short distance from the streams being 750 meters (2,461 feet) on each side.

The top of layer one appears to be defined by a digital elevation model to represent the ground surface which is standard for groundwater flow modeling. However, Toll and others (2017) defined the base of layer one as "40 meters below the bottom of the incised stream channels." It appears that they selected this depth to correlate with their conceptual model that conduit formation only occurs within 100 to 150 feet of land surface. We believe it would have been more representative to define the base of the layer using existing maps of the formation structure such as those by Reeves and Small (1973). Additional vertical refinement using MODFLOW-USG could then have been added to represent and test the conceptualization.

To simulate the streams in the model, the authors used drain boundary conditions. A limitation of the drain boundary condition is that it does not allow for flow back into the aquifer. To more realistically model the Devils River and its tributaries, we believe it would be more appropriate to use the River or Streamflow Routing package in MODFLOW which would allow water movement both into and out of the aquifer and stream. Allowing water to move in and out of the stream would better serve the model's purpose of evaluating the effects of pumping on streamflow by allowing the stream to contribute water to the aquifer if water levels are drawn down by a well field. Rather than setting up the model so that wells would only capture water that would otherwise discharge, a more robust simulation of the streams would better represent the physical processes by potentially allowing streamflow to enter the aquifer if a well field causes water levels to decline near a stream. In addition, the Streamflow Routing package would allow the modelers to input runoff results from the surface water model to better simulate the portion of flow from runoff as well as baseflow.

Model Hydraulic Parameters

For the hydraulic characteristics of the model aquifers, Toll and others (2017) assigned hydraulic conductivity ("K") and specific yield ("Sy") as follows:

- For matrix cells in layer one o
  K = 2 m/d (6.6 ft/d) o Sy
  = 0.012
- For conduit cells in layer one (that is, cells within 200 m (656 ft) of a stream)
  - K = 100 m/d (328 ft/d) for low-order stream tributaries
  - K = 1,000 m/d (3,280 ft/d) for higher order streams

  o Sy = 0.0001
- For matrix of layer two

  o K =1 m/d (3.3 ft/d)

  o Sy = 0.012
  - Specific Storage = 0.00001 m^{-1}

While it is common for a karst system to have lower specific yield and specific storage values than a sand aquifer, the value of 0.0001 for the conduit portion of the system is questionable when compared to the value used for the matrix (that is, non-preferential flow) areas of the aquifer. To check what the values used could mean for layer one of the flow system, we used our estimate of the grid dimensions, the thickness of the aquifer as 40 meters, and the specific yield values to calculate the volume of drainable water in a grid cell. Table 1 summarizes the calculated values assuming a fully saturated thickness.

Table 1. Calculated drainable volume based on reported specific yield values used in the Devils River Watershed model.

Grid Refinement Level	Cell Side Length, ft	Cell Volume, Acre-Feet	Specific Yield	Drainable Volume per Level 0 Area, Acre-Feet
0	4,921	72,964	0.012	875.6
1 (4 cells per level 0)	2,461	18,241	0.0001	7.3
2	1,230	4,560	0.0001	7.3

To ensure the calculations were comparable, the drainable volumes shown in Table 1 represent the same unit area. As the table illustrates, the drainable volume in the conduit cells is two orders of magnitude less than the non-conduit cells. The comparable low drainable volume in the conduit cells is highly questionable if it is to be consistent with the proposed preferential flow near the streams.

Unlike a porous media aquifer, water is stored and flows through fractures and conduits in the karst system. The calculated drainable volumes represent the minimum amount of open area within each grid block. While an over-simplification, if we assume fractures at regularly spaced intervals in the grid block, we can calculate the number of fractures and the average width of the fractures to achieve the minimum open area. For example, at 100 centimeter spacing there would 1,499 fractures in a grid refinement level 0 grid block and the average fracture width would be 1.2 centimeters (0.47 inch). Table 2 provides the calculated average fracture width at various fracture densities within a grid block.

Table 2. Calculated average fracture width for various fracture densities within a grid block.

