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Investigating the Water Resources of the Western Edwards-Trinity Aquifer

Final Report

Prepared for

Sutton County Groundwater Conservation District

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table **Page**

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Investigating the Water Resources of the Western Edwards-Trinity Aquifer

Executive Summary

A comprehensive assessment of the hydrogeology of the Edwards-Trinity Aquifer was undertaken to provide independent determination of "desired future conditions" for the western Edwards-Trinity Aquifer as required by HB 1976 (Mace et al., 2006). The Texas Water Development Board requests that a Texas Water Development Board approved groundwater management model (GAM) be used in the process of establishing Desired Future Conditions, but will accept alternative methodologies when uncertainty in GAM results is high. An acceptable alternative methodology is a quantitative water budget analysis. Water budget analyses were performed for an eight county area over the western Edwards-Trinity Aquifer. The eight counties included in the project were Crockett, Edwards, Kimble, Menard, Real, Schleicher, Sutton, and Val Verde. The assessments relied on water budget analyses of hydrologically distinct sub-areas in the western Edwards-Trinity Aquifer. Key findings during the study include the following:

- Groundwater catchments in the study area extend farther north compared with their overlying surface watersheds. Extension of a groundwater catchment from one surface watershed into another watershed results in groundwater piracy. Most notable are groundwater catchments for the Frio, Nueces, and Devils rivers.
- Counties with the greatest uncertainty in the water budget assessments are Crockett, Val Verde, and Menard. Crockett County has high uncertainty because it is part of a much larger hydrogeologic sub-area that includes the upper reaches of Pecos River and because there are limited data for the county. Val Verde County has high uncertainty because hydrologic conditions, including precipitation, vary significantly from east to west in the county. Menard County has high uncertainty because groundwater flow contributes significantly to the county water budget and this component has not been measured.
- River discharge measurements provide an opportunity to calculate recharge for the area that contributes to baseflow in the river. Long-term river discharge measurements were corrected for baseflow using an automated discharge recession separation algorithm. This analysis provided the fraction of total discharge that is attributed to baseflow.
- Long-term average annual river discharge values corrected to baseflow were converted to estimates for recharge for each contributing area analyzed. Refined groundwater catchment areas were assumed to be the contributing area for each discharge measurement.
- Recharge values were correlated with precipitation in the study area. The percentage of precipitation that recharged the Edwards-Trinity Aquifer varied from 7 percent in the eastern side of the study area where average annual precipitation is as high as 33 inch/year to 2 percent in the western side of the study area where average annual precipitation is 15 inch/year.

- Knowing the correlation between precipitation and recharge allowed prediction of how recharge in the study area will vary during periods when precipitation is less than the long-term average precipitation for extended periods.
- Recharge for each county in the study area was calculated for average precipitation conditions and predicted for periods when precipitation was reduced by 10, 20, and 30 percent. Calculated and predicted recharge is compared with recharge values assigned to the 2004 Edwards-Trinity Aquifer GAM and the groundwater availability documented in the 2007 Texas State Water Plan.
- Within the study area, Val Verde and Crockett counties are most vulnerable to drought because recharge is negligible when precipitation is reduced to less than 16-17 inch/year. Menard County is also vulnerable because it has minimal opportunity to store groundwater due to the limited thickness of the Edwards-Trinity Aquifer. Conversely, Real, Edwards, Kimble, and to a lesser degree, Sutton counties are less vulnerable to drought because they receive greater amounts of precipitation, on average, and their groundwater catchment areas extend beyond the extents of their surface watersheds.

Based on these findings, the sustainable yield of groundwater for each county is predicted using calculated recharge and recharge predicted for reduced precipitation. As examples, two plans are discussed. In Plan A, the sustainable yield of groundwater is set at 25 percent of calculated recharge for Crockett, Kimble, Menard, Schleicher, Sutton, and Val Verde counties and 15 percent for Edwards and Real counties. These percentages are reduced to 20 and 10 percent, respectively, in Plan B to reduce the risk to the water resource during periods of drought. Alternative calculations of sustainable yield of groundwater to reflect different risk levels can be made using recharge analysis results documented in this report.

INVESTIGATING THE WATER RESOURCES OF THE WESTERN EDWARDS-TRINITY AQUIFER

Introduction

The objective of the project is to investigate the recharge, discharge, and water budget of the Edwards-Trinity Aquifer in Crockett, Edwards, Kimble, Menard, Real, Schleicher, Sutton, and Val Verde counties, Texas. This information will be used to update and refine current characterization of those resources as they relate to establishment of Desired Future Conditions requested by the Texas Water Development Board as required by HB 1763 (Mace et al., 2006). The Texas Water Development Board requests that a Texas Water Development Board approved groundwater management model (GAM) be used in the process of establishing Desired Future Conditions, but will accept alternative methodologies when uncertainty in GAM results is high. A quantitative water budget analysis is an acceptable alternative methodology. Quantitative water budget analysis is deemed acceptable because an accurate water budget analysis should provide reasonable measures of recharge and discharge from a specific aquifer which in turn would allow for representative estimates of groundwater availability for pumping.

The Edwards-Trinity Aquifer GAM was first released by the Texas Water Development Board in 2004 (Anaya and Jones, 2004). This model covered 44,000 square miles, but was supported by relatively limited information on structural geology, recharge, water-level and streamflow data, hydraulic conductivity, specific storage, and specific yield. Uncertainty in the Edwards-Trinity Aquifer GAM is recognized by the Texas Water Development Board. Donnelly (2007a,b) reported that the official baseline GAM runs (i.e., GAM Run 07-03 and GAM Run 07-32) do not appropriately simulate the response of the aquifer to pumping in Glasscock and Reagan counties. This area of unacceptable uncertainty is hydraulically upgradient from the subject area of this project and serves as a potential source of its recharge. High uncertainty in this area of recharge suggests that the water budget for the subject area is not well represented by the 2004 version of the Edwards-Trinity GAM. This version of the GAM (Anaya and Jones, 2004) is recognized by the Texas Water Development Board as the official GAM of the Edwards-Trinity Aquifer.

A revised Edwards-Trinity Aquifer GAM was released by Texas Water Development Board in 2009 (Anaya and Jones, 2009). Anaya and Jones (2009) noted that there remains a paucity of information on the structural geology of the model area along the western margin of the Edwards-Trinity (Plateau) Aquifer in the revised GAM. Anaya and Jones (2009) added that no information on the spatial or seasonal distribution of recharge to the Pecos Valley Aquifer has been published and calibrated the recharge rates in the refined GAM by trial and error.

More recently, the 2009 version of the Edwards-Trinity Aquifer GAM (Anaya and Jones, 2009) was recalibrated using the semi-automated inversion technique PEST (Young et al., 2009). The primary difference between the Young et al. (2009) version of the Edwards-Trinity Aquifer GAM from the GAM by Anaya and Jones (2009) is that the trial and error calibration method used by Anaya and Jones (2009) was replaced with the PEST calibration method used by Young et al. (2009). It is important to note that the databases used by both were the same. The model recalibrated by Young et al. (2009) significantly reduced the differences between observed water levels and predicted water levels. The greatest improvement was exhibited in Upton and Reagan counties, the general area where Donnelly (2007a,b) reported the largest discrepancy in the baseline GAM results. The PEST version of the Edwards-Trinity Aquifer is currently being reviewed for consideration as the official Edwards-Trinity Aquifer GAM, however, as stated above, the 2004 version by Anaya and Jones (2004) is currently recognized as the only official GAM for the Edwards-Trinity Aquifer. In addition, The Texas Water Development Board is also developing another groundwater model for the Edwards-Trinity Aquifer due to be released in mid-2010.

The high level of uncertainty in 2004 Edwards-Trinity Aquifer GAM (Anaya and Jones, 2004) results (Donnelly, 2007a,b), particularly in the western portion of the aquifer, and the relative paucity of aquifer characterization data led the Sutton County Groundwater Conservation District to perform a quantitative water budget analysis to compare with the simulation results of the Edwards-Trinity Aquifer GAM. The water budget analysis could be used in lieu of the Edwards-Trinity Aquifer GAM to designate Desired Future Conditions for the western Edwards-Trinity Aquifer if the water budget analysis were shown to be more accurate than the existing GAM.

Study Area

The study area for the project includes the counties of Crockett, Edwards, Kimble, Menard, Real, Schleicher, Sutton, and Val Verde (Figure 1). In addition, the hydrogeology of adjoining areas was included in the study when key hydrogeological aspects in those areas were germane to the objective of the project. This typically occurred where watershed and groundwater capture boundaries extended beyond the jurisdictional boundaries of the eight counties in the study. As a result, parts of Pecos, Tom Green, Mason, Uvalde, and Kinney counties were included in specific aspects of the study.

Technical Approach

Existing information on aquifer structure, recharge, and hydrogeology are analyzed to calculate the water budget for the western Edwards-Trinity Aquifer. Evaluation of the data is similar to hydrogeological assessments of Kinney and Uvalde Counties (Green et al., 2006) and Wintergarden Groundwater Conservation District (Green, 2006; Green et al., 2008).

Existing technical reports and documents that pertain to the hydrogeology of the western Edwards-Trinity Aquifer were compiled and reviewed as part of this study. Principal sources of information were publications by the Texas Water Development Board, U.S. Geological Survey, Region F Water Planning Group studies, and local hydrogeological assessments. Specific technical subjects reviewed for this project included

- General geology including stratigraphy and structure
- Comprehensive regional-scale hydrogeological investigations and assessments
- Regional and local groundwater models
- River and stream gain/loss studies
- River and stream discharge measurements
- Precipitation records

A bibliography of all references reviewed for this project is included in Appendix A. The References section includes only those references specifically cited in this report.

Stratigraphy of the Western Edwards Plateau

The western Edwards Plateau hydrogeology was characterized, to the degree possible, using available reports, documents, and data. A description of the stratigraphy and structural geology of the Edwards Plateau is taken from Walker (1979). The discussion is from oldest (Cambrian) to youngest geologic units of interest in the study area. Not all geologic units discussed below are present everywhere in the study area, but all have some importance to the hydrogeology of the site and are discussed here. The stratigraphy is graphically summarized in Figure 2 and the surface geology is presented in Figure 3.

The Cambrian-age Hickory Sandstone Member of the Riley formation is the oldest geologic unit of interest in the study area. It lies unconformably on the uneven erosional surface of Precambrian-age metamorphic and igneous rocks. It is reported to be 320 ft thick in Gillespie County and 500 ft thick in Kimble County. Overlying the Hickory Sandstone is the Cambrian-age San Saba Member of the Wilberns Formation which averages 280 ft in thickness. It is absent to the east near Gillespie County and increases to 400 ft in thickness in the south of the study area. The sandstone section of the San Saba Member has a maximum thickness of 200 ft and the limestone section has a maximum of 150 ft.

Overlying the San Saba Limestone is the Ordovician-age Ellenburger Group. The Ellenburger Group consists of limestones and dolomites and underlies most of the Edwards Plateau. The thickness of the Ellenburger Group is highly variable. In Gillespie County it varies from zero to 1,000 ft thickness. It varies from 450 to 800 ft thick in Mason and Kimble counties and is as thick as 600 ft in western Menard County. The San Saba Limestone and the Ellenburger Group are jointly considered a single aquifer.
The Ellenburger-San Saba Aquifer is karstic (vugular and cavernous).

The four corner area of Schleicher, Menard, Kimble, and Sutton counties is the only region in the Edwards Plateau where the Permian-age sediments of the Santa Rosa Formation have fresh to slightly saline water. Elsewhere, where present, the Santa Rosa Formation is highly saline. The Santa Rosa Formation is in hydraulic contact with the Edwards and associated limestones in the four corner area.

The Cretaceous-age stratigraphy in the Edwards Plateau consists of the Comanche Series which is divided into, from oldest to youngest, the Trinity, Fredericksburg, and Washita Groups. The Trinity Group consists of Hosston, Sligo, Pearsall, and Glen Rose Formations and the Paluxy Sand. The Antlers Formation lies at the base of Trinity Group. The Fredericksburg Group consists of the Walnut, Comanche Peak, Edwards, and Kiamichi Formations. The Washita Group consists of the Georgetown, Del Rio, Buda, and the Eagle Ford Formations. There is a range of thicknesses and occurrences of these stratigraphic units throughout the Edwards Plateau, however, the elevation of the top of the Trinity Group decreases from a high of over 3,000 ft mean sea level (msl) in Ector County to a low of 0 ft msl level in southern Val Verde County. A contour map illustrating the saturated thickness of the Edwards-Trinity Aquifer is presented in Figure 4 (Barker and Ardis, 1996).

The Tertiary-age Ogallala System overlies the Edwards Plateau at its northern boundary. Pleistocene- and Quaternary-age alluvial deposits are found in stream and river beds throughout the Edwards Plateau. The maximum thickness of the alluvial deposits is typically 40 to 50 ft, but exceeds 100 ft in Crockett and Uvalde counties.

Hydrogeology of the Western Edwards Plateau

Water resources are found in a variety of geologic units in the western Edwards Plateau, although the preponderance of resources is in the Edwards portion of the Edwards-Trinity Aquifer. The following discussion of water-bearing units in the study area is taken from Walker (1979).

Groundwater in the Permian rocks is limited to where the Permian rocks are in apparent hydraulic communication with the overlying Cretaceous limestones. This occurs in southeastern Tom Green and northwestern Schleicher counties and in the four corner region of Sutton, Schleicher, Menard, and Kimble counties.

Wells in the Hickory Formation are limited to McCulloch, Mason, and San Saba counties. The direction of flow in the Hickory Aquifer is radially away from the Llano uplift. Well development in the Ellenburger-San Saba Aquifer is mostly in McCulloch, San Saba, and Gillespie counties with limited wells in Menard and Kimble counties. Typical well discharge is less than 500 gallons per minute (gpm). The direction of flow in the Ellenburger-San Saba Aquifer is not well defined, but thought to be radially away from the Llano uplift.

Lower Cretaceous aquifers include the Hosston, Sligo, Pearsall (Cow Creek Limestone and Hensell Sand Members), and Glen Rose Formations. They are only a significant source of groundwater near the eastern and southern edge of the Edwards Plateau. Where present, they are typically hydraulically connected and act as one aquifer. The Cow Creek Limestone and Hensell Sand Members of the Pearsall Formation are present in the southern portion of the Edwards Plateau. Well capacity in these units varies from a few gpm to as much as 300 gpm. The Glen Rose Formation varies in thickness from a few feet in the north to 1,700 ft in the south. Upper Glen Rose wells yield small amounts of slightly saline water while the lower Glen Rose yields small to moderate amounts of fresh water from massive limestones.

The Edwards-Trinity (Plateau) Aquifer includes all rocks of the Fredericksburg Group from the base of the Antlers Formation to the top of the Georgetown Formation. Regional flow of groundwater is southward although local flow is toward river and stream beds. The base of the Cretaceous strata dips to the south and southeast. There is a local depression in the potentiometric surface in the St. Lawrence irrigation area of south central Glasscock and north central Reagan counties. Groundwater flow in the southwestern portion is to the southwest toward the Rio Grande; in the north, northeast, and central portion is toward the east to the Colorado River; and in southeastern portion, toward the Nueces, San Antonio, and Guadalupe rivers.

In the northern Edwards Plateau (parts of Ector, Midland, Upton, Glasscock, and Reagan counties), the water table is below the limestones and fresh water is limited to the Antlers Formation. The Georgetown Formation in the northern section of the Edwards Plateau is not a significant source of groundwater due to its limited saturated thickness. Conversely, the Georgetown Formation contributes a major portion of the freshwater provided by the Edwards and associated limestones in the southern part of the Edwards Plateau.

The Ogallala Aquifer borders the northern boundary of the Edwards Plateau. It provides significant water in Midland and Glasscock counties. Groundwater flow in this part of the Ogallala is to the south and southeast where it recharges the Edwards-Trinity Aquifer.

Edwards Plateau alluvial aquifers are found along the Middle and North Concho Rivers in the north where the alluvial sediments overlie the Antlers Formation, and along the Frio, Nueces, Sabinal, and Guadalupe rivers in the south. The northern alluvial aquifers are recharged by the Antlers Formation and the southern alluvial aquifers are recharged by stream flood waters and discharge from the Edwards and associated limestones. The direction of flow in the alluvial aquifers is the same as the adjoining streams.

Water Well Development in the Western Edwards Plateau

An inventory of wells in the western Edwards Plateau with relatively high pump capacity was developed to provide an indication of geographical and hydrogeological areas of relatively high permeability. Wells with pumping capacity in excess of approximately 100 gpm are considered to be high for the western Edwards-Trinity Aquifer. Following is a county-by-county assessment of high pump-capacity wells in the western Edwards-Trinity Aquifer. Sources for data are cited for each county.

Crockett County – Data on large capacity wells in Crockett County were extracted from Inglehart (1967). There are 17 wells with capacity of 100 gpm or greater: Wells 45-64-901 and 45-64-902 are in alluvium and Antler Sand in Fivemile Creek just north of the Pecos River. Wells 54-02-706, 54-02-707, and 54-02-708 are in the alluvium and Antler Sand on the edge of the Pecos River. Wells 54-23-101, 54-23-106, 54-23-108, 54-23-201, 54-23-202, 54-23-203, and 54-23-204 are near or in Ozona close to Johnson Draw. Wells

4-35-201 and 54-35-801 are in alluvium next to the Pecos River. Well 54-48-501 is in the Edwards Aquifer in Cedar Bluff Canyon just north of Val Verde County.

Edwards County – Records of large capacity wells (100 gpm or greater) were provided by the Real-Edwards Conservation and Reclamation District staff. There are eight wells identified with capacities greater than 100 gpm. Six wells are in the Edwards and associated limestones. The formations tapped by the remaining two wells are not known. The three greatest capacity wells are approximately 500 gpm and are in the Edwards and associated limestones.

Kimble County – Data on large capacity wells in Kimble County were extracted from Standen and Lee-Brand (2009). There are ten wells with capacity of 100 gpm or greater. The direction of groundwater flow in western Kimble County is generally to the east although it also drains to the north toward the Llano River. The large capacity wells in Kimble County are apparently in the Paleozoic rocks in eastern end of the county.

Menard County – Data on Menard County wells were provided by the Menard County Underground Water District. Menard County Underground Water District staff prepared a map indicating locations of wells with high capacity pumps. The Menard County well map indicates 14 wells with capacity > 50 gpm, another 10 with capacity between 50 and 25 gpm, and about 25 with capacity between 10 and 25 gpm. Most, but not all, of the wells with capacity > 100 gpm tend to align near the San Saba River. Wells 5612328, 5612210, and 5612305 are in the eastern quarter of the county in the Paleozoic aquifers. Wells 5603803, 5603702, 5602609, and 5602901 are to the east of Menard. Wells 5602501 and 5602503 are to the west of Menard. Well 5601901 is near Beyer Crossing. Well 5616103 is near Fort McKavett. All these wells are proximal to the San Saba River. Well 5508403 is at the western county line away from the river.

Real County – Records of large capacity wells (100 gpm or greater) were provided by the Real-Edwards Conservation and Reclamation District staff. There are 18 wells identified with capacities greater than 100 gpm. Four wells are in the Edwards and associated limestones and eleven of the wells are in alluvium. The formations in which the other two wells are completed are not known. One alluvium well has a capacity of 600 gpm. Two other wells have capacities of 250 and 300 gpm. All remaining wells have capacities of less than 200 gpm.