Calculated Fracture Width (cm)				
Grid Refinement Level	Average Distance between Fractures (cm)			
	1	10	100	1,000
0	0.012	0.12	1.2	12.1
1 (4 cells per level 0)	0.0001	0.001	0.01	0.1
2 (16 cells per level 0)	0.0001	0.001	0.01	0.1

Understanding how the specific yield values may translate into fracture width at various fracture densities, as shown in Table 2, is important when modeling a karst system using a porous media modeling code. The importance is related to the cubic law for fracture flow that defines the hydraulic conductivity of the rock matrix based on fracture width (Snow, 1968). The relation is defined using the following formula:

$$K = \frac{\rho_w g b^2}{12\mu}$$

where ρ_w is the density of water, g is acceleration due to gravity, μ is the viscosity of the water, and b is the fracture width. Assuming constant fluid properties, the fracture width controls the hydraulic conductivity of the system and small changes in the width can change the hydraulic conductivity significantly. Using the average fracture widths shown in Table 2, we calculated the resulting hydraulic conductivity (in feet per day) assuming water at 20°C for comparison with the values used in the model (see Table 3).

Table 3. Calculated hydraulic conductivity for average fracture width at various fracture densities within a grid block.

Calculated Hydraulic Conductivity (ft/d)					Toll and others (2017) Hydraulic Conductivity (ft/d)
Grid Refinement Level	Average Distance between Fractures (cm)				
	1	10	100	1,000	
0	3,311	331,200	33,200,000	3,360,000,000	6.6
1 (4 cells per level 0)	0.23	23	2,300	236,000	328 to 3,280
2 (16 cells per level 0)	0.23	23	2,300	236,000	328 to 3,280

Calculated hydraulic conductivity values based on the required open volume in the rocks to meet the assigned specific yield do not appear to correlate with the hydraulic conductivity values assigned by Toll and others (2017). For example, to achieve the hydraulic conductivity of the matrix cells (grid refinement level 0) would require an average fracture spacing of just over0.001 cm (10 micrometers or 0.0004 inches). This extremely small average spacing would result in an average fracture width of about 0.000012 cm (0.12 micrometers or 0.000005 inches) which is 500 times smaller than the width of normal human hair. The required average fracture width is essentially equivalent to the pore throat size of a tight sandstone (Nelson, 2009) with a resulting grain size of a fine silt (Fetter, 1994) neither of which are accurate descriptions of the rocks that make up the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009). While the cubic law as shown above is known to overestimate hydraulic conductivity as it does not account for fracture roughness or tortuosity, it has been shown as valid in several studies [see discussion in Domenico and Schwartz (1998)]. Based on the information provided in the report, the aquifer parameters used in the model are not appropriate.

Model Calibration

Toll and others (2017) define the steady-state calibration of the model as the 16-year period from 2000 through 2015. Typically steady state refers to a simulation that represents the aquifer at a time prior to any significant stresses on the aquifer, such as pumping. It is possible that the authors incorrectly identified the period of time used for steady-state calibration as one of their figures contains the label "Observed Head 1960's Data" [see Figure 23 in Toll and others (2017)]. If the authors did use the 16-year period for calibration, they would need to include current pumping in the model as part of the calibration. In addition, the fluctuations of Lake Amistad would need to be included due to the strong correlation of aquifer water levels and reservoir levels (HDR, 2001; Anaya and Jones, 2009; EcoKai, 2014). The most appropriate representation of steady state would be to follow the method used by HDR (2001) and simulate aquifer conditions prior to the construction of Amistad Dam.

Regarding the degree of calibration, the only information provided is a statement that simulated water levels were within 25 to 30 feet of measured water levels and a plot of the simulated versus measured water levels. Calibration statistics for the model, which would allow users to assess the model's ability to match historical conditions, were not reported. These statistics are standard for any credible model and the lack of reporting suggests the model may be poorly calibrated to historical conditions. Visual review of the plot of simulated versus measured water levels for their steady-state period indicates some bias in the model; modeled water levels between 350 and 500 meters appear to be biased higher than measured levels and modeled water levels between 500 and 675 meters appear to be biased lower than measured levels (see Figure 3).

In assessing contributions to baseflow, the biases could have a significant impact. An overestimation bias results in water levels being higher than measured and potentially greater amounts of discharge to the surface water features if they are intersected by the groundwater level. Conversely, with an underestimation bias there may be areas where discharge should occur, but the modeled levels do not reach the elevation of the discharge location. We believe the apparent biases should be addressed and calibrations statistics reported.

For the transient calibration (that is, calibration of the model to historical measured conditions), the modelers refer to a 16-year period, but it is not clear how the period differs from their description of the steady-state calibration. Nonetheless, the available data allow for a much longer transient calibration period (HDR, 2001; EcoKai, 2014). To better understand the hydraulics of the aquifer system, Toll and others (2017) should have performed a transient calibration that began prior to the construction of Amistad Dam and used the changes in aquifer water levels as Lake Amistad filled to inform the model parameters.

No comparison of measured versus simulated water levels is provided or discussed by the modelers for their transient calibration. It is not possible to provide any meaningful assessment of the transient model calibration due to the absence of information in the model report. Based on the bias evident in the so-called steady-state calibration, it is likely that the model bias is also present in the transient model.

The modelers state that the "coupled surface-water and groundwater model produces a baseflow that responds much better with regards to the variation in magnitude of discharge" at Pafford Crossing. In support of their statement they present Figure 4 in which they identify the results as baseflow. However, the results shown on Figure 4 appear to be measurements of streamflow at the Pafford Crossing gaging station which would include contributions from runoff. As there is no discussion of how the baseflow component of flow is being calculated from the drain cell results, the statement that the model produces a better baseflow response is not supported by the reported results.