Schleicher County – Records of large capacity wells (100 gpm or greater) were provided by the Plateau Underground Water Conservation and Supply District staff. There are 1,500 to 1,600 wells in Schleicher County. Total pumpage is estimated at 4,000 acre-ft/yr. There are 79 wells with a reported capacity of 100 gpm or greater. Of these, 12 wells had capacities of 500 to 1,000 gpm and 8 more wells had capacities of 1,000 to 1,500 gpm. No information on the geologic formations tapped by these wells is available. Most of the high capacity wells are located near either Devils, South Concho, or San Saba rivers, however, 4 of these high capacity wells are located on a plateau in the central portion of the county near the Crockett County line.

Sutton County – Data on large capacity wells in Sutton County were extracted from Standen and Kirby (2009). There are 10 wells with capacity of 100 gpm or greater. The high capacity wells in Sutton County are aligned with two rivers: Granger Draw and Devils River. Even though the wells are set in the Edwards Aquifer, they have increased capacity due to preferential flow of groundwater through the floodplains. The alluvium well 5533802 is located in Granger Draw not far upstream from its confluence with Devils River. This suggests there is probably appreciable underflow going into the Devils River. This is consistent with the interpretation that groundwater drainage in western Sutton County is to the south toward the Devils River. Wells 5525302, 5518703, and 5533802 are located along Granger Draw. 5517603 is not far from Granger Draw. Wells 5527602, 5527604, 5527615, and 5527613 are located near Devils River. Well 5528702 is slightly east of Devils River**.**

Val Verde County – Data on large capacity wells in Val Verde County were extracted Reeves and Small (1973). There are ten wells with capacity of 100 gpm or greater (listed by owner and state tracking number). Wells YA-70-33-101, YA-70-33-201, YA-70-33-502, and YA-70-33-602 are in the Edwards Limestone on the south side of Amistad Reservoir. Well YA-70-33-903 (2,120 gpm) is in the Edwards Aquifer located at the north end of Del Rio about 1.3 miles east of Cienegas Creek. Wells YA-70-42-205, YA-70-42-208, and YA-70-42-209 are in the Edwards Aquifer at Laughlin Air Force Base. Wells YA-71-40-302 and YA-71-40-303 are Edwards Aquifer wells owned by the International Boundary and Water Commission at Amistad Village on the south side of Amistad Reservoir.

River Basins in the Western Edwards Plateau

The western Edwards Plateau is bisected by a surface water divide between the surface-water basins for the Colorado River and the Rio Grande (Figure 5). In general, the northeastern half of the study area lies in the Colorado River surface water basin and the southwestern half lies in the Rio Grande surface-water basin. The study area is further divided into several small contributing surface-water basins including the Rio Grande-Amistad, Lower Pecos, Devils, Middle Colorado-Concho, Middle Colorado-Llano, Nueces, and Rio Grande-Falcon (Figure 5).

The study area serves as the headwaters for numerous rivers, streams, and their tributaries. The most notable of these are the Devils, Nueces, Llano, San Saba, and Frio rivers. The upper reaches of these rivers typically flow intermittently. Perennial flow is experienced downstream with the exception of rivers and streams which lose flow to the subsurface where they flow across recharge zones for aquifers such as the Edwards.

River Discharge in the Western Edwards Plateau

The U.S. Geological Survey and the International Boundary and Water Commission have maintained river gauging stations in and surrounding the study area for many decades. These data provide valuable information when calculating the water budget for prescribed domains in the study area. Tables 1 and 2 are lists of river gauging stations evaluated during this project. Table 1 contains a list of International Boundary and Water Commission river gauging stations and Table 2 contains a list of river gauging stations operated by the U.S. Geological Survey. Accurate locations of the International Boundary and Water Commission river gauging stations are not available. The locations of the U.S. Geological Survey gauging stations are illustrated on a map in Figure 6.

River gain/loss surveys conducted in the study area were compiled by Slade et al. (2002). These measurements provide quantifiable evidence of where groundwater is discharged into rivers (gain) or where rivers discharge to the subsurface (loss). For each measurement, the reach is described, followed by the date of the measurement, the length of the survey reach, the number of measurements, the total gain or loss in terms of cubic feet per second (cfs), and the gain/loss calculated per mile (cfs/mile). A gain to the river is denoted by a positive number and a loss from the river is denoted as a negative number.

Concho River

- Concho River confluence of North and South Concho rivers (08136000) to FM 1929, February 25–26, 1986, 54.7 miles, 10 measurements, 7.25 cfs gain, 0.0133 cfs/mile

- Concho River confluence of North and South Concho rivers (08136000) to FM 1929, January 6–7, 1987, 54.7 miles, 10 measurements, 36.23 cfs gain, 0.662 cfs/mile

- Concho River confluence of North and South Concho rivers (08136000) to FM 1929, February 28–March 1, 1989, 54.7 miles, 10 measurements, 37.8 cfs gain, 0.691 cfs/mile

- Concho River confluence of North and South Concho rivers to mouth, March 27–28, 1918, 51.5 miles, 14 measurements, 4.6 cfs gain, 0.089 cfs/mile

- Concho River confluence of North and South Concho rivers to mouth, March 17–20, 1925, 54.5 miles, 28 measurements, 6.6 cfs gain, 0.121 cfs/mile

South Concho River

- South Concho River above Christoval to mouth, March 12–16, 1925, 24.8 miles, 12 measurements, 19.6 cfs gain, 0.79 cfs/mile

- South Concho River above Middle Concho River to 3.5 mile below Middle Concho River, April 2, 1918, 1 mile, 3 measurements, 2.2 cfs gain, 2.2 cfs/mile

- South Concho River at Christoval to confluence with North Concho River, March 27–28, 1918, 19.8 miles, 13 measurements, 13.3 cfs gain, 0.672 cfs/mile

- South Concho River south of Christoval to above Lake Nasworthy, June18, 1953, 12 miles, 6 measurements, 4.64 cfs loss, -0.387 cfs/mile

Dove Creek

- Dove Creek 9 mile above Knickerbocker to mouth, March 4–5, 1925, 11.8 miles, 8 measurements, 15.7 cfs gain, 1.331 cfs/mile

Llano River

- Johnson Fork Llano River headwater springs to mouth, February 6–1, 1925, 16.8 miles, 9 measurements, 8.9 cfs gain, 0.53 cfs/mile

- Llano River confluence of North and South Llano River to Llano River (08151500), January 17–24, 1962, 83.5 miles, 56 measurements, 7.84 cfs gain, 0.094 cfs/mile

- Llano River Junction gauging station to Llano River (08151500), September 3–4, 1952, 79 miles, 12 measurements, 18.83 cfs loss, -0.238 cfs/mile

- Llano River Junction to mouth, March 31–April 3, 1918, 106 miles, 26 measurements, 22.3 cfs gain, 0.21 cfs/mile

- Llano River confluence of North and South Llano rivers to mouth, February 14–2, 1925, 105 miles, 23 measurements, 5.7 cfs gain, 0.054 cfs/mile

South Llano River

- South Llano River above Telegraph to confluence with North Llano River, April 1, 1918, 18.5 miles, 5 measurements, 2.3 cfs gain, 0.124 cfs/mile

- South Llano River below confluence of West and South Fork to mouth, February 10–14, 1925, 25.9 miles, 12 measurements, 26.7 cfs gain, 1.031 cfs/mile

San Saba River

- San Saba River above Fort McKavett to Brady Creek, July 27–August 2, 1933, 80.1 miles, 32 measurements, 7.7 cfs gain, 0.096 cfs/mile

- San Saba River below Fort McKavett to Menard (08144500), February 20–22, 1940, 20.9 miles, 13 measurements, 4.0 cfs loss, 0.191 cfs/mile

- San Saba River near Dorans Ranch to San Saba River (08146000), November 17–18, 1921, 14 miles, 6 measurements, 0.9 cfs loss, -0.064 cfs/mile

- San Saba River near Fort McKavett to mouth, March 29–3, 1918, 105 miles, 29 measurements, 2.5 cfs, loss, -0.024 cfs/mile

Brady Creek

- Brady Creek to mouth, March 29, 1918, 28 miles, 3 measurements, 1.7 cfs gain, 0.061 cfs/mile

Springs Creek

- Spring Creek above Mertzon to mouth, March 6–11, 1925, 26.5 miles, 17 measurements, 25.6 cfs gain, 0.966 cfs/mile

- Spring Creek above Seven Springs to mouth, March 27, 1918, 27 miles, 15 measurements, 10.5 cfs gain, 0.389 cfs/mile

Dry Frio River

- Dry Frio River above Real-Uvalde County line to below Reagan Wells (08196000), December 16–20, 1954, 20 miles, 24 measurements, 0.75 cfs loss, -0.038 cfs/mile

- Dry Frio River above Real-Uvalde County line to below Reagan Wells (08196000), September 9–13, 1955, 28 miles, 26 measurements, 2.18 cfs loss, -0.078 cfs/mile

- Dry Frio River above Real-Uvalde County line to Reagan Wells (08196000) January 15–20, 1958, 26 miles, 35 measurements, 10.01 cfs gain, 0.384 cfs/mile

- Dry Frio River near Reagan Wells, June 28, 1925, 15.5 miles, 7 measurements, 1.0 cfs loss, -0.065 cfs/mile

East Frio River

- East Frio River 11 mile above mouth to mouth, January 5–6, 1955, 11 miles, 12 measurements, 7.01 cfs loss, -0.637 cfs/mile

- East Frio River 11 mile above mouth to mouth, September 7–9, 1955, 11 miles, 12 measurements, 4.1 cfs loss, -0.374 cfs/mile

- East Frio River 5.2 mile above mouth to mouth, February 14, 1955, 5.2 miles, 5 measurements, 6.95 cfs loss, -1.337 cfs/mile

- East Frio River 5.2 mile above mouth to mouth, July 9, 1957, 5.2 miles, 5 measurements, 8.49 cfs loss, -1.633 cfs/mile

- East Frio River 11.8 mile above Leakey to 7 mile below Concan, June 26–28, 1925, 38.3 miles, 24 measurements, 17.71 cfs loss, -0.462 cfs/mile

- East Frio River 11 mile above Leakey to 3.7 mile below Concan (08195000), May 17–23, 1954, 38.5 miles, 16 measurements, 1.57 cfs gain, 0.041 cfs/mile

Short Prong Frio River

- Short Prong Frio River 16 mile above Leakey to Concan (08195000), January 4–7, 1955, 39.5 miles, 26 measurements, 10.06 cfs gain, 0.255 cfs/mile

- Short Prong Frio River 16 mile above Leakey to Concan (08195000), September 8–10, 1955, 39.5 miles, 28 measurements, 8.54 cfs gain, 0.216 cfs/mile

West Frio River

- West Frio River 11.6 mile above confluence with East Frio River to Concan (08195000), July 8–12, 1957, 35 miles, 11 measurements, 30.86 cfs gain, 0.882 cfs/mile

- West Frio River 8 mile above Leakey to Concan (08195000), February 14–18, 1955, 31.7 miles, 7 measurements, 11.59 cfs gain, 0.366 cfs/mile

Devils River

- Devils River 30 mile above Del Rio to mouth, January 26–28, 1921, 27.2 miles, 5 measurements, 140.0 cfs gain, 5.147 cfs/mile

- Devils River 30 mile above Del Rio to mouth, October 6–7, 1921, 7.8 miles, 4 measurements, 52.0 cfs gain, 6.667 cfs/mile

- Devils River Beaver Lake to Juno (08449000), August 8–13, 1925, 76 miles, 21 measurements, 426.1 cfs gain, 5.607 cfs/mile

- Devils River Dolans Creek to near Comstock, February 14–20, 1928, 22.3 miles, 22 measurements, 91.98 cfs gain, 4.125 cfs/mile

- Devils River near Comstock to Southern Pacific Rail Road bridge, February 7–11, 1928, 16.5 miles, 30 measurements, 97.91 cfs gain, 5.934 cfs/mile

Pecos River

- Pecos River at Angeles (08409500) to Girvin, May 28–30, 1918, 203 miles, 26 measurements, 105.5 cfs loss, -0.52 cfs/mile

- Pecos River at Girvin (08446500) to Comstock (IBWC 08447700), February 6–9, 1968, 193.6 miles, 19 measurements, 74.97 cfs gain, 0.387 cfs/mile

- Pecos River at Orla (08410000) to Girvin (08446500), March, 3–5, 1964, 188.05 miles, 21 measurements, 184.8 cfs loss, -0.983 cfs/mile

- Pecos River at Orla (08410000) to Girvin (08446500), May 10–12, 1965, 188.05 miles, 25 measurements, 8.92 cfs gain, 0.047 cfs/mile

- Pecos River at Orla (08410000) to Girvin (08446500), April 17–19, 1967, 185.5 miles, 23 measurements, 189.29 cfs loss, -1.02 cfs/mile

The survey results indicate that most rivers gain in the study area, which is an indication that groundwater is discharging to the rivers. The Devils River is the most significant gaining river in the study area with an average gain of over 5 cfs/mile for the four surveys. The remaining gaining rivers gain groundwater at a rate of less than 1 cfs/mile on average. The lower San Saba (i.e., south of Dorans Ranch), various reaches of the Pecos, the Dry Frio, and the Frio rivers are losing rivers. The Frio and Dry Frio rivers lose where they cross the Edwards Aquifer recharge zone.

Groundwater Basins in the Western Edwards Plateau

Groundwater discharged into rivers is supplied by the groundwater basins upgradient from the points of discharge. The extent of a groundwater basin is not easily determined and is commonly approximated by the overlying surface watershed area. This approximation is not always valid. There are additional complications when attempting to determine groundwater basins for a karst aquifer. Preferential flow paths in karst aquifers cause the flow regime to be anisotropic. An anisotropic flow regime allows groundwater to flow in directions that are not orthogonal to potentiometric contour lines (Bear, 1979). In addition, the presence of preferential flow in a karst aquifer increases the prospect that the geographical boundary of a groundwater basin is not coincident with the overlying surface watershed (White and White, 2001; White, 2006). This leads to the potential for groundwater piracy, the condition where groundwater flows from one surface-water basin to another.

Groundwater basins in karst aquifers can only be unambiguously delineated using techniques such as dye tracing, cave surveying, water chemistry sampling and assessment, development of potentiometric maps, and the full use of local geology (White, 2006). In the absence of dye tracer, water chemistry, and cave survey information, an existing potentiometric map of the Edwards-Trinity Aquifer is used to characterize groundwater basins in the study area. In this case, the groundwater basins for the study area are approximated in the same way that a surface water basin is determined, except that the potentiometric surface is used to locate groundwater catchment divides.

In the absence of a synoptic survey of groundwater elevations, the potentiometric map prepared by Kuniansky and Holligan (1979) and reproduced by Barker and Ardis (1996) is used to delineate the groundwater basin in the western Edwards Plateau (Figure 7). The surface-water divide between the Colorado River and the Rio Grande watersheds is overlain on the potentiometric surface to compare the extent of the groundwater basins to the surface-water basins. There are areas in Upton, Reagan, Sutton, Schleicher, and Edwards counties where the groundwater basin that flows toward the Rio Grande appears to extend farther north and east than the Rio Grande surface-water basin. The revised groundwater catchment boundary location is assessed in a later section of this report.

Springs in the Western Edwards Plateau

Springs and seeps in the study area occur mostly where rivers and streams have been in incised into the perimeter of the Edwards Plateau. These springs and seeps are generally from gravity drainage at locations where permeable media overlying a confining layer are exposed at the surface. There are occasional artesian springs associated with local faulting. The most prominent springs in the Edwards-Trinity Plateau are found near its perimeter and most of these are at its southern boundary due to the south dip of the Edwards and associated limestones. Discharge at seeps and springs from the Edwards and associated limestones at the south and southeast boundaries of the Edwards Plateau is typically greatest due to the increased thickness of these units to the south and southeast.

A single comprehensive inventory of springs in the study area was not available. One task of this project was to compile an inventory of springs in the study area from available documents and data sources (Brune, 1975; Walker, 1979; Standen and Kirby, 2009; U.S. Geological Survey website: http://pubs.usgs.gov/of/2003/ofr03-315/ accessed on February 12, 2010). The initial list from all data sources had over 270 entries, however some entries were repetitive and many had inadequate descriptions to allow for unique and unambiguous identification. A list of major springs in the study area was extracted from the initial list. The summary list is presented in Table 3 and the springs are illustrated on a map in Figure 8.

Springs offer an important opportunity to measure key components to the water budget. Springs act as gauge points for the entire basin upstream, including both the surface and underground components (White, 2006). In the absence of spring discharge measurements, gauging of rivers downstream from the springs is used to approximate spring discharge. This approximation is valid if the distance from the spring to the river gauging station is not excessive and if the river along the reach from the spring to the gauging station neither gains or losses significant water to the subsurface. The use of river gauging as a surrogate for spring discharge measurement is necessary in the western Edwards Plateau because discharge at local springs has not been measured on a regular basis.

Surface Watershed Discharge Analysis

Information collected during this project was assembled, synthesized, and integrated to provide an assessment of the water budget for the study area in the western Edwards-Trinity Aquifer. Water budgets were analyzed for sub-areas within the study area. These sub-areas were delineated based on local natural hydrogeological boundaries where possible. Boundaries were defined using either natural surface water or groundwater basin boundaries.

Water budget analyses are performed for the following sub-areas:

- Pecos River and Devils River sub-area
- Nueces and West Nueces River sub-area
- Frio River sub-area
- Llano River sub-area
- San Saba River sub-area

The sub-area is a combination of surface watershed and groundwater catchment that contributes to the river flow. The water budget for each of these sub-areas is individually assessed using available hydrogoelogical information. In the absence of spring discharge measurements, river gauging measurements are used to estimate discharge from the groundwater catchment areas. Fortunately, river discharge has been measured at rivers in the study area for relatively long periods of time. Discharge measurements for the Pecos and Devils rivers are recorded by the Boundary and Water Commission and for all other rivers in the study area by the U.S. Geological Survey.

River discharge has two principal flow components, baseflow and surface runoff. Baseflow is considered to be the groundwater contribution to stream flow and is interpreted to equal recharge (Arnold et al., 1995; White and White, 2001; White, 2006). Baseflow recession is the rate at which the stream flow diminishes in the absence of recharge. The discharged volume is equated to the amount of recharge to the shallow aquifer that discharges to the river. Recession characteristics are useful parameters to estimate water supply and stream-aquifer interactions. The slope of baseflow recession is referred to as the recession constant and provides an estimate for the volume of water in storage in the watershed basin above the level of the stream channel. The recession constant can be used to determine aquifer storage and transmissivity (Ford and Williams, 1989). A steep recession curve with a large value for the recession constant is indicative of rapid drainage and little storage. In a carbonate formation such as the Edwards-Trinity Aquifer, a large value for the recession constant implies conduit flow.