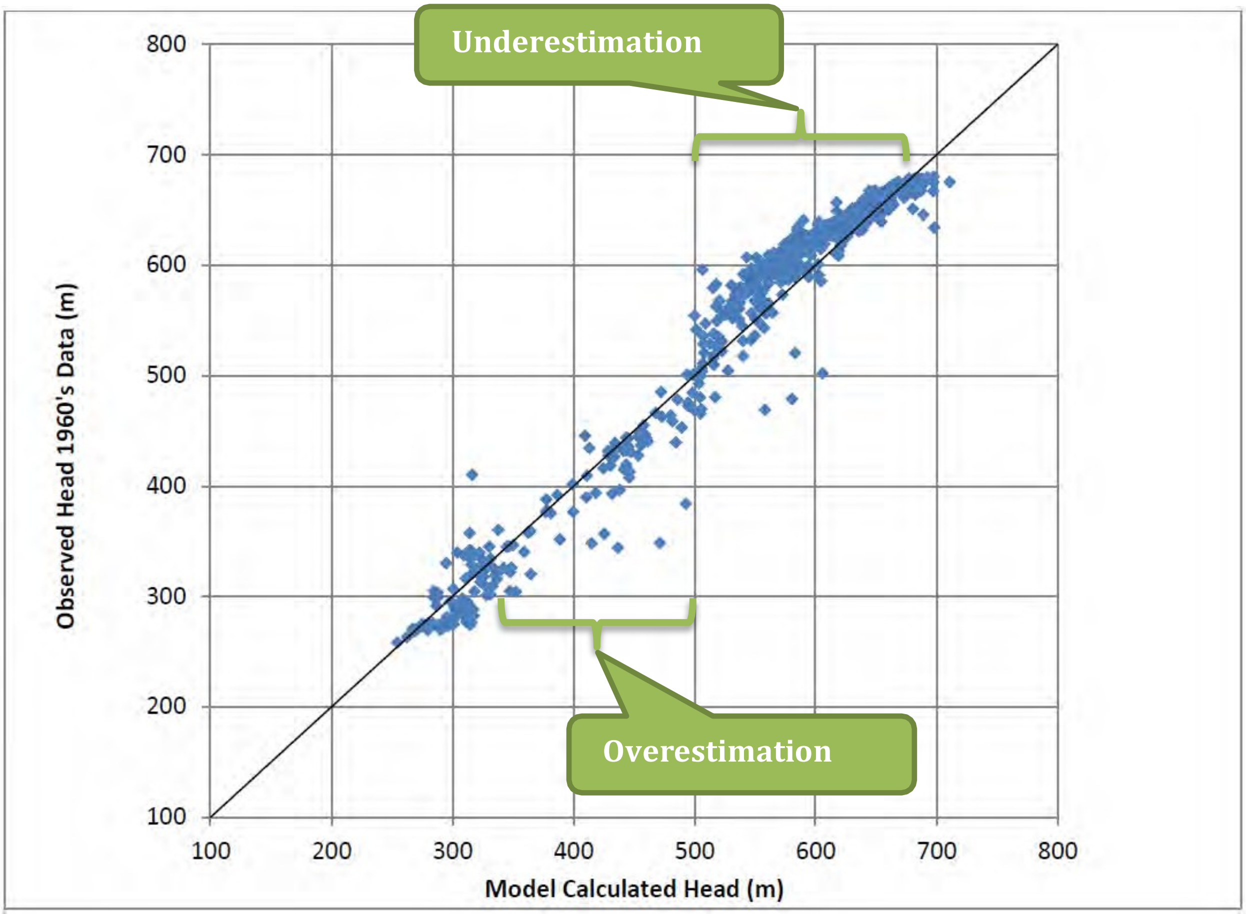

Figure 3. Measured (that is, observed) versus modeled water levels (that is, head) reported by Toll and others (2017). Shown as Figure 23 in their report. Note that the figure indicates the observed water levels are from the 1960s, but the report text states they are from 2000-2015.