The fraction of river discharge attributed to baseflow was calculated for each river gauging station analyzed in this study. An automated baseflow separation and recession analysis tool, BASEFLOW, is used to estimate the amount of stream flow attributed to baseflow (Arnold et al., 1995; Arnold and Allen, 1999). The automated procedure predicts baseflow recession from the point on the hydrograph where it is assumed that all surface flow has ceased. For those instances when there were gaps in the gauging station time series, recession is analyzed for each individual time series segment. As a consequence, gauging stations with gaps in their time series have multiple values for the fraction of river discharge attributed to baseflow. A singular value for baseflow fraction for each river watershed is calculated by averaging the baseflow fraction for each time segment weighted by the number of days in the time series subset. For most watersheds, the baseflow fractions for the individual segments are similar. In a limited number of cases, however, there are differences in the individual baseflow fractions (i.e., Dove Creek at Knickerbocker, Johnson Creek at Ingram, and San Saba River at Menard). These typically occurred when a time series segment was not long and was more representative of short duration recharge events. Baseflow fractions of river discharge for the watersheds in the study area are summarized in Table 4.

Pecos River and Devils River Watersheds – There are several river gauging stations in the Pecos River and Devils River watersheds with sufficient measurement histories to allow for meaningful assessment of recharge to the groundwater basin associated with the Pecos River and Devils River watershed. The water budget of the Amistad Reservoir is first evaluated to ascertain if the river gauging measurements associated with the reservoir are internally consistent. In other words, do the river gauge flow measurements provide a water budget in which water input equates to water output?

Long-term average-flow measurements for rivers proximal to Amistad Reservoir are calculated using data from the International Boundary and Water Commission website (http://www.ibwc.state.gov/Water_Data/histflo1.htm). A schematic of river input and output near Amistad Reservoir is illustrated in Figure 9. As shown, Amistad Reservoir gains water from the Rio Grande, Pecos River, and Devils River. Not shown is input from Goodenough Spring which discharges into the base of Amistad Reservoir. If meaningful and consistent, the long-term average for these river inputs should equal the long-term average discharge from Amistad Reservoir. The inputs to Amistad Reservoir are 1,479 cfs from the Rio Grande, 268 cfs from the Pecos River, 364 cfs from the Devils River, and an estimated 140 cfs from Goodenough Spring (Brune, 1975). The total input to Amistad Reservoir is 2,251 cfs which compares well with the measured discharge of 2,292 cfs from Amistad Reservoir. This self consistent water budget provides confidence that the river flow measurements near Amistad Reservoir are representative of actual flow and can be used in water budget analysis for the groundwater basins and estimates of recharge.

The extent of the groundwater basin that discharges into the Rio Grande in Val Verde County is estimated using the potentiometric map by Barker and Ardis (1996) (Figure 10). Isotropic flow was assumed in drawing the lateral boundaries of the groundwater basin. Although the assumption of isotropic flow may prove to be inappropriate for the karstic Edwards-Trinity Aquifer, it is the most appropriate estimate in the absence of dye tracer test results or water chemistry analyses. The upstream extent of the groundwater basin that includes the Pecos River floodplain is indeterminate due to changing water resource practices undertaken during the time when river gauging data were collected (i.e., March 1, 1965 to November 30, 2009) (Table 1). High levels of pumping for irrigation in Pecos County during the 1960s developed a regional depression in the water table near Fort Stockton that interrupted groundwater flow that previously flowed south and eventually discharged into the Rio Grande. Current pumping rates are significantly less than the high pump rates of the 1960s, but the time when pumping decreased enough to allow groundwater to resume flowing through Pecos County to the south is not known. For this reason the northern boundary of the groundwater basin is designated here to be near Fort Stockton. Additional analysis of groundwater flow and recharge in the upper Pecos River watershed (e.g. river gain/loss measurements, spring flow discharge, water budget analysis) is needed to more accurately determine the extent of this groundwater catchment area.

The area of the groundwater basin designated in Figure 11 that discharges to the Rio Grande in Val Verde County is approximately 10,000,000 acres. This area includes the drainage areas for both the Pecos and Devils river watersheds. The drainage area for the Devils River watershed is calculated by the U.S. Geological Survey as 3,961 mi^2 (2,535,040 acres). Average discharge of the Devils River measured at Pafford Crossing for the period of March 1, 1965 to November 30, 2009 is 364 cfs. This average includes both surface runoff and baseflow. The baseflow fraction of total discharge is 0.76 (Table 4), thus the baseflow component to discharge in Devils River at Pafford Crossing is 276 cfs.

Average recharge is calculated for the Devils River groundwater basin using baseflow discharge measurements for the Devils River at Pafford Crossing and an estimate of the area of the groundwater basin. The groundwater basin size could be approximated as the size of the drainage area upstream from the Pafford Crossing gauging station, however, inspection of the groundwater potentiometric map (Figure 11) provides evidence that the actual groundwater basin extends north into Irion and Schleicher counties and east into Sutton and possibly Edwards counties. If the groundwater basin is estimated to be 10 to 15 percent larger than the drainage area of the Devils River, the groundwater basin would have an area of approximately 2,789,000 to 2,915,000 acres. Recharge averaged over the revised estimated area for the groundwater basin that discharges into the Devils River is calculated to be 0.86 to 0.83 inch/year.

The average baseflow fraction of total flow of the Pecos River is calculated using BASEFLOW to be 0.66, 0.77, 0.79, and 0.74.at Orla, Girvin, Sheffield, and Langtry, respectively (Table 4). The baseflow fraction calculated at Langtry represents the most downstream gauging station on the Pecos River. Using this information suggests that 198 cfs of the total average flow of the 268 cfs measured on the Pecos River at Langtry is attributed to baseflow.

A similar estimate for recharge is calculated for the Pecos River portion of the groundwater basin that discharges into the Rio Grande in Val Verde County. The area of the groundwater basin is estimated to be approximately 7,100,000 acres by subtracting the area of the Devils River drainage area from the estimate for the entire groundwater basin that discharges into the Rio Grande in Val Verde County. The baseflow of the Pecos River flow measured at Langtry would equate to 0.02 inch/year if uniformly averaged over the entire groundwater basin. Uniform recharge is not likely given that average annual precipitation decreases from 20 inch/year in the east side of the Pecos

River watershed to 11 inch/year in the west (Figure 12). Recharge is also affected by focused recharge from the mountains located to the west of the Pecos River basin. Regardless, this estimate for recharge does provide a first-order measure of how much water is recharged to the Rio Grande from the Pecos River basin.

Frio River Watershed – Long (1958) calculated recharge for the Frio River watershed using 32 years (1924-1956) of records of winter (November through March) baseflow. Average annual flow at Concan was estimated at 43,000 acre-feet. For an estimated recharge area of 405 mi^2 (260,000 acres), the annual recharge would be 2 inches. Long (1958) suggested that this estimate of recharge was probably low because precipitation is less in the winter than during the summer. Increased evapotranspiration in the summer, however, could reduce summer recharge

The U.S. Geological Survey gauging station on the Frio River at Concan provides an opportunity to estimate groundwater discharge in the Frio River groundwater basin in northeastern Real County. An average discharge of 125.5 cfs (90,860 acre-feet/year) was measured at the station over the period October 26, 1923 to May 12, 2010. The baseflow fraction for the Frio River is calculated at 0.75, thus the baseflow component to flow is 94 cfs. The surface drainage area upstream of Concan is measured by the U.S. Geological Survey to be 383 mi^2 (245,120 acres). This equates to a recharge rate of 3.36 inch/year if uniformly averaged over the 383 mi^2 drainage area. This estimate for recharge is greater than the recharge for Real County estimated by Long (1958).

Nueces and West Nueces River Watershed – The average discharge in the Nueces River at Laguna was 165 cfs for the period October 1, 1923 to May 12, 2010. The baseflow fraction is 0.71 of total flow or 117 cfs. This equates to 84,662 acre-feet/year. There are 471,680 acres in the Nueces River watershed above this gauging station. This equates to an average of 0.18 feet/year or 2.15 inch/year of recharge. The average discharge in the West Nueces River near Brackettville is 34.2 cfs for the period October 1939 to present. This equates to 24,760 acre-feet/yr. There are 444,160 acres in the West Nueces River watershed. This equates to an average of 0.056 feet/year or 0.67 inch/year of recharge. When corrected for surface runoff, baseflow is 0.17 inch/year.

There are reasons why flow in the West Nueces River near Brackettville is substantially less than flow measured in the Nueces River at Laguna or the Frio River at Concan. The riverbed upstream from the West Nueces River gauging station is on the Edwards Aquifer recharge zone (Green et al., 2006). In contrast, the riverbed upstream from the Nueces River at Laguna or the Frio River gauging station at Concan is the Trinity Aquifer. There is greater opportunity for water to be lost to the subsurface (via fractures, faults, vuggy porosity, and other karst features) where the river crosses the Edwards Aquifer outcrop belt compared with the Trinity Aquifer. As a result, much of the flow in the West Nueces River has already been lost to the Edwards Aquifer prior to arriving at the West Nueces River gauging station. Thus, not all water recharged in the West Nueces River drainage area upstream from the gauging station is observed as baseflow at the West Nueces River gauging station. Once recharged into the Edwards Aquifer in Kinney

County, groundwater flows to the southwest toward either the Pinto or Las Moras springs.

Llano River Watershed – There are two U.S. Geological Survey river gauging stations on the Llano River, one on the North Llano River immediately upstream from its confluence with the South Llano River and one on the Llano River immediately downstream from this same confluence. The North Llano River watershed roughly covers the eastern half of Sutton County and the western half of Kimble County. The South Llano River watershed covers the northern eastern quarter of Edwards County. Surface flow from the South Llano River watershed eventually merges into the Llano River and discharges into the Colorado River.

The South Llano River watershed provides a large amount of recharge to the Llano and Colorado rivers, particularly during periods of drought (Broad, 2008). Average annual precipitation in the South Llano River watershed is 22-24 inches. The first 35 miles of the South Llano River above the confluence of the South Llano River and Paint Creek flow intermittently. The lower 20 miles of the South Llano River flow continuously to Junction where the North and South Llano rivers converge to form the Llano River. The main sources of water to the South Llano River are springs near the confluence with Big Paint Creek. Included are Seven Hundred Springs, Tanner Springs, and Big Paint Springs. Several gain/loss studies indicate that approximately half of the flow in the South Llano River comes from above the confluence with Big Paint Creek (i.e., Seven Hundred Springs and Tanner Springs) and half comes from Big Paint Creek (Slade et al., 2002).

The South Llano River has never ceased to flow during recorded history. There is a U.S. Geological Survey gauging station (08150000) on the Llano River at Junction immediately below the confluence of the North and South Llano rivers. Average discharge in the Llano River at Junction was 198 cfs for the period October 1, 1915 to May 12, 2010. This equates to 143,346 acre-ft/yr. There are 1,186,560 acres in the drainage area upstream of Junction. This equates to an average of 0.121 feet/year or 1.45 inch/year for the watershed. When corrected for a baseflow factor of 0.64, recharge is calculated as 0.93 inch/year.

The average flow of the North Llano River at Junction was 67.6 cfs for the period October 1, 1915 to May 12, 2010. This equates to 48,279 acre-ft/yr. There are 584,960 acres in the drainage area upstream of the gauging station. This equates to an average of 0.084 feet/year or 1.00 inch/year over the drainage area. Recharge is calculated as 0.46 inch/year when corrected for a baseflow fraction of 0.46.

As a check of the recharge calculated for the Llano River basin, recharge is calculated for the gauging station on Beaver Creek near Mason in Mason County. Precipitation in the Beaver Creek watershed (25 to 27 in/year) is similar to that in the Llano River watershed (29 inch/year) (Figure 6). The average discharge for Beaver Creek is 19 cfs or 13,755 acre-ft/year. The drainage area of Beaver Creek is 215 mi^2 (137,600 acres). When corrected for a baseflow factor of 0.42, this equates 0.50 in/yr of recharge, similar to the average recharge calculated for the North Llano River basin and somewhat higher than recharge for the entire Llano River drainage area.

San Saba River Watershed – Flow in the San Saba River is evaluated at several locations. Flow in the San Saba River originates at Government Springs at Fort McKavett. Wilkinson Springs discharges to Clear Creek which discharges into San Saba River about 15 miles downstream from Government Springs and 10 miles upstream from Menard. The Noyes irrigation channel diverts water from the San Saba River about five miles upstream from Menard and eventually returns flow to the San Saba River about five miles downstream from Menard after providing for irrigation along its flow path.

Average discharge in the San Saba River was 60.1 cfs at Menard for the period October 1, 1915 to May 5, 2010. This equates to 43,496 acre-feet/yr. There are 721,920 acres in the San Saba River drainage area above this gauging station. This watershed covers the eastern half of Schleicher County and the western half of Menard County. River discharge corrected for a baseflow factor of 0.48 equates to an average 0.35 inch/year of recharge.

There was a U.S. Geological Survey gauging station on the Noyes channel that operated from April 1924 to September 1984. Average flow in the Noyes channel was 13.75 cfs during the period of measurement. For this same period, flow in the San Saba River at Menard averaged 63.0 cfs. Flow in the Noyes channel was 21.8 percent of the flow in the San Saba River. If this percentage were representative for the period of October 1, 1915 to May 5, 2010, then the combined flow of the San Saba River and the Noyes channel would have been 73.2 cfs or 52,978 acre-feet/year. Recharge for the drainage area upstream from Menard would have been 0.42 inch/year.

Discharge in the San Saba River is checked by assessing the gauging station on the San Saba River at Brady, Texas. These data are for the period July 1, 1979 to May 5, 2010. The average discharge of the San Saba River at Brady was 70.5 cfs (51,040 acre-feet/year) for the period. The drainage area is 1,040,640 acres. This equates to 0.34 inch/year (29,603 acre-ft/year) of recharge after being corrected to a baseflow factor of 0.58 and averaged over the entire San Saba River drainage area at the Brady gauging station.

Because the recharge value is lower at Brady than at Menard, San Saba River is apparently losing between the Menard and the Brady gauging stations. If the San Saba River watershed upstream of Brady were recharged at same rate measured at Menard (i.e., 0.42 inch/year), the total rate at Brady, including surface flow and underflow, would have been 1,040,640 acres at 0.074 feet/year or 77,007 acre-feet/year. This suggests that 36,422 – 29,603 = 6,819 acre-feet/year are lost from the San Saba River between Menard and Brady gauging stations. The distance from the Menard gauging station to the Brady gauging station is 45.2 miles, with meanders (calculated using Terrain Navigator). This suggests that 150 acre-feet/year per mile are lost from the San Saba River, presumably to the Edwards-Trinity Aquifer. This amount could be greater if actual recharge is greater than 0.42 inch/year.

Additional Surface Watershed Discharge Analyses

Six additional watersheds outside of the eight-county study area are evaluated provide a broader measure of recharge in the western Edwards Plateau and adjoining areas. The following watersheds are evaluated to provide this added information on regional recharge and local hydrogeological conditions.

- Dove Creek watershed
- Johnson Creek watershed
- Medina River watershed
- Middle Concho River watershed
- South Concho River watershed
- Brady Creek watershed

Dove Creek Watershed – The average discharge in Dove Creek at Knickerbocker, Texas was 15.8 cfs for the period October 1960 to September 2009. This equates to 11,438 acre-feet/year. The baseflow component is 8,667 acre-feet/year. There are 139,520 acres in the Dove Creek drainage area above this gauging station. This equates to an average of 0.74 inch/year of recharge.

Johnson Creek Watershed – The average discharge in Johnson Creek near Ingram in Kerr County was 26.0 cfs for the period October 1941 to September 2009. This equates to 18,824 acre-feet/year of which 11, 645 acre-feet/year is baseflow. There are 72,960 acres in the Johnson Creek drainage area above this gauging station. This equates to an average of 1.92 inch/year of recharge.

Medina River Watershed – The average discharge in Medina River at Bandera, Texas was 163.58 cfs for the period October 1982 to September 2009. This equates to 118,432 acre-feet/year of which 80,534 acre-feet/year is baseflow. There are 209,920 acres in the Medina River drainage area above this gauging station. This equates to an average of 4.54 inch/year of recharge.

Middle Concho River Watershed – The average discharge in Middle Concho River above Tankersley, Texas was 14.16 cfs for the period April 1961 to September 2009. This equates to 10,251 acre-feet/year. The baseflow component to flow is 2,253 acre-feet/year. There are 714,240 acres in the Middle Concho River drainage area above this gauging station. This equates to an average of 0.04 inch/year of recharge.

South Concho River Watershed – The average discharge in South Concho River at Christoval, Texas was 29.9 cfs for the period March 1930 to September 2009. This equates to 21,647 acre-feet/year of which 13,060 acre-feet/year is baseflow. There are 226,560 acres in the South Concho River drainage area above this gauging station. This equates to an average of 0.69 inch/year of recharge.

Brady Creek Watershed – The average discharge in Brady Creek near Brady, Texas was 6.67 cfs for the period October 1962 to September 2009. This equates to 4,829 acre-feet/year or 1,383 acre-feet/year when corrected to baseflow. There are 376,362 acres in the Brady Creek drainage area above this gauging station. This equates to an average of 0.04 inch/year of recharge.

Hydraulic Relationships between Surface Watersheds and Groundwater Catchment Areas

Groundwater recharge rates determined from river discharge measurements are illustrated at their drainage area locations in Figure 6. Assessment of the recharge values indicate a notable contrast in calculated recharge rates between the headwaters of the Nueces and Frio river watersheds and the Llano River watershed. The recharge rates for the Llano River and its tributaries which flow north are significantly less than those for both the Nueces and Frio river watersheds which flow south, and the Guadalupe and Medina river watersheds which flow east. Inspection of precipitation measured for the study area (Figure 12) suggests that this significance difference in calculated recharge rates cannot be attributed to the minor variations in precipitation observed across the eastern portion of the study area.

Significant differences in calculated recharge rates between northern and southern portions of the study area are interpreted to indicate that groundwater catchment areas for the Nueces, Frio, Medina, and Guadalupe rivers extend farther north than the boundaries of the overlying surface watersheds. This interpretation is consistent with the combined surface watershed and groundwater flow map that indicates that groundwater catchment boundaries do not coincide with surface watershed boundaries (Figure 11). Groundwater piracy from the north-facing watersheds results in lower calculated recharge rates for the watersheds of the Llano River and it tributaries, and higher calculated recharge rates for the watersheds to the south and east. Actual recharge rates are greater than the low values to the north and less than the high values to the south and east.

There is justification for the hypothesis for groundwater piracy in the study area. Groundwater flow through karst aquifers can occur as porous media flow through the aquifer matrix and as preferential flow through conduits or other solution cavity enhanced flow pathways. There is a tendency for conduits or similar preferential flow pathways to be coincident with rivers and streams in karst aquifers. These preferential flow paths are formed over long periods of time by flowing water forming solution openings in the rock in the beds of the rivers and streams. Increased permeability is developed in the river beds as a result of this flow and is supported by the observation that higher capacity wells tend to be located in bedrock near rivers and streams compared with lower capacity wells in interstream areas. The preponderance of higher capacity wells near the San Saba River in Menard County is a clear example of this. Similar preferential pathways near rivers have been observed in the Edwards Aquifer in Kinney and Uvalde counties (Green et al., 2006).

In addition, alluvial development in river and stream beds provides another avenue for enhanced groundwater flow. Although some rivers on the Edwards Plateau are mostly devoid of alluvial sediments, rivers and streams incised into the boundaries of the Edwards Plateau, such as the Frio River, do have alluvial aquifers that support many of the higher capacity wells in the region.

Groundwater piracy from adjoining surface watersheds does not occur in river and stream beds or in the preferential flow pathways associated with surface water drainage or in the shallow subsurface. Groundwater piracy is interpreted to occur deeper in the subsurface below the effect of surface-water related processes. Groundwater piracy would be more likely to occur in areas where the affected aquifer is thick and deep rather than thin and shallow. The Edwards-Trinity Aquifer is significantly thicker in Sutton, Edwards, Real, Val Verde, and southern Kimble and Schleicher counties relative to the Edwards-Trinity Aquifer to the north.

It is in areas of a thicker and deeper aquifer where the evidence of groundwater piracy is most apparent. As a consequence of this deeper flow, areas from which groundwater has been pirated will have less discharge into rivers and streams and smaller calculated recharge rates. Examples of this in the study area are the recharge rates calculated for the North Llano at Junction, the South Llano at Junction, and the West Nueces at Brackettville. Areas which gain from pirated groundwater will have greater discharge into rivers and streams and higher rates of calculated recharge. Examples of this are recharge rates calculated for the Frio River at Concan and the Nueces River at Laguna. Gauging stations on Johnson Creek at Ingram and the Medina River at Bandera also exhibit increased discharge which is attributed to groundwater piracy.

The extent to which groundwater is pirated from one surface watershed to another is difficult to measure, but can be estimated. Because factors that influence recharge (i.e., precipitation, soil and vegetation type, topography) are relatively uniform over the areas where groundwater piracy is thought to occur, actual recharge rates should be relatively uniform. Using this approach, recharge rates were averaged along lines of equal precipitation (isohyetal) to estimate the uniform rate of recharge. Because the isohyetals are essentially north trending in the eastern portion of the study area (Figure 13), recharge was averaged between the gauging stations on the Frio River at Concan and on the South Llano River at Junction and between the gauging stations on the Nueces River at Laguna and on the North Llano River at Junction. In this manner, an average recharge rate of 2.95 inch/year was assigned to the combined watersheds of the upper Frio River and the South Llano River. Similarly, an average recharge rate of 2.01 was assigned to the combined watersheds of the upper Nueces River and the North Llano River.

The extent to which the groundwater catchment areas of the Frio and Nueces rivers extend north beyond the surface-water divide between the Rio Grande and the Colorado River are interpreted to be influenced by the saturated thickness of the Edwards-Trinity Aquifer. The surface-water divide is overlain on a contour map of the saturated thickness of the Edwards-Trinity Aquifer in Figure 14. As illustrated, the greatest potential for groundwater piracy in the study area is northern Edwards, eastern Sutton, most of

Kimble, eastern Schleicher, and Kerr counties. The limit to which groundwater piracy extends to the north can only be definitively determined with field verification such as dye tracer results. In the absence of field verification, the area of potential groundwater piracy is estimated by the 200-ft saturated thickness contour in the Edwards-Trinity Aquifer in Figure 14.

Regional Recharge Assessments

Recharge rates are calculated for each of the eight counties in the study area using data and analyses reported in this investigation. The methodology equated recharge to the baseflow discharge calculations that are averaged over the interpreted groundwater catchment areas. A key assumption in the approach is that the recharge rate varies smoothly in the study area. In order to make the recharge rate vary smoothly across surface-water divides, this averaging scheme increased the sizes of the groundwater catchment areas in the south and decreased the sizes of the groundwater catchments in the north. The total volume of recharge remained constant through this re-allocation process.

Recharge is assumed to be essentially uniform for equal rates of precipitation (Figure 13). Long-term precipitation rates also exhibit a marked decrease from east to west suggesting that recharge should not be averaged in the east to west direction (Figure 12). In this methodology, each county was assigned a single calculated recharge rate representative of a uniform recharge rate for the county. This does not imply that recharge was uniform across each county, but it is the highest reasonable resolution possible given the limited amount of data available.

A recharge rate of 2.14 inch/year is assigned to the eastern border of the study area by averaging the baseflow calculated recharge rates for the Frio River at Concan (3.36 inch/year) and for the Llano River at Junction (0.92 inch/year). This recharge rate is assumed to be approximately uniform for the area with a long-term precipitation rate of 29 to 33 inch/year. It is calculated that recharge amounted to approximately 7 percent of precipitation.

Recharge of 2.14 inch/year is assigned to Real County to reflect the observation that the groundwater catchment area of Frio River discharge at Concan extends farther north than the Frio River watershed. Recharge in Kimble County is estimated at 1.50 inch/year to account for the 0.92 inch/year discharged in the Llano River in the north and piracy of groundwater to the south. Recharge in Menard County is estimated at 0.50 inch/year which is slightly greater than the 0.42 inch/year discharge measured in the San Saba River. There is no evidence of groundwater piracy in Menard County based on the groundwater flow map (Figure 14) and the limited thickness of the Edwards-Trinity Aquifer. There is an eastward-flowing groundwater component to recharge indicated by preferential subsurface flow proximal to the San Saba River. The magnitude of the San Saba River groundwater flow component is not well characterized and is assumed to be approximately 0.08 inch/year which equates to 20 percent of the combined flow of the San Saba River and the Noyes Channel. Additional investigation is needed to substantiate the estimate that the subsurface flow component equates to 0.08 inch/year.

Recharge of 1.30 inch/year is assigned to the area around north-central Edwards County by averaging the baseflow calculated recharge rates for the Nueces River at Laguna (2.25 inch/year) and for the North Llano River at Junction (0.46 inch/year). This recharge rate is assumed uniform for the area with a long-term precipitation rate of 21 to 25 inch/year and supports the contention of groundwater piracy from the north. Recharge for this area accounted for approximately 5 percent of precipitation. Based on this analysis, recharge of 1.30 inch/year is assigned to Edwards County to account for the increased size of the groundwater catchment area that discharges to the Nueces River.

The estimated recharge rate for Devils River watershed (i.e., 0.95 inch/year) is believed to be excessive because the actual groundwater catchment area for water discharged via Devils River exceeds the extent of the surface watershed by an estimated 40 to 50 percent (Figure 6). If the groundwater catchment area were 50 percent greater in area than the watershed area, the average recharge rate would be reduced from 0.95 to 0.63 inch/year. The Devils River watershed precipitation is approximately 19 to 21 inches/year, thus a recharge rate of 0.63 inch/year constitutes an average of approximately 3 percent of the precipitation in the Devils River watershed. The decreased recharge value assigned to the Devils River watershed is balanced by the increased recharge assigned to areas where groundwater piracy is suspected; eastern Sutton, central Schleicher, and a small area in northern Crockett counties.

Recharge is assumed to be 1.00 inch/year in Sutton County determined by averaging the 1.30 inch/year recharge calculated for the eastern portion of the county and recharge of 0.63 inch/year in the Pecos River catchment area. Recharge in Schleicher County is assumed to be 0.80 inch/year, which is slightly greater than the 0.74 and 0.69 inch/year recharge rates calculated for Dove Creek and Middle Concho River, respectively, to account for groundwater piracy to the south. Improved resolution of the groundwater potentiometric surface map would allow refinement of these calculations.

Less information is available to estimate recharge at the western boundary of the study area. River discharge measured on the Pecos River does not provide a valid estimate for recharge solely in Crockett County or western Val Verde County because the discharge measurements from the Pecos River at Pafford Crossing reflect recharge for the entire upstream catchment area of the Pecos River, not just the Pecos River surface watershed in Crockett County. Recharge for Val Verde County is interpreted to decrease significantly from the east side of the county where precipitation averages 23 inch/year to the west where precipitation averages as low as 15 inch/year. Recharge for the county is estimated at 0.63 inch/year, although there is higher uncertainty in this estimate than in recharge estimates to the east due to lack of gauging stations in the west.

Recharge for western Crockett County is estimated to be 1 to 2 percent of precipitation (i.e., 17 inch/year) or 0.17 to 0.34 inch/year. Inherent in this assumption is that the percentage of precipitation that becomes recharge decreases with precipitation, an assumption that is supported by an east-to-west decrease in previously calculated recharge percentages in the study area. Supporting this low percentage of recharge rate are studies of recharge in semi-arid environments that indicate that recharge becomes negligible when precipitation is less than 20 inch/year (Scanlon, 2004; Scanlon et al., 2006). Recharge of 0.25 inch/year is assumed representative for Crockett County to account for the high level of uncertainty in the eastern portion of the study area.

Recharge compiled for the eight counties in the study area using the analyses conducted in this study are compared with recharge values cited in the 2004 TWDB 04-17 GAM report (Anaya, 2004) (Table 5). Recharge rates calculated for Menard, Val Verde, and Crockett counties are comparable to the rates cited by the TWDB in the GAM report (Anaya, 2004). In these three counties, however, the level of uncertainty in the calculations remains high. Recharge rates calculated in this investigation for Edwards, Kimble, Real, Schleicher, and Sutton counties are significantly higher than the recharge rates cited in the 2004 TWDB GAM report. The primary justification for larger recharge rates in this area as implied by the river discharge measurements is groundwater piracy of additional recharge from north of the surface water divide.

Recharge-Precipitation Relationship

An understanding of regional recharge and precipitation can be used to establish a relationship of recharge to precipitation. A graph is prepared with average annual recharge and precipitation for each county (Figure 15). As illustrated, there is an approximately linear relationship between recharge and precipitation with the exception of Menard County. The graphed relationship suggests that recharge decreases linearly as precipitation decreases from 31 inch/year in the southeastern corner of the study area to a low of about 17 inch/year in the northwest corner of the study area. Recharge approaches zero when precipitation decreases below about 17 inch/year. This observation is consistent with findings by Scanlon (2005) and Scanlon et al. (2006) which suggested that recharge was minimal or negligible in semi-arid environments at precipitation rates below 20 inch/year. A mathematical relation describing the correlation of recharge to precipitation can be written as

$$R = 0.15(P - 16.5) \text{ for } P > 16.5,\ R = 0 \text{ for } P \leq 16.5 \quad \text{Eq (1)}$$

where R is recharge (inch/year) and P is precipitation (inch/year). This expression provides a basis to predict hypothetical recharge based on anticipated precipitation for the study area.

Sub-Area Water Budget Interdependency

The hydrogeologic relationships of the sub-areas in the study area are complex and difficult to fully describe due to the lack of distinct hydraulic boundaries among surface watersheds, groundwater catchments, or counties. Because of this interdependency, water resource management actions taken in one sub-area can impact adjacent sub-areas, particularly those that are downgradient. As illustrated by the groundwater catchment map (Figure 14), this interdependency extends beyond the limits of the study area. More precise delineation of the groundwater catchment areas and a better understanding of whether groundwater catchment boundaries can migrate with changes in groundwater stage are not possible in the absence of accurate groundwater potentiometric maps. A series of synoptic groundwater elevation surveys at different groundwater stages is required before these issues can be acceptably resolved.

In general, water resource actions within or upgradient from the surface watershed or groundwater catchment can impact the water resources of a sub-area. Table 6 identifies which counties are impacted or can be impacted by water resource actions in adjacent counties. Table 6 also differentiates between counties marginally or significantly impacted.

Effect of Drought on Recharge

Precipitation varies in the Edwards Plateau from year to year. Extended periods of less than average precipitation will obviously result in reduced recharge. The precipitation-recharge correlation calculated for the study area is used to predict the amount of recharge for reduced precipitation. Reductions in precipitation equaling 10, 20, and 30 percent are considered in this analysis. There are several assumptions in these predictions. First, all counties are assumed to be recharged according to the precipitation-recharge correlation calculated for the study area. This assumption is also applied to Menard County, even though the county had a low calculated recharge rate of 0.5 inch/year. This assumption is supported by the observation that recharge calculated for Menard County had a relatively high level of uncertainty. It is possible that recharge in Menard County is closer to 1.25 inch/year than to 0.5 inch/year and that a significant portion of the recharge in Menard County is not discharged into the San Saba River.

The second assumption is that the period of low precipitation is sufficiently long to significantly affect groundwater storage in the aquifer. The response of storage in an aquifer to a drought could vary with location. The time required for aquifers with limited saturated thickness, such as in Menard County, could be less than other areas with greater saturated aquifer thickness, such as in Real or Edwards counties. Correlation analyses among precipitation, groundwater elevation, and spring discharge are needed to ascertain the time required by an aquifer to respond to changes in precipitation. Karst aquifers, such as the Edwards-Trinity Aquifer, tend to be considerably more responsive than porous media aquifers, such as the Ogallala Aquifer, for example. However, the actual time for the Edwards-Trinity Aquifer to respond to pumping or recharge is not well known.

There is an important caveat to these calculations. This analysis addresses recharge that is distributed over areas where the Edwards-Trinity Aquifer is recharged. Distributed recharge is sensitive to precipitation rates and becomes minimal when recharge is less than 20 inch/year (Scanlon, 2004; Scanlon et al., 2006). Recharge can also be focused in river and stream beds in those reaches where the rivers and streams are losing. Aquifers, therefore can experience recharge via river and stream beds during periods of drought even when precipitation is curtailed provided that water is present in the river and stream beds. As discussed earlier in this report, most rivers and streams in the study area are gaining, thus the potential for focused recharge is not high. However there are insufficient field investigation results to be able categorically dismiss focused recharge particularly if there are flash flood events during periods of drought when stream flow is high and the groundwater surface is low. The recharge analysis performed here has not included focused recharge, therefore recharge calculations and predictions are conservative.

Recharge is predicted based on Equation (1) for each county with precipitation reduced by 10, 20, and 30 percent (Table 7). As prescribed by the precipitation-recharge correlation calculated for the study area, the percentage of precipitation that becomes recharge decreases with the rate of precipitation and becomes negligible when precipitation approaches 16 to 17 inch/year. Therefore, as illustrated in Table 7, recharge becomes negligible in Crockett and Val Verde counties when precipitation is reduced to 80 percent of average annual precipitation. At 70 percent of average annual precipitation, only Edwards, Kimble, Menard, and Real counties receive any recharge and those recharge rates are minimal (i.e., 300 to 5,200 acre-feet/year).

Long-term time series of precipitation data collected in the study area were evaluated to provide a measure of how much precipitation deviates from its long-term average and for how long, particularly during periods when lower than average precipitation persist for multiple years. Annual precipitation data recorded at the Del Rio National Weather Service station during the period 1920-2000 are illustrated in Figure 16. The average annual precipitation at this location is 18.4 inches. Precipitation levels at 90, 80, and 70 percent of average annual precipitation equates to 16.6, 14.7, and 12.9 inch/year. Lines for the average and the three reduced levels of precipitation are also illustrated in Figure 16. From this graph it can be seen that that 90, 80, and 70 percent of average annual precipitation occurred approximately 40, 30, and 20 percent of the time during 1920-2000.

Calculated recharge and recharge predicted for three levels of reduced precipitation are compared with the 2004 GAM values for recharge (Table 7) (Anaya, 2004). Values of recharge calculated for the eight counties in this assessment exceed the 2004 GAM values for all counties with the exception of Crockett and Val Verde counties. At 90 percent of average annual precipitation, recharge in the other six counties still exceeds the 2004 GAM recharge values. However, recharge values predicted at Edwards, Schleicher, and Sutton counties at 80 percent of average annual precipitation are significantly less than the 2004 GAM values. At 70 percent of average annual precipitation, there is minimal recharge in any county and all predicted recharge values are less than the 2004 GAM values (Anaya, 2004).

Predicted recharge is also compared with groundwater availability documented in the 2007 Texas State Water Plan (Table 8, data extracted from the Texas Water Development Board website on May 15, 2010). The 2007 Texas State Plan groundwater availability quantities were less than the calculated recharge values in all eight counties for average precipitation. The Texas State Water Plan groundwater availability quantities exceed recharge in Crockett and Val Verde counties when there is 90 percent of average annual precipitation. At 80 percent of average annual precipitation, recharge in Schleicher County is less than the quantity of groundwater available in the 2007 Texas State Water Plan. At 70 percent of the average annual precipitation, predicted recharge in all eight counties is less than the 2007 Texas State Water Plan available groundwater.

Discussion

Recharge for the study area has been assessed to provide a basis to determine a sustainable water balance for the eight county study area. Recharge values are summarized in Table 9 for comparison. Table 9 includes recharge calculated using river baseflow calculations, recharge predicted for 90, 80, and 70 percent of average precipitation, groundwater availability documented in the 2007 Texas State Water Plan, and recharge assigned to the 2004 Edwards-Trinity Aquifer GAM. The analysis of the water budget did not explicitly account for groundwater removal by pumping. Refinement of well inventories is needed to calculate the effect of pumping on the water budget.

The quantity of groundwater that is sustainable and available needs be identified to be able to establish the Desired Future Conditions. Information and insight gained during the execution of this project provide guidance in establishing defensible levels of available groundwater. This study demonstrates that Crockett and Val Verde counties are most vulnerable to drought because recharge is negligible when precipitation is reduced to less than 16-17 inch/year. Menard County is also vulnerable to drought because it has minimal opportunity to store groundwater due to the limited saturated thickness of the Edwards-Trinity Aquifer in Menard County. Conversely, Real, Edwards, Kimble, and to a lesser degree, Sutton counties are least vulnerable to drought because they receive greater amounts of precipitation, on average, and their groundwater catchment areas limits extend beyond the extents of their surface watersheds.

Two potential plans for establishing sustainable and available yield of groundwater are identified. In Plan A, sustainable yield is set at 25 percent of average recharge for Crockett, Kimble, Menard, Schleicher, Sutton, and Val Verde counties. Sustainable recharge for Edwards and Real counties is set at 15 percent of average recharge. Their sustainable yield is set to a lower percentage than the other six counties because these two counties and their extended groundwater catchments are the principal source of recharge to the western San Antonio segment to the Edwards Aquifer. Plan B is more conservative than Plan A. In Plan B, sustainable yield is reduced from 25 to 20 percent for Crockett, Kimble, Menard, Schleicher, Sutton, and Val Verde counties and from 15 to 10 percent for Edwards and Real counties. Specific recharge values for each plan are included in Table 9. These two potential plans are recommendations based on currently available data. Final groundwater yield determinations must also account for an acceptable level of risk. The acceptable level of risk is determined by the local groundwater conservation districts assigned with managing the resource.

Summary

A comprehensive assessment of the hydrogeology of the Edwards-Trinity Aquifer was undertaken to provide independent determination of "desired future conditions" for the western Edwards-Trinity Aquifer as required by HB 1976 (Mace et al., 2006). Eight counties were included in the project; Crockett, Edwards, Kimble, Menard, Real, Schleicher, Sutton, and Val Verde. The assessments relied on water budget analyses of hydrological distinct sub-areas in the eight county study area.