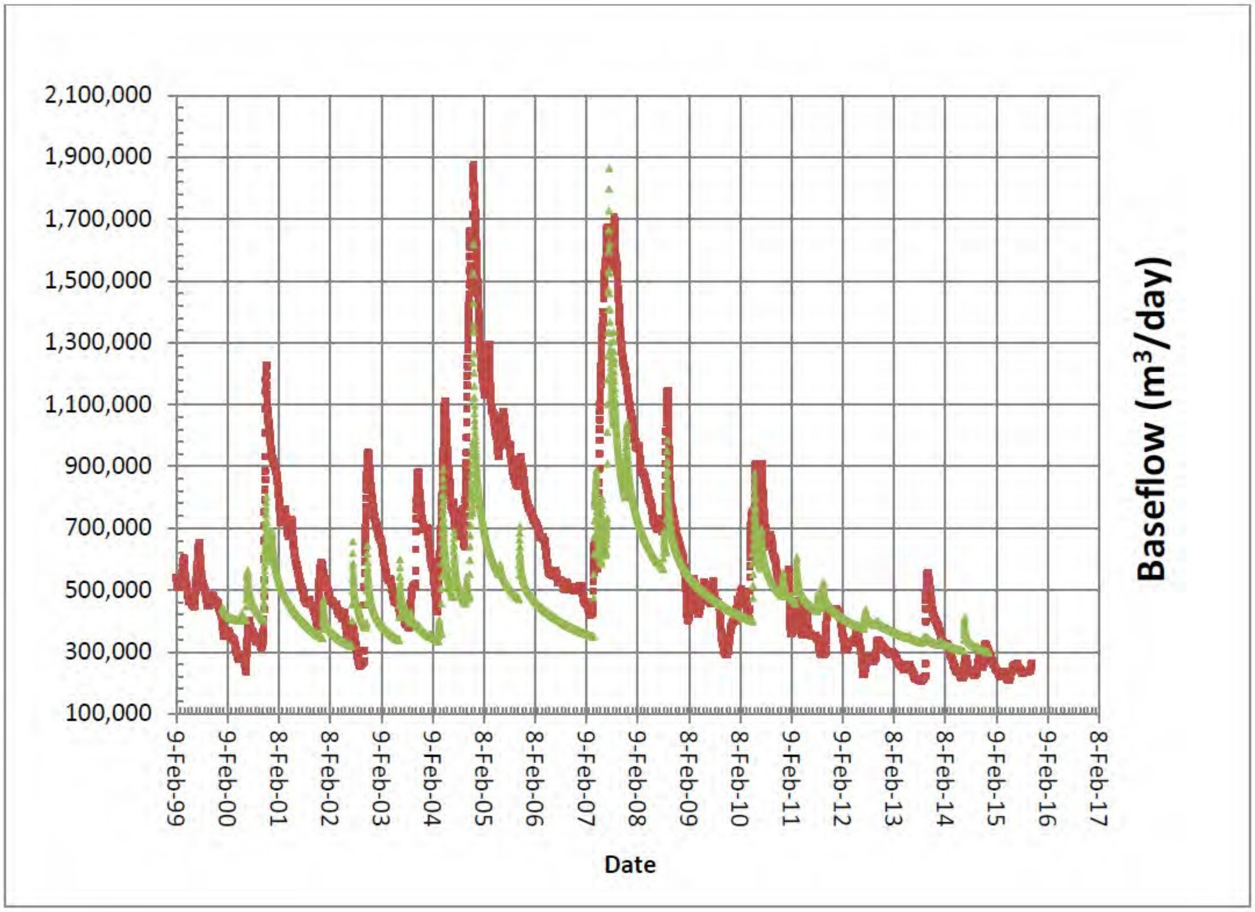

Figure 4. Toll and others (2017) describe the above chart as "Model predicted baseflow (green triangles) versus observed baseflow (red squares) at Pafford Crossing, 2000-2015." Shown as Figure 24 in their report.

As part of the transient simulations, Toll and others (2017) applied 14,000 acre-feet per year of pumping in the model. The value applied was to account for uncertainty in pumping estimates and appears to be applied as a constant value throughout the simulation. Locations of pumping were not included in the report. A more representative temporal pumping distribution could have been obtained using estimates from the Texas Water Development Board (TWDB, 2018) along with known well locations and estimated yields. Within their report conclusions, Toll and others (2017) first state that estimated pumping has not exceeded 7,000 acre-feet per year since 1960. Even with the uncertainty in pumping amounts claimed by the model authors, it appears that the pumping value applied in the model is too high. As argued by Green (2012a) regarding pumping amounts in the Kinney County model (Hutchison and others, 2011), a model should be calibrated "using realistic pumping rates before the model can be used to provide credible simulations of the Edwards Aquifer."

Other items we believe are missing from the groundwater model discussion by Toll and others (2017), but are beyond the scope of this preliminary review, are:

- The water budget results from the model, which is standard for any credible model, to ascertain if the results are reasonable. Without the water budget results, it is impossible to determine if the model properly balances water inflow and outflow, resulting in zero-net creation or loss of water. Such a condition is a requirement for a realistic and properly developed groundwater model
- Sensitivity of model parameters to the calibration results which is standard for any credible model to inform user of how much a small change in a parameter may affect the model simulation results
- Connection between the formations of the Edwards-Trinity (Plateau) Aquifer

Though ample information exists to develop a numerical model of the Devils River watershed, the model reported by Toll and others (2017) does not appear to incorporate all the available information on the aquifer system. By focusing on a single component of the system, the resulting model, as reported, does not appear to be a realistic representation of the aquifer system and its interaction with the local surface water features.

Discussion

The following provides a brief discussion of some of the issues identified in the model report.

Aquifer Hydraulic Properties and Pumping

In their observations, Toll and others (2017) state that "[g]roundwater flow and sustainability in the Devils River watershed appears to be controlled by the morphology of the area more than the bulk hydraulic properties of the rocks." They claim that discharge to the Devils River was replicated only through the way they set up the "distribution, morphology, and alignment of conduits relative to the watershed topography." However, the discharge they illustrate is of total streamflow which is not reflective of baseflow to the Devils River. Though Toll and others (2017) state that the model "replicates both flashy flow and low baseflow in the Devils River" as a coupled surface-water/groundwater model, they consistently address all flow in the river as baseflow (that is, the flow attributed to groundwater discharge). Based on the reported information, they setup the structure and hydraulics of the model to reproduce streamflow, but the hydraulic properties assigned to the aquifer are not consistent with their conceptualization nor are they shown to be realistic or comparable to aquifer test results. In particular, the low specific yield used along the streams is not consistent with the conduits they suggest exist and it would require lower hydraulic conductivity values for a karst aquifer.