Key findings of the study include the following:

- Groundwater catchments in the study area extend farther north compared with their overlying surface watersheds. Extension of a groundwater catchment from one surface watershed into another watershed results in groundwater piracy. Most notable are groundwater catchments for the Frio, Nueces, and Devils rivers.
- Counties with the greatest uncertainty in water budget assessments are Crockett, Val Verde, and Menard. Crockett County has high uncertainty because it is part of a much larger hydrogeologic sub-area that includes the upper reaches of Pecos River and because there are limited data for the county. Val Verde County has high uncertainty because hydrologic conditions, including precipitation, vary significantly from east to west in the county. Menard County has high uncertainty because groundwater flow contributes significantly to the county water budget and this component has not been measured.
- River discharge measurements provide an opportunity to calculate recharge for the area that contributes to baseflow in the river. Long-term river discharge measurements were corrected for baseflow using an automated discharge recession separation algorithm. This analysis provided the fraction of total discharge that is attributed to baseflow.
- Long-term average annual river discharge values corrected to baseflow were converted to estimates for recharge for each contributing area analyzed. Refined groundwater catchment areas were assumed to be the contributing area for each discharge measurement.
- Recharge values were correlated with precipitation in the study area. The percentage of precipitation that recharged the Edwards-Trinity Aquifer varied from 7 percent in the eastern side of the study area where average annual precipitation is as high as 33 inch/year to 2 percent in the western side of the study area where average annual precipitation is 15 inch/year.
- Knowing the correlation between precipitation and recharge allowed prediction of how recharge in the study area will vary during periods when precipitation is less than the long-term average precipitation for extended periods.
- Recharge for each county in the study area was calculated for average precipitation conditions and predicted for periods when precipitation was reduced by 10, 20, and 30 percent. Calculated and predicted recharge is compared with recharge values assigned to the 2004 Edwards-Trinity Aquifer GAM and the groundwater availability documented in the 2007 Texas State Water Plan.

- Within the study area, Val Verde and Crockett counties are most vulnerable to drought because recharge is negligible when precipitation is reduced to less than 16-17 inch/year. Menard County is also vulnerable because it has minimal opportunity to store groundwater due to the limited thickness of the Edwards-Trinity Aquifer. Conversely, Real, Edwards, Kimble, and to a lesser degree, Sutton counties are less vulnerable to drought because they receive greater amounts of precipitation, on average, and their groundwater catchment areas extend beyond the extents of their surface watersheds.
- The analysis of the water budget did not explicitly account for groundwater removal by pumping. Refinement of well inventories is needed to calculate the effect of pumping on the water budget.

Based on these findings, the sustainable yield of groundwater for each county is predicted using calculated recharge and recharge predicted for reduced precipitation. As examples, two plans are discussed. In Plan A, the sustainable yield of groundwater is set at 25 percent of calculated recharge for Crockett, Kimble, Menard, Schleicher, Sutton, and Val Verde counties and 15 percent for Edwards and Real counties. These percentages are reduced to 20 and 10 percent, respectively, in Plan B to reduce the risk to the water resource during periods of drought. Alternative calculations of sustainable yield of groundwater to reflect different risk levels can be made using recharge analysis results documented in this report.

Recommendations

Recent hydrogeological assessments and groundwater modeling analyses of the Edwards-Trinity Aquifer clearly demonstrate that water resources of the Edwards Plateau are not adequately characterized. The greatest limitation to an improved understanding of the Edwards-Trinity Aquifer water resources is an inadequate characterization of the regional hydrogeology. Key information needed are an accurate groundwater-elevation contour map, recharge rates, hydrogeological boundary conditions, hydraulic characterization of the aquifer, spring discharge rates, and an understanding of surface water/groundwater interactions. A series of tasks are identified that, if implemented, would help alleviate this inadequacy of data and reduce uncertainty in water-resource management decision making. Specific tasks to alleviate this data inadequacy include:

- Synoptic groundwater elevation survey. Included in this is a survey to identify candidate monitoring wells, a survey to establish the elevation of each monitor well, and a series of synoptic groundwater elevation surveys to develop more accurate groundwater catchment areas and determine whether groundwater flow varies with stage (i.e., groundwater elevation).
- Water chemistry analysis of well, spring, and river water samples. This information is key to determination of the source, location, and chemical identity of different waters, both groundwater and surface water. Development of a water chemistry baseline will allow for clear determination whether future water resource actions result in changes to water quality.
- Spring and stream discharge analyses. Refined discharge measurements of spring and stream discharge provide information critical to water-balance calculations, determination of recharge, and determination of sustainable levels of pumping.
- Spring flow hydrograph recession separation using chemical, isotope, and hydrologic approaches.
- Establishment of evapotranspiration flux towers to collect climatological data from the Edwards Plateau to reduce uncertainty in estimated and calculated distributed recharge rates. Evapotranspiration flux towers provide data on specific local climatological conditions. These data improve accuracy in recharge estimates by reducing assumptions made on actual local conditions.
- Near-surface geophysical surveys of river and stream floodplains to determine the potential for subsurface flow and to help establish the hydraulic relationship between groundwater and surface water.
- Establish an improved, more accurate well inventory. The inventory should include all exempt wells because exempt wells account for the overwhelming majority of wells in the Edwards-Trinity Aquifer. The use of each well should be identified. Domestic wells will have different average pumping rates than stock wells. Determine actual pumping rates for all categories of wells. This information will reduce uncertainty in water budget analyses.
- Discharge analyses in the San Saba watershed, including discharge measurements of Wilkerson Spring into Clear Creek.
- Chloride profile analysis to determine infiltration rates.

- Correlation analyses to develop an understanding of correlations among precipitation, groundwater elevation, and spring discharge.
- Development of an updated Edwards-Trinity Aquifer groundwater flow model. Data collection and improved characterization of the Edwards-Trinity Aquifer will be incorporated into an improved groundwater flow model. The model will be used to evaluate future groundwater resource management strategies, including development of Desired Future Conditions as required by HB 1763.

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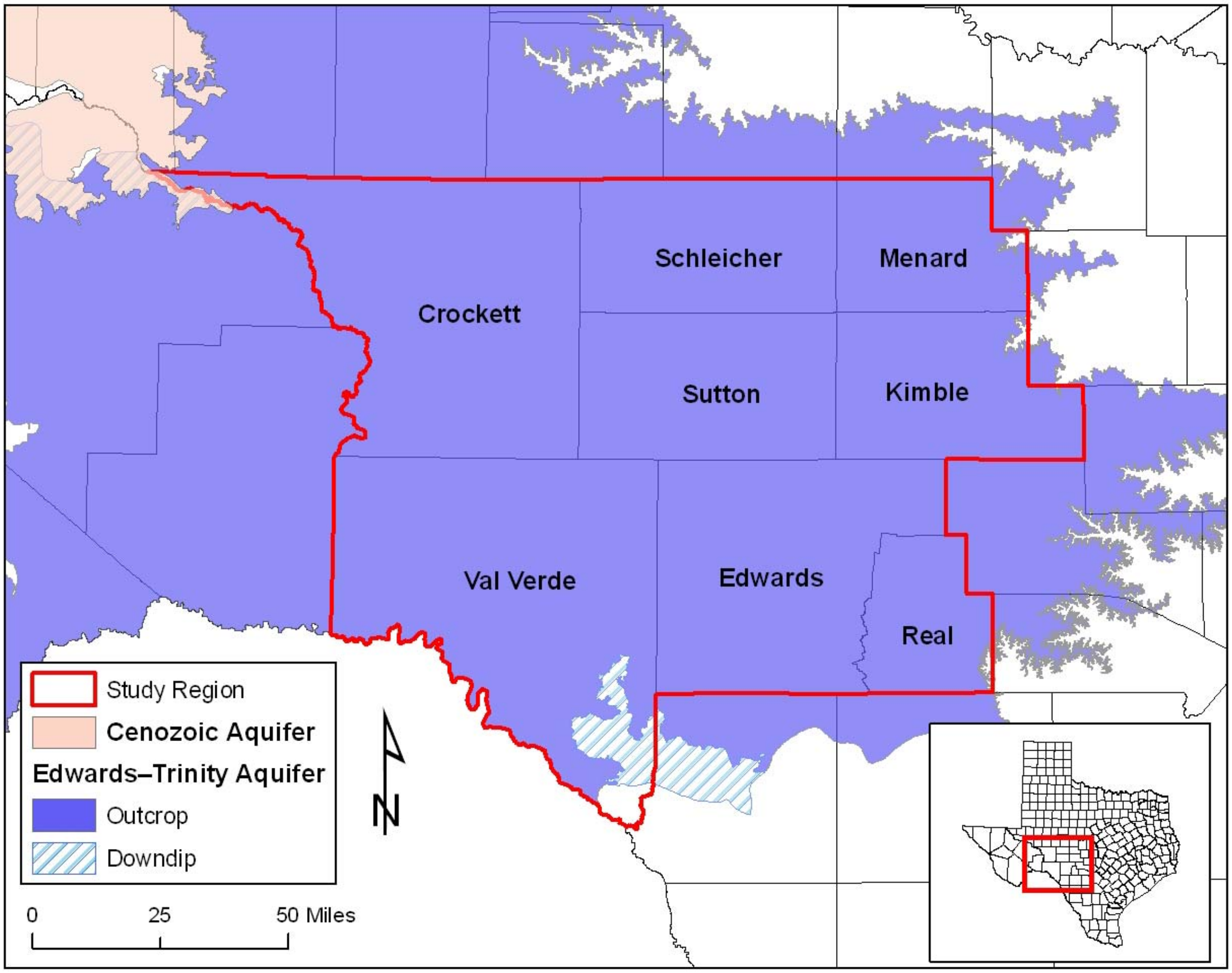

Figure 1. Map of the study area.

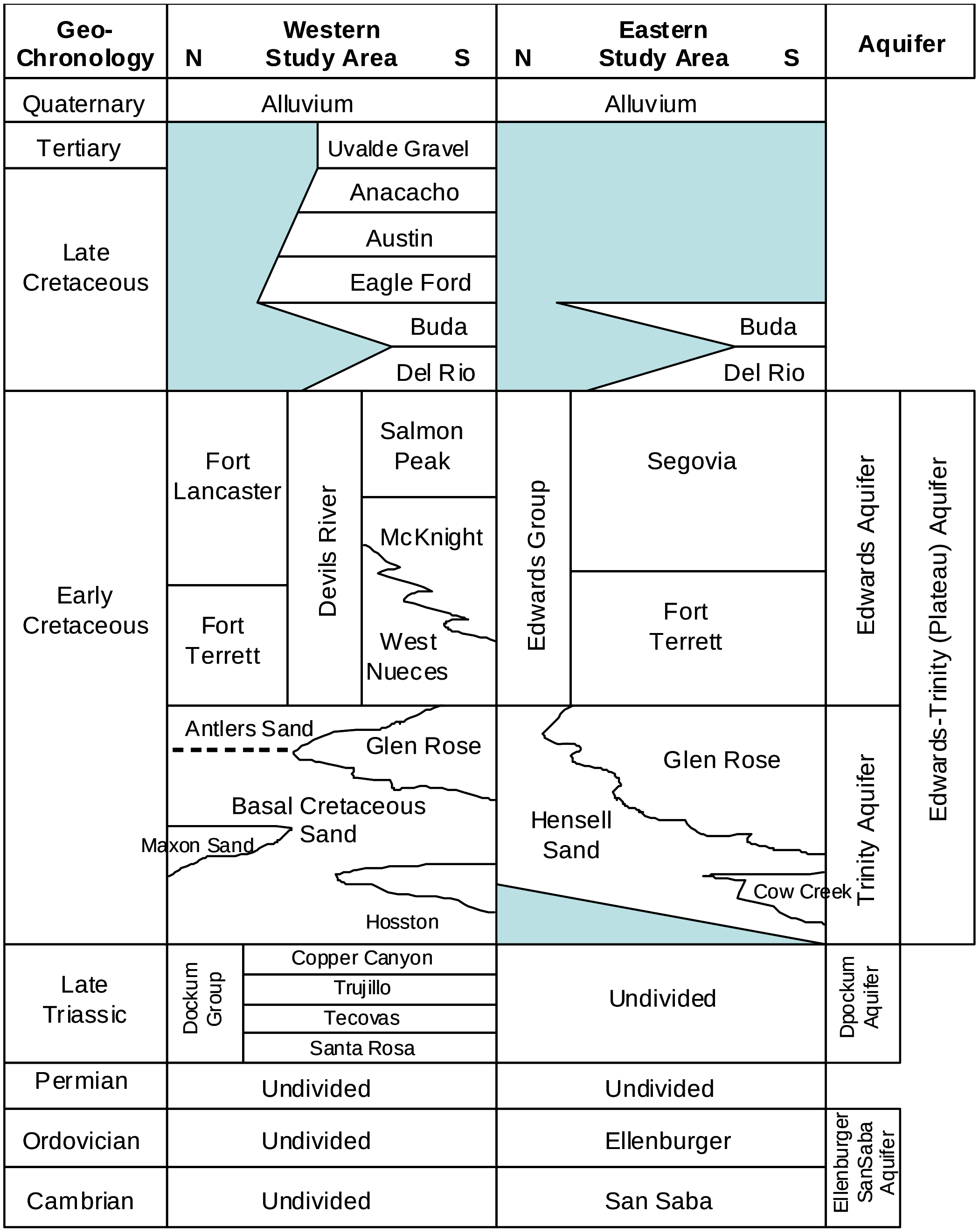

Figure 2. Stratigraphy of Edwards Plateau in the study area (adapted from Anaya and Jones, 2009).

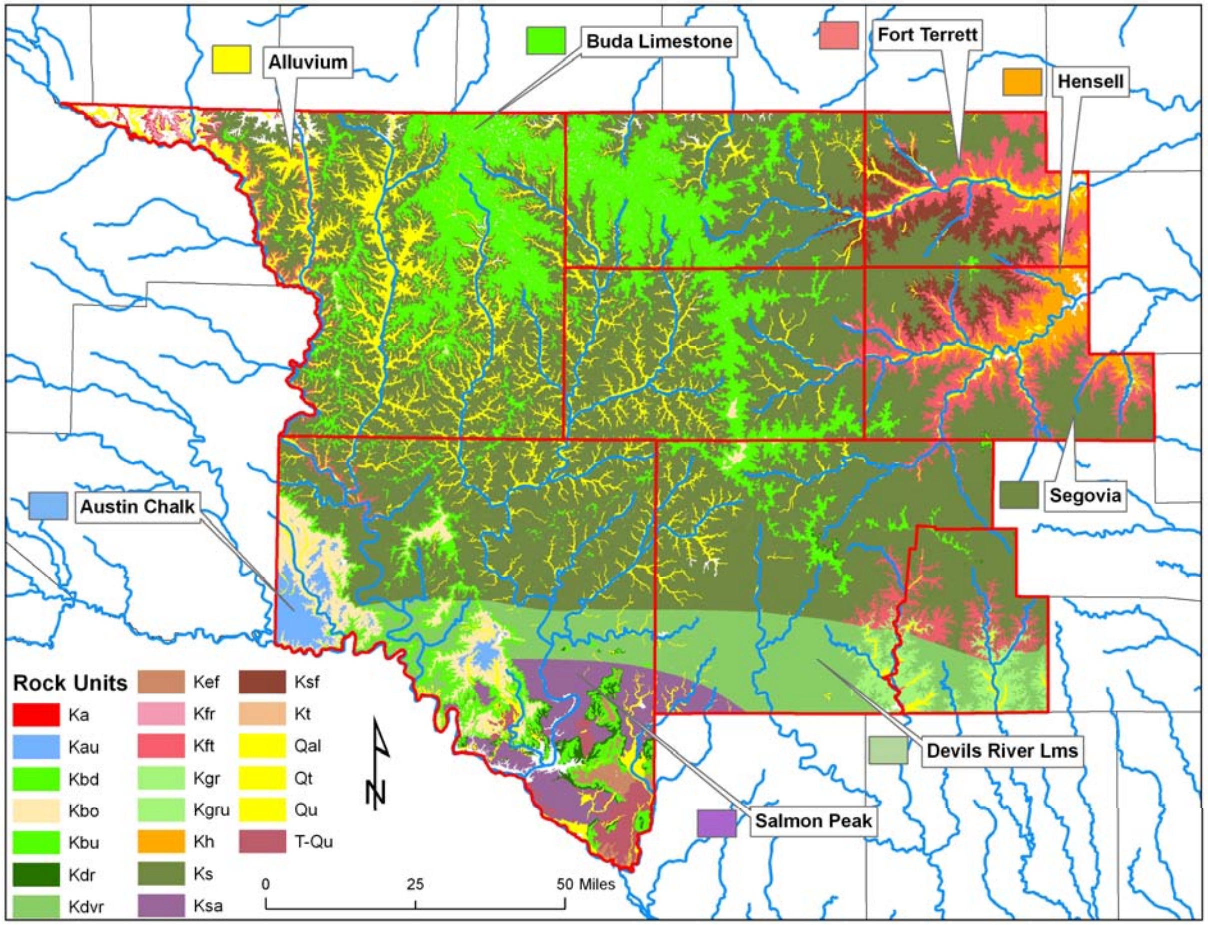

Figure 3. Surface geology of the study area. Major rock units shown include: Ka–Antler Sandstone, Kau–Austin Chalk, Kbd/Kbu–Buda Limestone, Kbo–Boquillas Formation, Kdr–Del Rio Clay, Kdvr–Devils River Limestone, Kef–Eagle Ford Formation, Kfr–Fredericksburg Group undivided, Kft–Fort Terrett Limestone, Kgr/Kgru–Glen Rose Limestone, Kh–Hensell Sand, Ks–Segovia Limestone, Ksa–Salmon Peak Limestone, Ksf–Segovia/Fort Terrett undivided, Kt–Trinity Group undivided, Qal/Qt/Qu–Quaternary alluvial deposits, T-Qu–Uvalde Gravel.

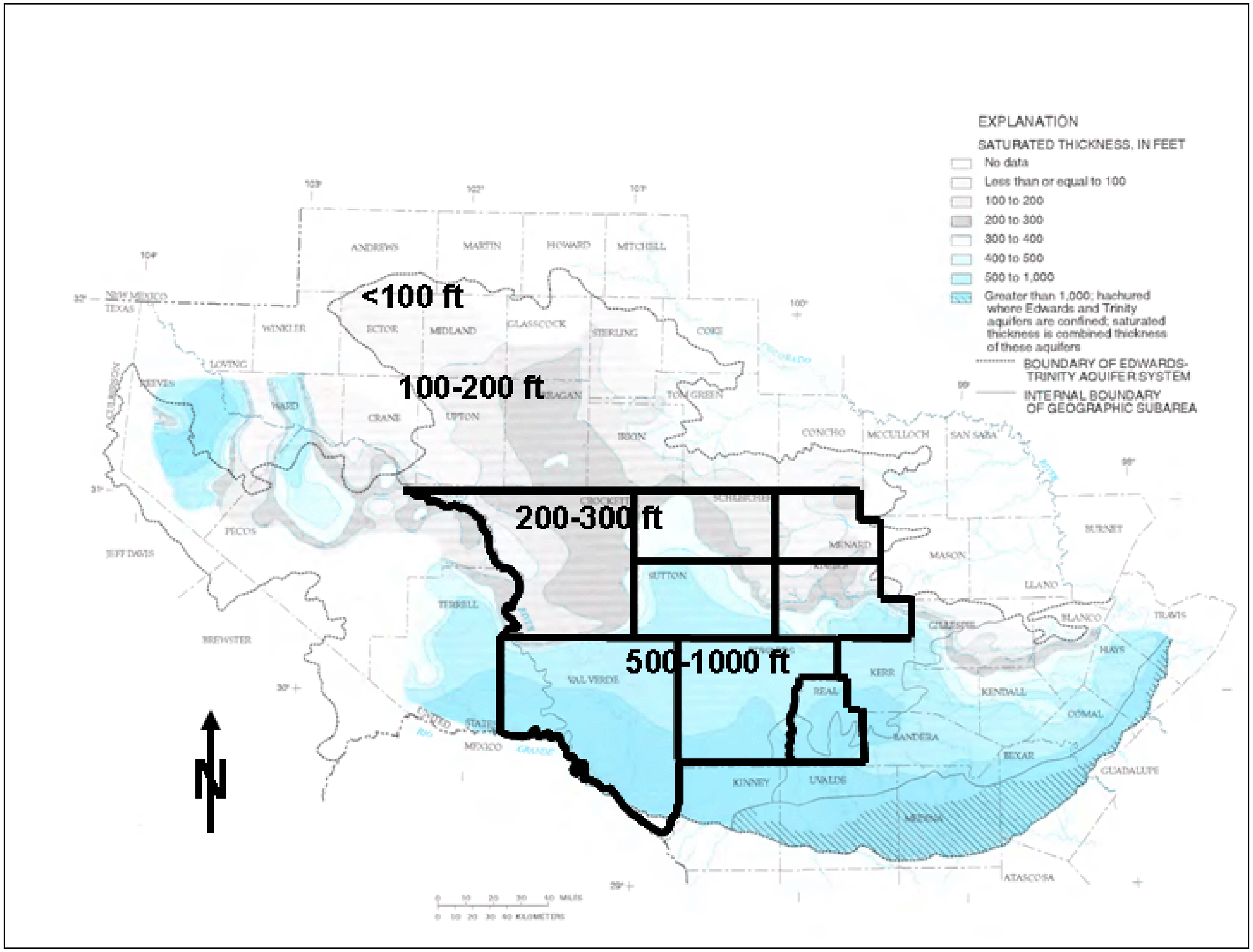

Figure 4. Contour map of the saturated thickness of the Edwards-Trinity Aquifer (Barker and Ardis, 1996).

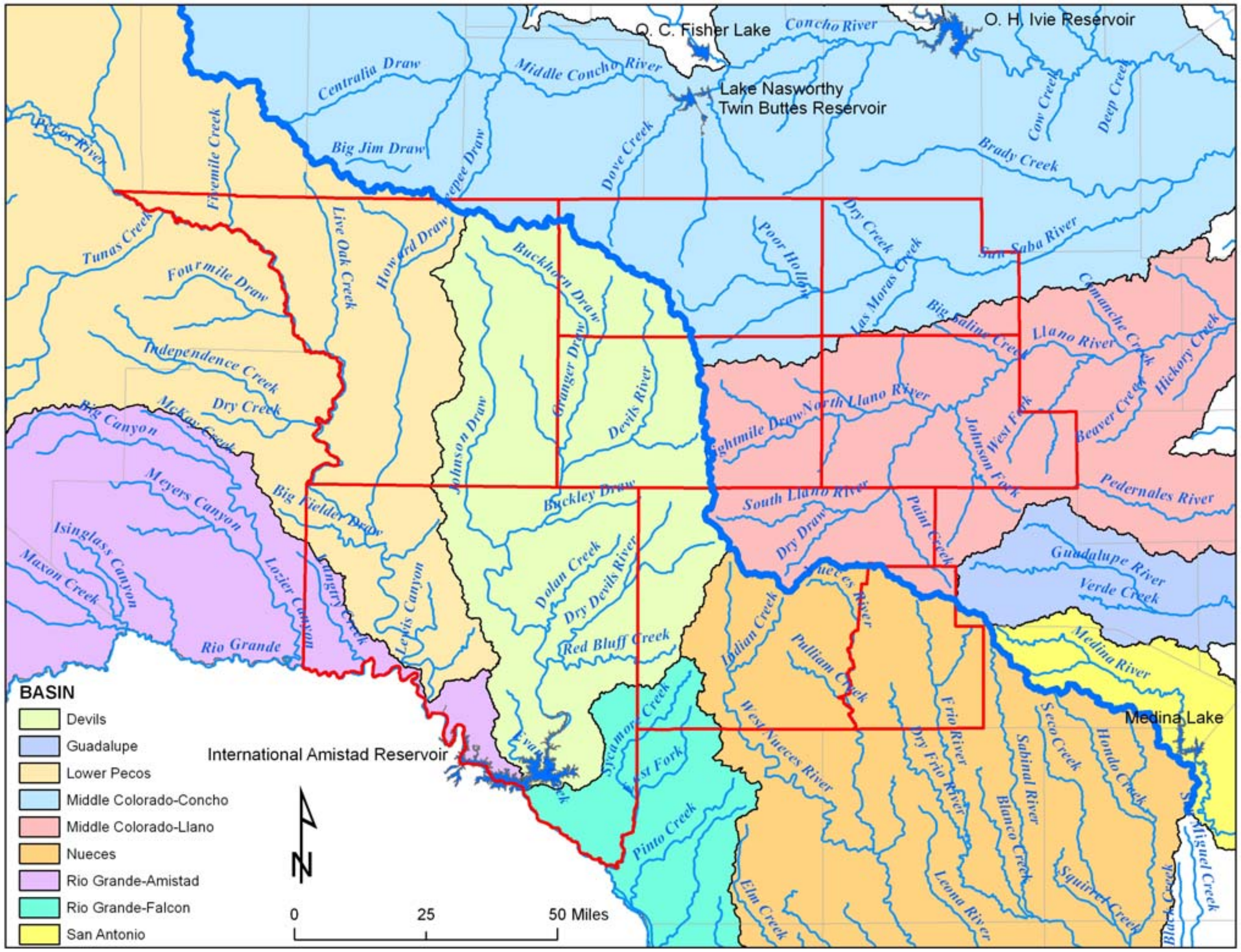

Figure 5. Map of the major rivers and streams and the watershed basins of the major rivers of the study area. The blue line denotes the watershed divide between the Rio Grande on the southwest and the Colorado River on the northeast.

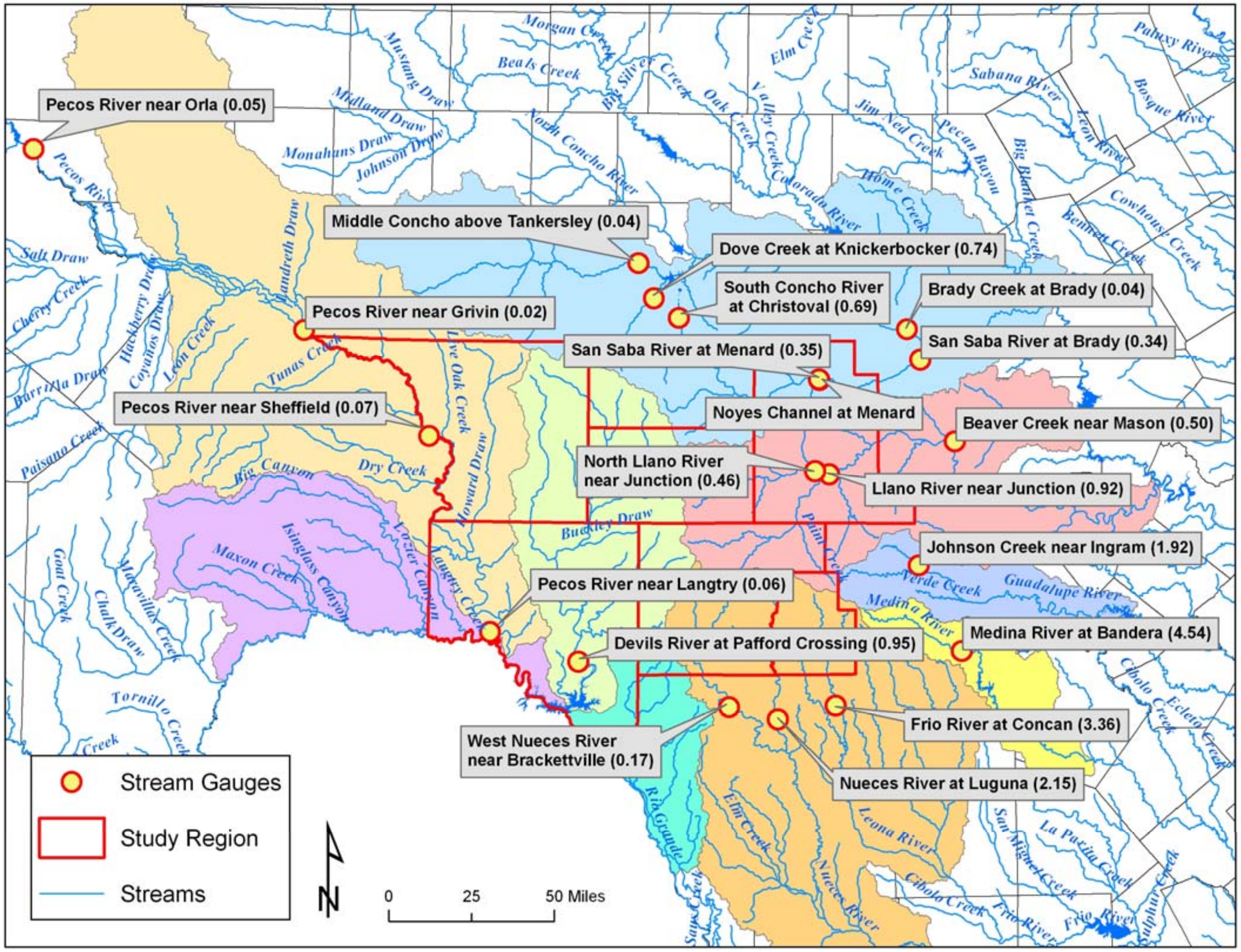

Figure 6. Locations of the U.S. Geological Survey gauging stations in and near the study area. Numbers in parentheses denote recharge rates in inches/year calculated using river discharge rates and corrected for base flow.

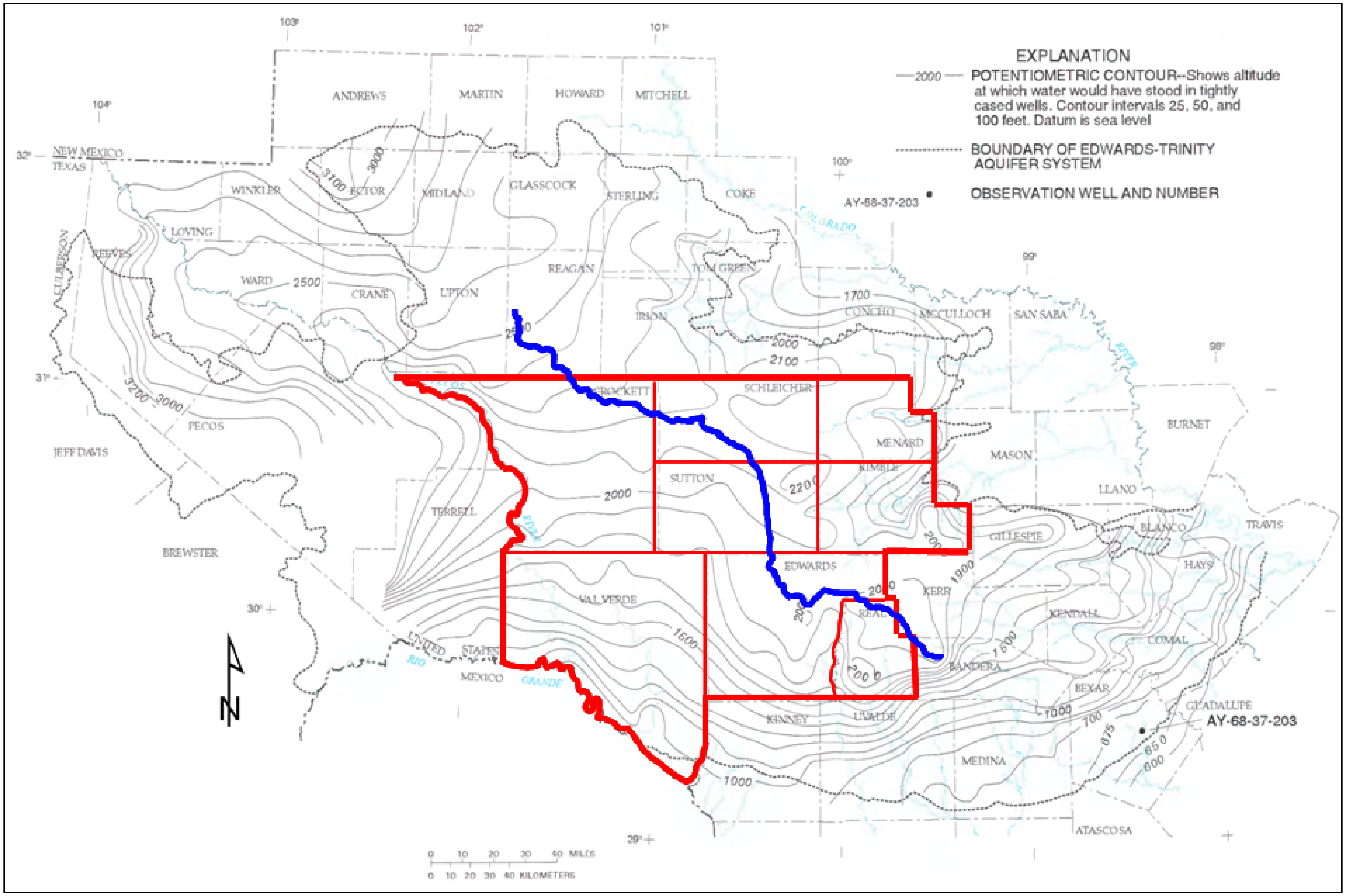

Figure 7. Contour map of the potentiometric surface of the study area. Taken from Barker and Ardis (1996). The blue line denotes the watershed divide between the Rio Grande on the southwest and the Colorado River on the northeast.

Figure 8. Map of the major springs of the study area.

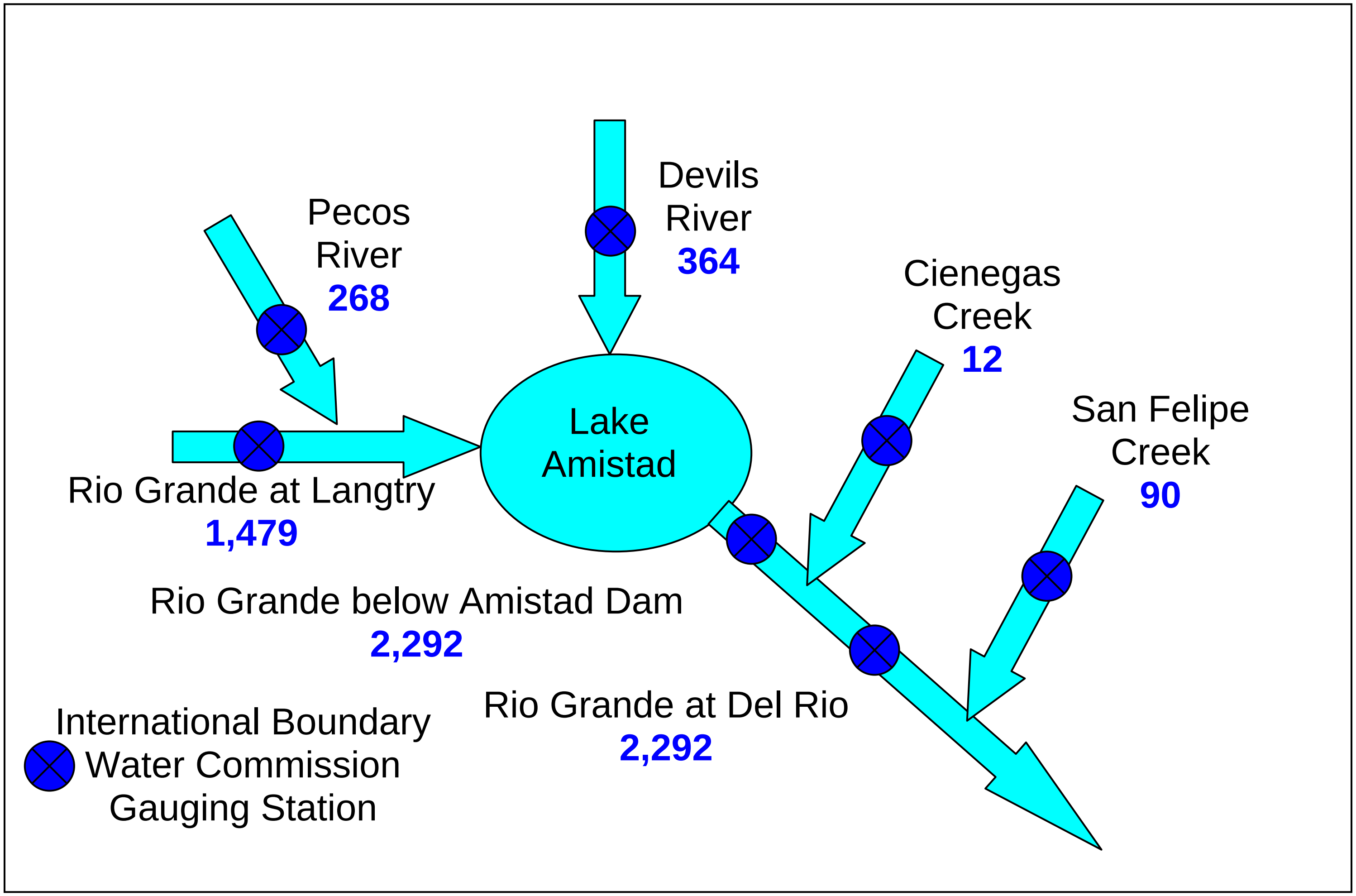

Figure 9. Schematic of the water budget for Amistad Reservoir. Blue numbers denote average annual discharge measurements (cfs). Data are from the International Boundary and Water Commission website [http://www.ibwc.state.gov/Water_Data/rio_grande_ WF.html#Stream].