One significant effect of using a low specific yield near the streams is that it increases the drawdown associated with pumping. For example, using the specific yield of 0.0001 that Toll and others (2017) assigned to the conduit cells along with hydraulic conductivity value from the model would result in more that five feet of drawdown one mile away from a well pumping 500 gallons per minute for three days. Using the same parameters, but increasing the specific yield to 0.001

reduces the drawdown to essentially zero at one mile and increasing the value to 0.01 reduces the extent of drawdown to less than one-half mile. The parameterization of the model hydraulic parameters has a significant impact how pumping effects are simulated.

The simulated effects of pumping in the model is a critical issue for the model. With the opinion of Toll and others (2017) being that the "Devils River watershed basin is being threatened by proposed large-scale groundwater export projects" it is important that they accurately represent the effects of pumping in their model. However, as demonstrated previously, the specific yields assigned in their model are nonsensical when compared to the hydraulic conductivity for a karst system.

Toll and others (2017) may have been able to address some to the issues with the hydraulic properties with a robust calibration of the model. However, based on the information reported, the calibration appears to be poorly constrained by available data. In addition, the calibration does not consider the significant effect the completion of Amistad Dam had on water levels within the watershed (HDR, 2001; EcoKai, 2014). Also, the 14,000 acre-feet per year of pumping reportedly included for the transient calibration is double the maximum amount Toll and others (2017) state has occurred since 1960 which by itself, per the opinion of Green (2012a) regarding pumping amounts in the Kinney County model (Hutchison and others, 2011), makes the model not credible.

Beaver Lake

In their report, Toll and others (2017) point to the simulation results around Beaver Lake as an illustration of the impacts of pumping on the Devils River watershed. They claim that their "transient calibration of the groundwater flow model predicted that spring discharges occur further upstream in the Devils River basin then currently observed." They imply that the simulated springflow is occurring at Beaver Lake and represents the accounts of continuous discharge that occurred there at sometimes between 1535 and 1900. They then claim that it is the pumping within the Devils River watershed that has caused this springflow to cease and move downstream.

There is no reason to doubt the historical accounts of flow at Beaver Lake. However, the reference cited by Toll and others (2017) focuses on a nearly 400 hundred year historical period where the flow may have occurred during periods of wetter conditions such as those used by Groundwater Management Area 9 to model groundwater availability (Hutchison, 2010). More recent accounts discussed by the current landowners indicate that there has not been significant groundwater discharge at Beaver Lake in over a century with flow only occurring intermittently following flooding on the Devils River (Hodge, 2018). Appendix 1 contains a copy of the local landowners account of recent conditions at Beaver Lake.

With regard to the simulated flow at Beaver Lake, it is important to recall the underestimation bias in the model for elevations above 500 meters mean sea level (1,640 feet mean sea level). The simulated flow to Beaver Lake occurs when the modelers remove all pumping from the model which allows simulated water levels rise, intersect land surface, and discharge to the river. However, the transient model calibration, which includes 14,000 acre-feet per year of pumping, is significantly biased to predict too low of a water level in the higher elevations such as Beaver Lake at approximately 1,710 feet mean sea level. Notwithstanding the other issues with the model, if an appropriate pumping amount were included in the model then water levels may be at or near discharging into Beaver Lake.

Toll and others (2017) only discuss their simulation results with regard to the impacts of pumping on flows at Beaver Lake. While not discussed in their modeled report it is important to note that a long history of measurements from an observation well near Beaver Lake does not correlate to the simulated results. The Texas Water Development Board's Groundwater Database has water level measurements for State Well Number 54-56-403 dating back to 1955. The most recent measurement (collected in February 2018) showed a water level of 1,700 feet mean sea level. Looking back over more than 60 years of measurements, the water level has remained relatively stable between 1,690 and 1,710 feet mean sea level. That is, the effects of pumping on water levels in the aquifer as simulated by Toll and others (2017) do not appear to match observations.