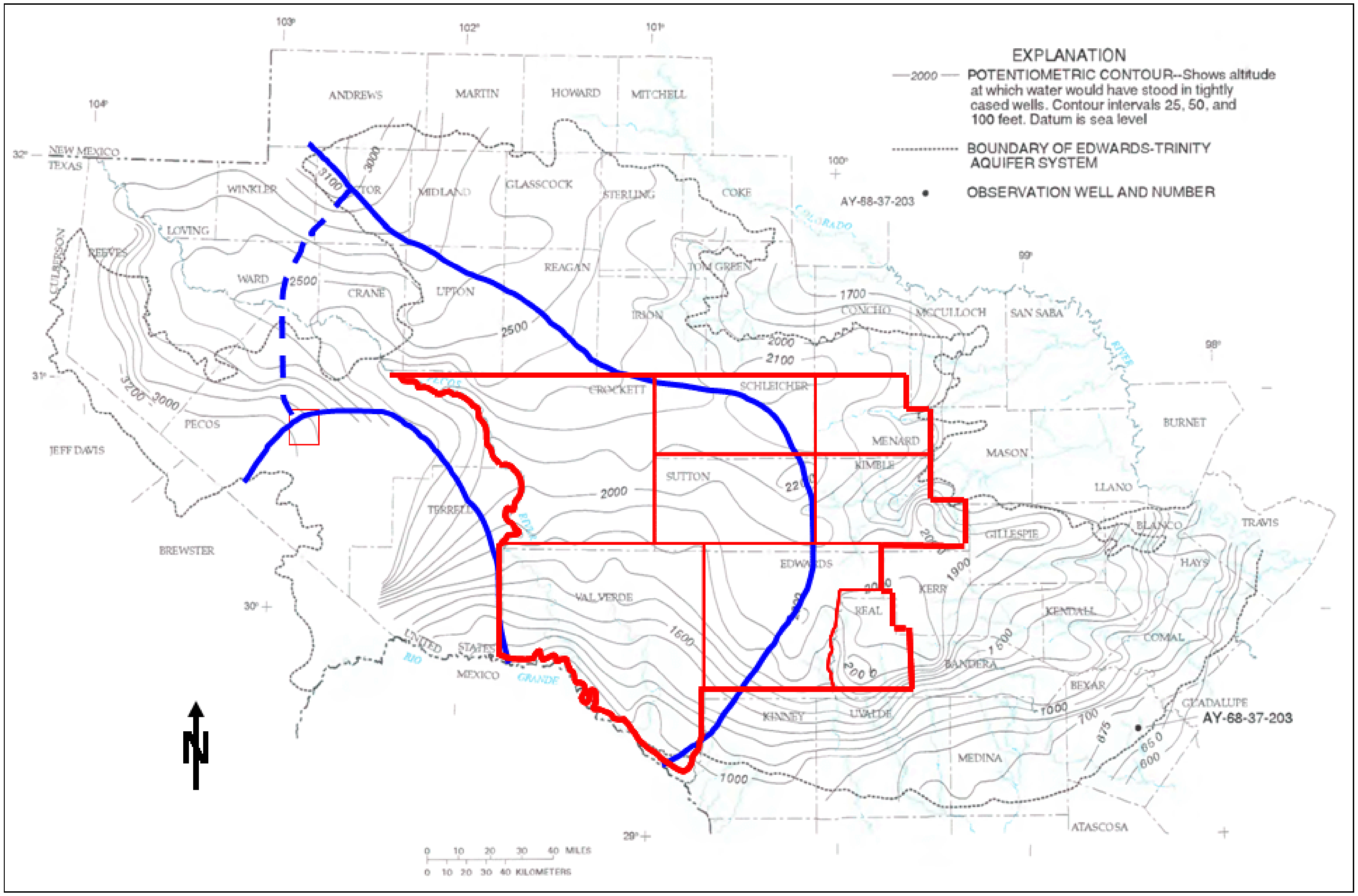

Figure 10. Extent of the groundwater catchment area that discharges into the Rio Grande in Val Verde County. Blue line delineates Edwards-Trinity Aquifer groundwater catchment area that discharges to the Rio Grande in Val Verde County. Base map from Barker and Ardis (1996).

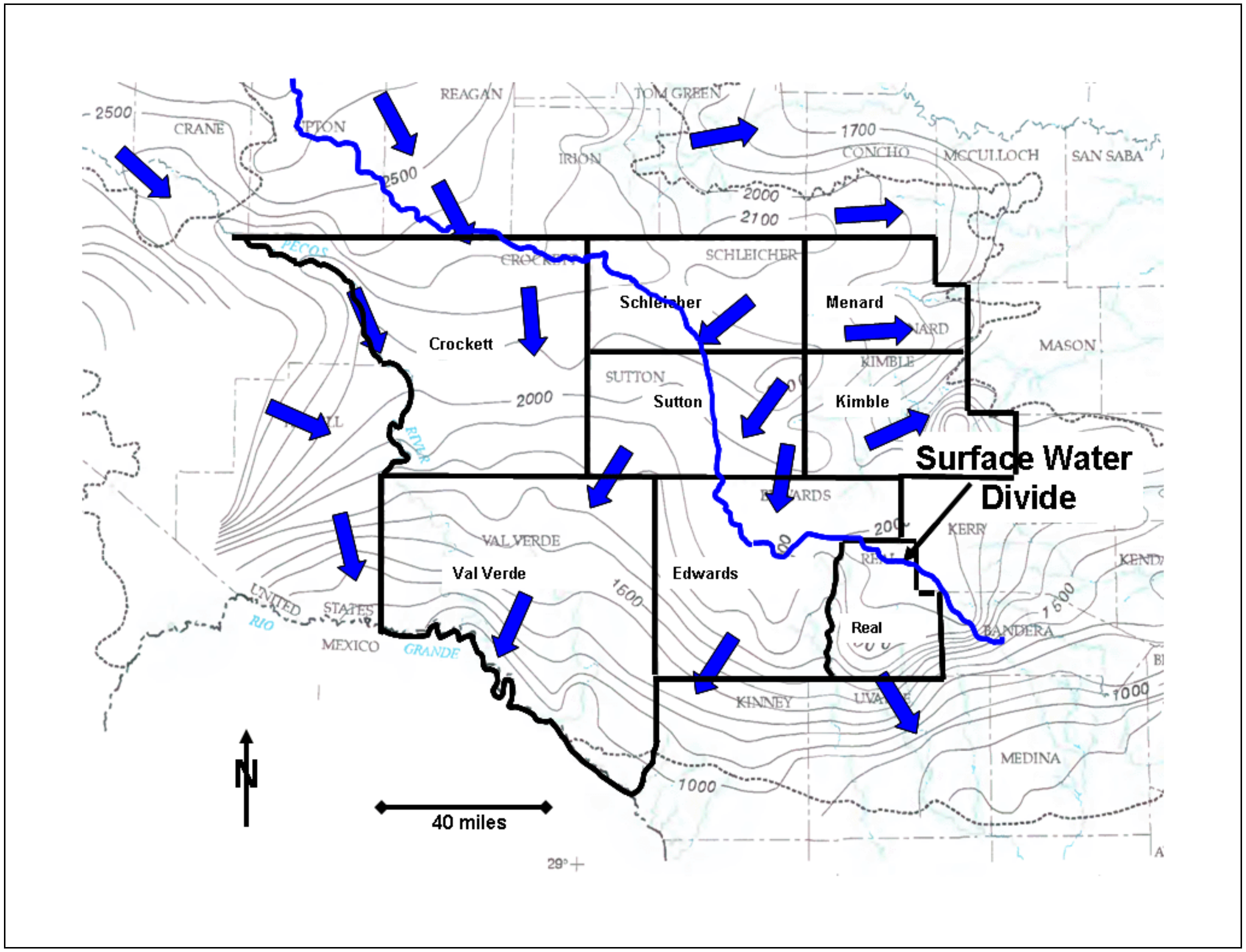

Figure 11. Map of the Rio Grande-Colorado River surface-water divide overlying the groundwater poteniometric surface. Blue arrows are added to denote the direction of groundwater flow based on the assumption of porous media flow. Base map is from Barker and Ardis (1996).

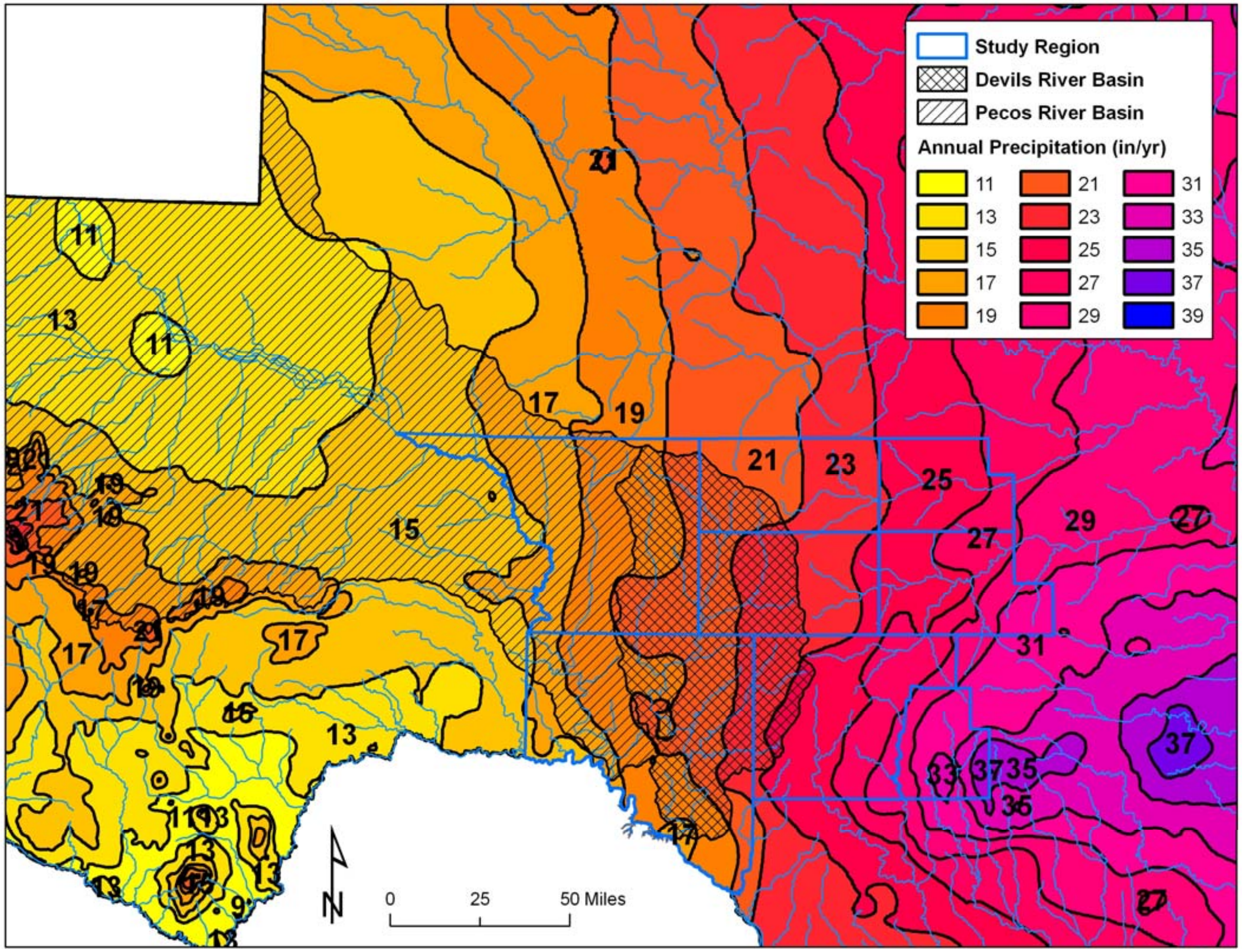

Figure 12. Map showing average annual precipitation (inch/year) for the study area.

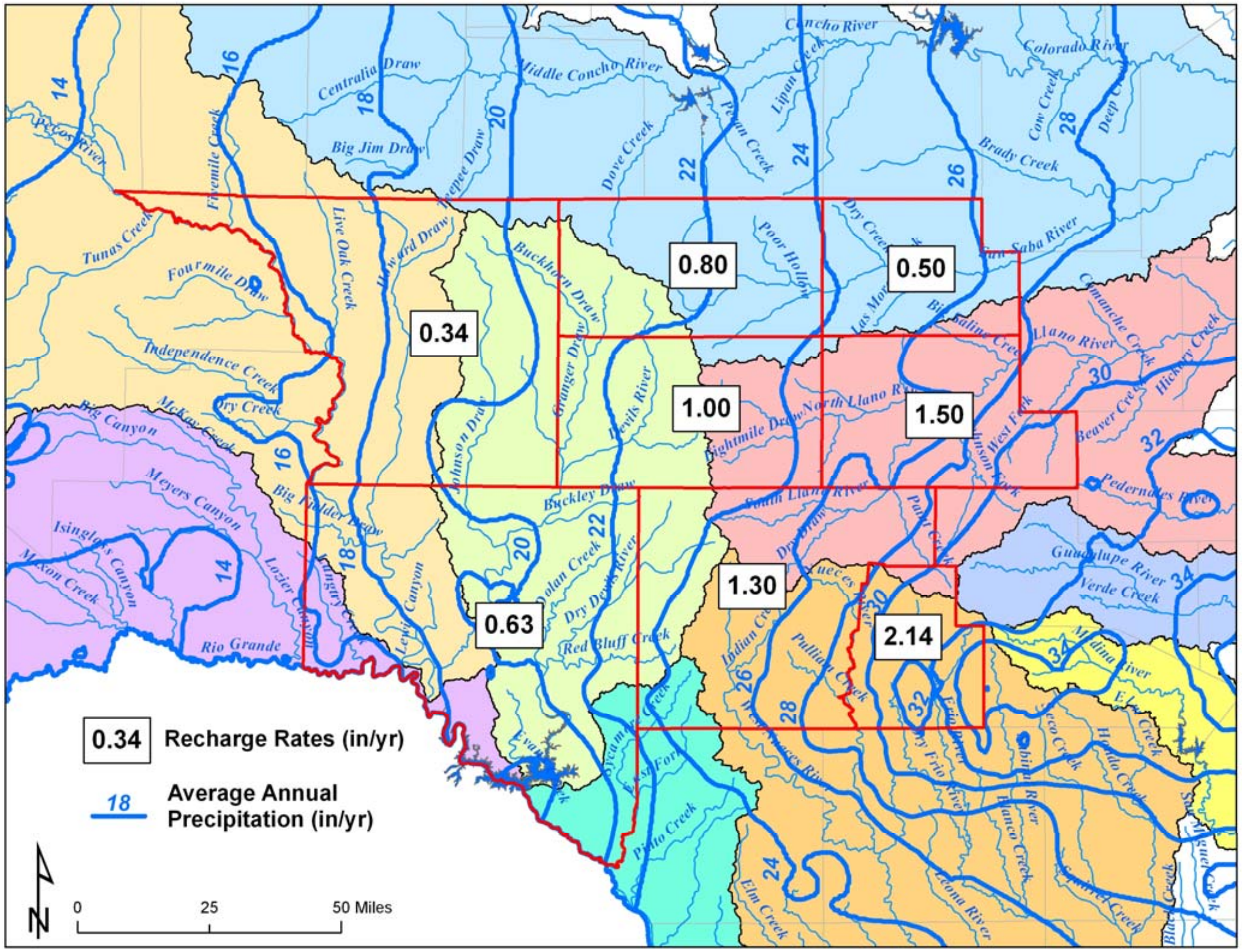

Figure 13. Recharge rates (inch/year) calculated for river watershed basins. Blue lines denote contours for average annual precipitation (inch/year).

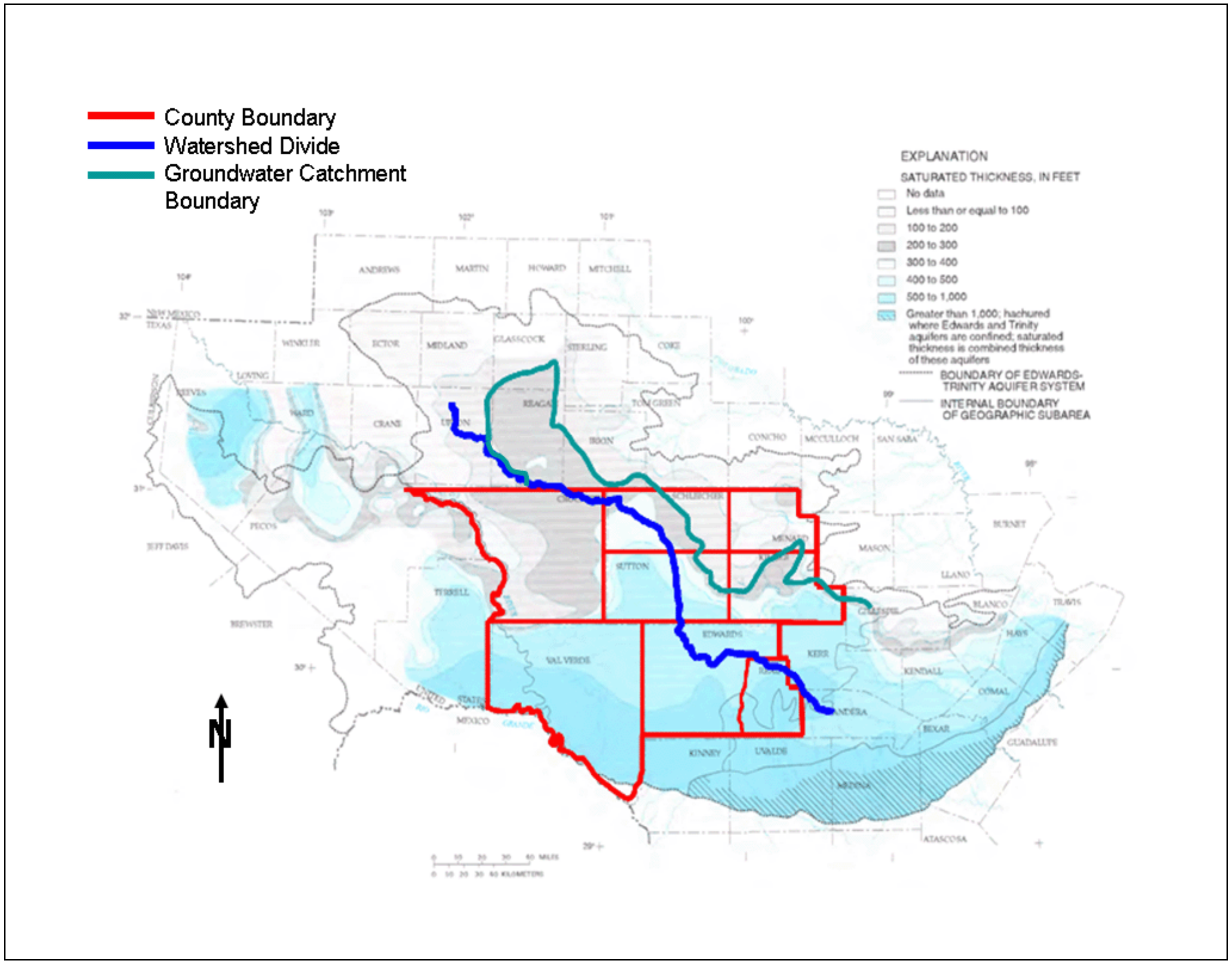

Figure 14. Contour map of the saturated thickness of the Edwards-Trinity Aquifer with the surface-water divide separating the Rio Grande watershed from the Colorado River watershed (blue line) and the extent of groundwater piracy estimated using the 200-ft saturated thickness contour of the Edwards-Trinity Aquifer (green line).