Summary

There are many significant flaws in the model reported Toll and others (2017). The model report authors conclude that the "model is available to evaluate future water-resource management scenarios to be able to ascertain what impact groundwater extraction would have on downstream river flow." However, due to numerous apparent flaws, the reported simulation results are not credible and should not be used for planning or assessing impacts of proposed production. To evaluate the potential effects of pumping on the aquifer and its interaction with the Devils River, the model should be reconceptualized to incorporate reasonable aquifer hydraulic parameters, aquifer structure, historical pumping, construction of Amistad Dam, and surface water interaction. The numerical model can then be developed to represent the conceptual model taking into account and reporting all available data and model results so that stakeholders may better understand simulation results, limitations, and uncertainty.

Conclusions

While there are some merits to the conceptual model of the Devils River watershed, development of the numerical model does not reasonably represent the overall aquifer characteristics or the interaction between surface water and groundwater. The following summarizes our conclusions for the conceptual, surface water, and groundwater models.

- The conceptual model does not capture the full complexity of flow within the aquifer.
    - Development of preferential flow along streams is reasonable for the groundwater flow system, but it is not necessarily aligned with the channels.
    - It is unlikely that there is a "dynamic response of baseflow in the river" and it is more likely that baseflow is a steady contributor to the measured discharge.

- Karst feature development is likely to occur at depths greater than 150 feet below land surface which is contrary to the authors' conceptual model.
- Aquifer hydraulic properties (transmissivity, hydraulic conductivity, and storage coefficients) as determined from well specific capacity data, pumping tests, or other means are not reported and should be incorporated into the conceptual model.
- As a major feature affecting the groundwater system, the conceptual model should include the effect of Lake Amistad on the groundwater conditions in the Devils River basin.
- Previous investigators, including William F. Guyton and Associates (1964) and Reeves and Small (1973), have reported a conceptual water budget for the system which, if not reevaluated by the model authors, should be incorporated.

- The surface-water model is not described very well.
  - Recharge was a critical calibration target of the surface-water model, but it is unclear as to how the model was calibrated to recharge.
  - The model authors did not report calibration statistics for the model preventing any quantitative assessment of the model's ability to match measured data.
  - Toll and others (2017) focus on the comparison between the modeled and measured discharges after the larger storm events rather than on the comparisons between modeled and observed discharge after minor storm events that have a greater effect on recharge.
  - Due to the poor documentation, it is unknown if the physical properties in the model are realistic and provide a reasonable representation of potential recharge.
- The groundwater model does not appear to be a realistic representation of the aquifer system and its interaction with the local surface water features.
  - MODFLOW-USG is an appropriate code for modeling the groundwater system.
  - Toll and others (2017) defined the base of layer one as 40 meters below the bottom of the incised channels, but it would have been more representative to define the base of the model layers using available data on the formation structure.
  - Rather than using drain cells, it would be more appropriate to use the River or Streamflow Routing package in MODFLOW to model the streams.
  - Based on the information provided in the report, the aquifer parameters used in the model are not appropriate for representing the groundwater flow system nor do they reasonably represent the model authors' conceptual model.
  - The steady-state model reportedly represents a 16-year period from 2000 through 2015 but should have been set up to represent conditions prior to the construction of Amistad Dam.
  - The transient period also represents the 16-year period from 2000 through 2015 but includes pumping of 14,000 acre-feet per year which is approximately twice the reported historical pumping value for the area. The transient period should have included pumping as part of the model for calibration.

- The transient calibration period should have started prior to the construction of Amistad Dam and used the changes in aquifer water levels as Lake Amistad filled to inform the model parameters.
- Calibration statistics are not provided for the model. These statistics should be reported to allow readers to understand how well the model matches historical conditions. Calibration statistics are standard for any credible model and the lack of reporting suggests the model may be poorly calibrated to historical conditions.
- Graphical information provided regarding how well the simulated water levels match the measured water levels for the steady-state model shows a clear bias in model results. Comparison of modeled and measured water levels for the transient model were not provided which raises questions regarding the ability of the model to match historical aquifer conditions.
- Toll and others (2017) consistently equivocate measured surface water discharge at a gaging station (flow from groundwater discharge and surface runoff) and baseflow (the portion of streamflow attributed to groundwater discharge only). As there is no discussion of how they calculated the baseflow component from the drain cell results, the claim that the model produces a better baseflow response is not supported by the reported results.
- The report should include a discussion of the water budget results from the model. Without such a discussion, it is unclear if the results are reasonable when compared to water budget results from previous investigations such as that of William F. Guyton and Associates (1964) or Reeves and Small (1973)
- Toll and others (2017) should document how sensitive their calibration is to changes in model parameters. Such a sensitivity analysis is standard for any credible model. While they claim the model is "relatively insensitive to assignment of hydraulic properties" to the aquifer units, no data are provided to substantiate the claim. Since small changes in specific yield can significantly affect the drawdown associated with pumping, it is unlikely that their claim can be substantiated by a standard sensitivity analysis.
- There is no discussion of the hydraulic connection between the formations of the Edwards and Trinity even though the Trinity is included as a layer in the model. The connection between the modeled aquifers should be documented.

Many of the conclusions stated by Toll and others (2017) may be due to the model bias or boundary conditions. For example, their conclusions regarding springs drying due to pumping could simply be due to a bias in their steady-state calibration or the low specific yield applied near the drain cells, not to mention the artificially high modeled pumping compared to historical conditions. Toll and others (2017) conclusion that "[t]his model clearly demonstrates the strong linkage of groundwater extraction from the watershed on Devils River flow" stems from how the model was constructed. That is, the model was constructed to demonstrate a strong linkage between pumping and stream flow rather than allowing the model development, calibration, and testing process determine if there is a strong linkage, the strength of the linkage, and the uncertainty in the linkage.

This model should be revisited to incorporate reported geologic structure, more robust boundary conditions for surface water flow, realistic hydraulic parameters, pre-Amistad Dam steady-state conditions, a longer transient calibration period, robust calibration, model parameter sensitivity, and uncertainty in the simulation results. Based on the information in the model report, the model in its current state is not a defensible tool and does not credibly meet its purpose of evaluating how pumping in the upper Devils River watershed would affect downstream discharge in the Devils River. Contrary to the model authors claim that the "model is available to evaluate future water- resource management scenarios to be able to ascertain what impact groundwater extraction would have on downstream river flow," due to numerous apparent flaws, the reported simulation results are not credible and should not be used for planning or assessing impacts of proposed production.

Recommendations

Based on our review of the information reported, the model for the Devils River Watershed should be re-conceptualized, re-parameterized, and re-calibrated. To understand the potential effects of groundwater production on surface water flows, we recommend development of a well- documented model that realistically represents the aquifer system and the interaction between surface water and groundwater. As suggested above, a model for the area should incorporate the best available understanding of geologic structure and faulting, more robust boundary conditions for surface water flow, realistic hydraulic parameters, pre-Amistad Dam steady-state conditions, a transient calibration period that extends from pre-Amistad Dam through present time, a robust calibration, and a model parameter sensitivity and uncertainty analysis. To accomplish development of this model, we have included a proposed scope of work that outlines the tasks required which is included as Appendix 2.

We appreciate being able to provide you with this brief assessment. If you have any questions, please contact me at (512) 962-7660.

Geoscientist and Engineer Seals

This report documents the work of the following licensed professional geoscientists and licensed professional engineers with LRE Water, LLC, a licensed professional geoscientist firm in the State of Texas (License No. 50516) and licensed professional engineering firm in the State of Texas (License No. 14368).

Mr. Keester was responsible for review of the conceptual model and the groundwater flow model.

Pocket Seal

The seal appearing on this document was authorized by Michael R. Keester, P.G. on September 10, 2018.

Michael R. Keester, P.G.
Project Manager / Hydrogeologist

Dr. Furnans was responsible for review of the surface-water model.

Jordan Furnans, Ph.D., P.E. P.G.
Vice President – Texas Operations

TX PE Firm: #14368 9/10/2018

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(Note: Appendices 1 and 2 of this memorandum are not reproduced here but are available upon request from the Texas Water Development Board)