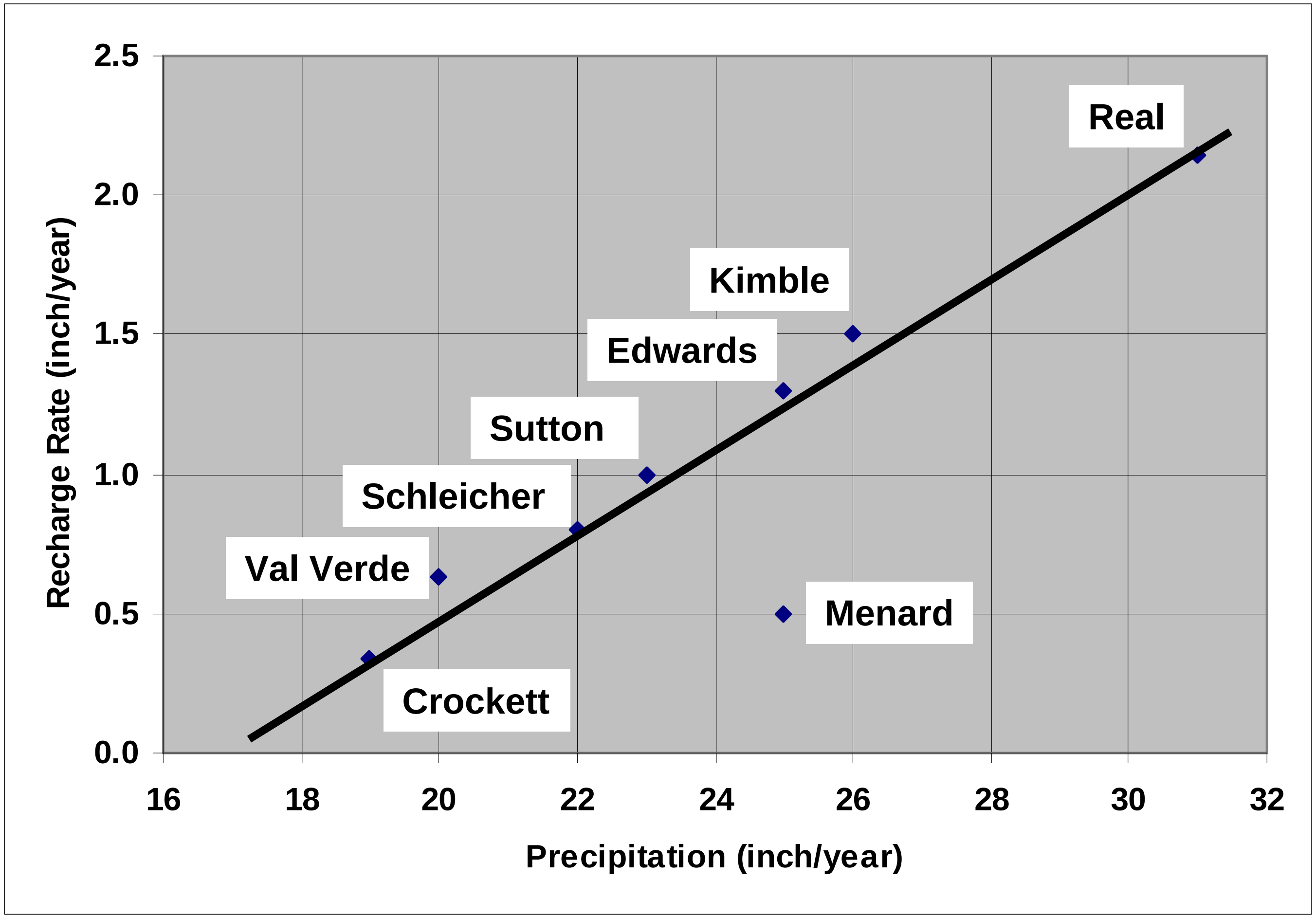

Figure 15. Graph of calculated recharge versus annual average precipitation for the eight counties in the study area. The black line is a linear approximation of the relationship between precipitation and recharge, excluding the outlier data point for Menard County.

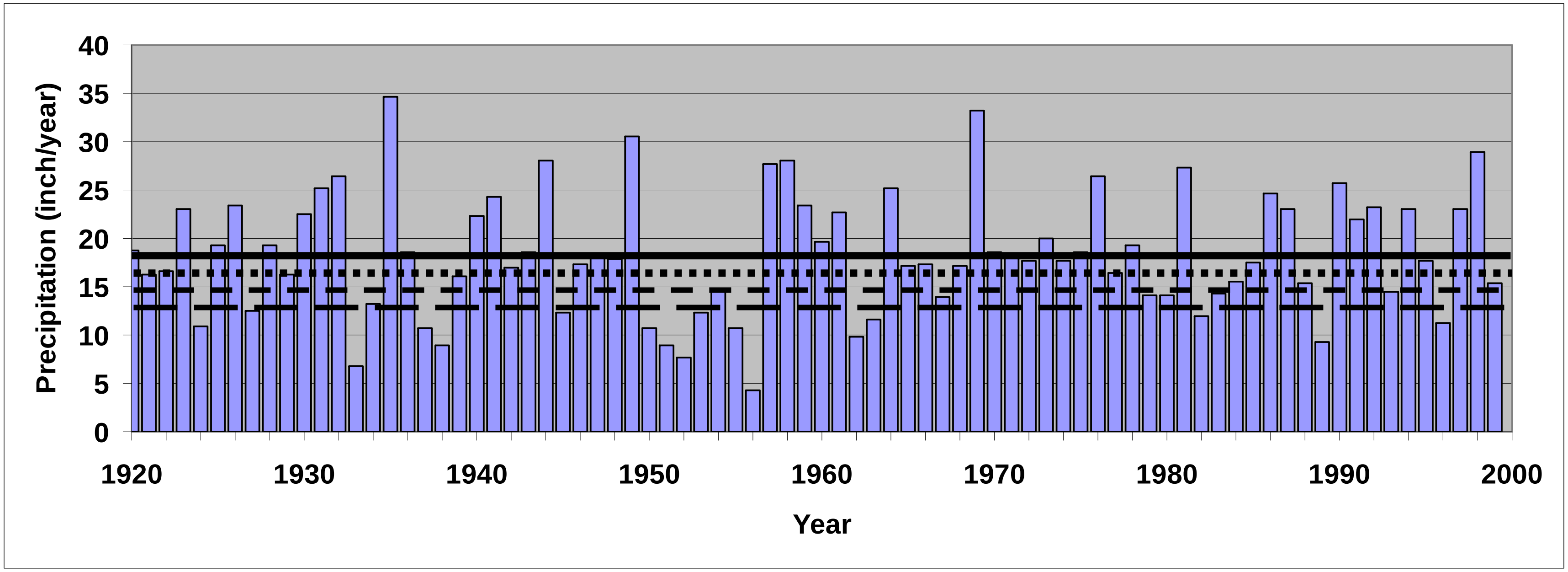

Figure 16. Annual precipitation measured at Del Rio by the National Weather Service. The top heavy line denotes the average annual precipitation of 18.43 inches. The dotted, short-dashed, and long-dashed lines below the solid line denote 90, 80, and 70 percent of average annual precipitation which equate with 16.59, 14.74, and 12.90 inches, respectively.

Table 1. River gauging stations operated by the International Boundary and Water Commission. Average river discharge data were extracted from the International Boundary and Water Commission website: http://www.ibwc.state.gov/Water_Data/histflo1.htm, on March 13, 2010.

Location	**Initial Gauge Measurement (month/date/year)**	**Discharge (cfs)**	**Discharge (acre-ft/year)**
Pinto Creek	11/22/1928	21	15,203
Devils River near Pafford Crossing	1/1/1960	364	263,525
Pecos River near Langtry	3/1/1965	268	197,024
Cienagas Creek	3/1/1965	11.95	8,651
Cantu Spring	3/1/1961	5.75	4,163
San Felipe Creek	9/1/1931	89.98	65,143
San Felipe Springs	2/1/1921	116.4	84,270
Rio Grande at Eagle Pass	1/1/1965	1,534	1,110,570
Rio Grande at Quemado	1/1/1965	1,534	1,110,570
Rio Grande below Amistad Dam	9/1/1954	2,292	1,659,340
Rio Grande at Del Rio	1/1/1968	2,292	1,659,340
Rio Grande at Foster Ranch	1/1/1968	1,479	1,070,750

Table 2. List of U.S. Geological Survey river gauging stations used in the water budget analysis. Adjusted discharge rates have been corrected for baseflow.

Station Number	**River**	**County**	**Latitude**	**Longitude**	**Drainage Area (acre)**	**Gauging Start Date (month/year)**	**Gross Discharge (inch/year)**	**Adjusted Discharge (inch/year)**
08190000	Nueces River at Laguna	Uvalde	29°25'42	99°59'49	471,680	10/1923	3.03	2.15
08190500	West Nueces River near Brackettville	Kinney	29°28'52"	100°14'21"	444,160	9/1939	0.67	0.17
08195000	Frio River at Concan	Uvalde	29°29'18"	99°42'16"	284,960	10/1923	4.45	3.36
08178880	Medina River at Bandera	Bandera	29°43'25	99°04'11	209,920	10/1982	6.77	4.54
08166000	Johnson Creek at Ingram	Kerr	30°06'00"	99°16'58"	72,960	10/1941	3.10	1.92
08145000	Brady Creek at Brady	McCulloch	31°08'17"	99°20'05"	376,320	6/1939	0.15	0.04
08144600	San Saba River near Brady	McCulloch	31°00'14"	99°16'07"	1,045,120	7/1979	0.59	0.34
08144500	San Saba River at Menard	Menard	30°55'08"	99°47'07"	721,920	10/1915	0.72	0.35
08150800	Beaver Creek near Mason	Mason	30°38'36"	99°05'44"	137,600	8/1963	1.20	0.50
08148500	North Llano River at Junction	Kimble	30°31'02"	99°48'21"	584,960	10/1915	1.00	0.46
08150000	Llano River at Junction	Kimble	30°30'15"	99°44'03"	1,183,360	10/1915	1.45	0.92
08128000	South Concho River at Christoval	Tom Green	31°11'13"	100°30'06"	226,560	3/1930	1.15	0.69
08130500	Dove Creek at Knickerbocker	Tom Green	31°16'26"	100°37'50"	139,520	10/1960	0.98	0.74

Station Number	River	County	Latitude	Longitude	Drainage Area (acre)	Gauging Start Date (month/year)	Gross Discharge (inch/year)	Adjusted Discharge (inch/year)
08128400	Middle Concho River at Tankersley	Irion	31°25'38"	100°42'39	714,240	4/1961	0.17	0.04
08449400	Devils River at Pafford Crossing	Val Verde	29°40'35"	101°00'00"	2,535,040	1/1960	1.25	0.95
08412500	Pecos River near Orla	Reeves	31°52'21"	103°49'52"	13,586,560	10/1937	0.08	0.05
08446500	Pecos River near Girvin	Pecos	31°06'47"	102°25'02"	18,918,400	9/1939	0.03	0.02
08447000	Pecos River near Sheffield	Pecos	30°39'34	101°46'11	20,384,000	10/1975	0.09	0.07
08447410	Pecos River near Langtry	Val Verde	N/A	N/A	28,352,000	1/1/1967	0.08	0.06

N/A – Data not Available

Table 3. List of major springs in the study area.

Name	County	Elevation (ft, msl)	Latitude	Longitude
Cedar Springs	Crockett	2014	30.509ºN	101.692ºW
Live Oak Spring	Crockett	2332	30.758ºN	101.692ºW
Big Paint Springs	Edwards	1998	30.275ºN	99.892ºW
Seven Hundred Springs	Edwards	1876	30.271ºN	99.926ºW
Tanner Springs	Edwards	1906	30.259ºN	99.942ºW
Christmas Canyon Spring	Kimble	2024	30.325ºN	99.925ºW
Coleman Springs	Kimble	1991	30.375ºN	99.909ºW
Gentry Springs	Kimble	2116	30.659ºN	99.925ºW
Headquarters Springs	Kimble	1988	30.375ºN	99.625ºW
Iona Springs	Kimble	2001	30.709ºN	99.692ºW
Scott Springs	Kimble	1899	30.625ºN	99.659ºW
Wilkinson Springs	Menard	2099	30.942ºN	99.892ºW
Government Springs (Main)	Schleicher	2102	30.842ºN	100.109ºW
Fort Terrett Spring	Sutton	2089	30.454ºN	100.192 ºW
Big Spring	Real	1893	29.844ºN	99.651ºW
Bee Cave Hollow Springs	Real	1958	29.914ºN	99.784ºW
Chittim Springs	Real	2260	29.959ºN	99.759ºW
Evans Springs	Real	1597	29.882ºN	99.814ºW
Leakey Springs	Real	1578	29.727ºN	99.754ºW
Morriss Spring	Real	1925	29.959ºN	99.959ºW
Old Faithful Spring	Real	1456	29.680ºN	100.014ºW
Pecan Springs	Real	2027	29.866ºN	99.919ºW
Cox Springs	Val Verde	1778	30.042ºN	101.542ºW
Dolan Springs	Val Verde	1351	29.897ºN	100.984ºW
Finegan Springs	Val Verde	1532	29.909ºN	101.009ºW
Gillis Springs	Val Verde	1401	29.725ºN	101.042ºW
Goodenough Springs	Val Verde	1109	29.542ºN	101.259ºW
Hudspeth Springs	Val Verde	1673	30.025ºN	101.175ºW
Huffstutler Springs	Val Verde	1489	29.959ºN	101.142ºW
Juno Springs	Val Verde	2017	30.159ºN	101.125ºW
McKee Springs	Val Verde	912	29.425ºN	101.042ºW
Pecan Springs	Val Verde	N/A	30.05ºN	101.17ºW
San Felipe Springs	Val Verde	N/A	29.367ºN	100.883ºW
Tardy Springs	Val Verde	N/A	30.133ºN	101.533ºW
Slaughter Bend Springs	Val Verde	N/A	29.67ºN	100.94ºW
Cantu Spring	Val Verde	981	29.388ºN	100.933ºW
Howard Springs	Val Verde	1929	30.159ºN	101.542ºW
Dead Man Springs	Val Verde	1394	29.792ºN	101.359ºW

N/A – Data Not Available

Table 4. Baseflow fraction of river discharge. Discharge hydrograph recession separation was calculated using BASEFLOW.

Station Number	**Station Name**	**Time Period**						**Number of Days**	**Baseflow Fraction**	**Time Weighted Baseflow Fraction**
		Initial			**End**					
		year	**month**	**day**	**year**	**month**	**day**			
8150800	Beaver Creek at Mason	1963	8	1	2010	5	12	17,087	0.42	0.42
8145000	Brady Creek at Brady	1939	6	1	1986	9	30	17,289	0.28	0.29
8145000	Brady Creek at Brady	2001	4	26	2010	5	12	3,304	0.32	
8449400	Devils River Pafford Crossing	1960	1	1	2009	11	30	18,232	0.76	0.76
8130500	Dove Creek at Knickerbocker	1960	10	1	1996	5	8	13,004	0.69	0.76
8130500	Dove Creek at Knickerbocker	1998	12	30	2010	5	12	4,152	0.97	
8195000	Frio River at Concan	1923	10	26	1929	9	30	2,167	0.81	0.75
8195000	Frio River at Concan	1930	10	1	2010	5	12	29,079	0.75	
8166000	Johnson Creek at Ingram	1941	9	24	1959	11	30	6,642	0.69	0.62
8166000	Johnson Creek at Ingram	1961	10	1	1993	9	30	11,688	0.65	
8166000	Johnson Creek at Ingram	1999	4	19	2010	5	12	4,042	0.41	
8150000	Llano River at Junction	1915	10	1	1993	5	10	28,347	0.63	0.64
8150000	Llano River at Junction	1997	10	1	2010	5	12	4,607	0.67	
8128500	Middle Concho at Tankersley	1930	3	1	1961	3	31	11,354	0.21	0.21

Station	Station	Time Period						Number	Baseflow	Time
8178880	Medina River at Bandera	1982	10	1	2010	5	12	10,086	0.68	0.68
8148500	North Llano River at Junction	1915	10	1	1977	10	26	22,672	0.47	0.46
8148500	North Llano River at Junction	2001	6	13	2010	5	12	3,256	0.36	
8144000	Noyes Channel at Menard	1924	4	1	1983	10	5	21,737	0.77	0.77
8190000	Nueces River at Laguna	1923	10	1	2010	5	12	31,636	0.71	0.71
8446500	Pecos River at Girvin	1939	9	1	2010	5	12	25,822	0.77	0.77
8412500	Pecos River at Orla	1937	6	1	2010	5	12	26,644	0.66	0.66
8447410	Pecos River at Langtry	1967	7	1	2009	11	30	15,494	0.74	0.74
8447000	Pecos River at Sheffield	1921	10	1	1925	4	30	1,308	0.75	0.79
8447000	Pecos River at Sheffield	1939	10	1	1949	9	30	3,653	0.77	
8447000	Pecos River at Sheffield	2007	7	13	2010	5	12	1,035	0.89	
8144600	San Saba River at Brady	1979	7	1	1993	9	30	5,206	0.57	0.58
8144600	San Saba River at Brady	1997	10	1	2010	5	12	4,607	0.6	
8144500	San Saba River at Menard	1915	10	1	1993	9	30	28,490	0.45	0.48
8144500	San Saba River at Menard	1997	10	1	2010	5	12	4,607	0.66	

Station	Station	Time Period						Number	Baseflow	Time
8128000	South Concho River at Cristoval	1930	3	1	1995	9	30	23,955	0.59	0.60
8128000	South Concho River at Christoval	2001	5	1	2010	5	12	3,299	0.7	
8190500	West Nueces River at Brackettville	1939	9	28	1950	9	30	4,021	0.2	0.25
8190500	West Nueces River at Brackettville	1956	4	1	2010	5	12	19,765	0.26	

Table 5. Recharge rates calculated in this study compared with recharge rates for the Edwards-Trinity Aquifer GAM (GAM run 04-17) (Anaya , 2004).

	Crockett	Edwards	Kimble	Menard	Real	Schleicher	Sutton	Val Verde
Area (mi^2)	2,807	2,120	1,251	901	700	1,311	1,453	3,232
Area (acres)	1,796,480	1,356,800	800,640	576,640	448,000	839,040	929,920	2,068,480
Calculated recharge rate (inch/yr)	0.25	1.30	1.50	0.50	2.14	0.80	1.00	0.63
Calculated recharge (acre-ft/yr)	37,427	146,987	100,080	24,027	79,893	55,936	77,493	108,595
2004 GAM Recharge (inch/yr)	0.31	0.85	0.50	0.49	0.88	0.34	0.37	0.65
2004 GAM Recharge (acre-ft/yr)	45,700	96,000	32,300	22,800	32,700	23,800	28,900	99,900

Table 6. Interdependency of water resource management by counties in the study area.

	Significantly Impacted by Upgradient Counties	**Moderately Impacted by Upgradient Counties**	**Significantly Impacts Down Gradient Counties**	**Moderately Impacts Down Gradient Counties**
Crockett	Pecos, Reeves	-	Val Verde	Sutton
Edwards	Sutton	Kimble, Schleicher	Kinney	-
Kimble	Edwards, Sutton	Menard	Edwards, Mason	-
Menard	Schleicher	-	McCulloch	-
Real	-	Kerr, Kimble	Uvalde	Sutton
Schleicher	Menard	Tom Green	-	Tom Green
Sutton	Schleicher	-	Edwards, Val Verde	Crockett
Val Verde	Crockett, Pecos	Terrell, Reeves	-	-

Table 7. Prediction of recharge for each county based on the precipitation and recharge correlation calculated for the study area. Recharge rate is expressed in inch/year and recharge is expressed in acre-feet/year.

	Crockett	Edwards	Kimble	Menard	Real	Schleicher	Sutton	Val Verde
Area (acres)	1,796,480	1,356,800	800,640	576,640	448,000	839,040	929,920	2,068,480
Calculated Recharge rate	0.34	1.3	1.5	0.5	2.14	0.8	1.0	0.63
Calculated Recharge	50,900	146,987	100,080	24,027	79,893	55,936	77,493	108,595
Predicted Recharge Rate	0.375	1.275	1.425	1.275	2.175	0.825	0.975	0.525
Predicted Recharge	56,140	144,160	95,076	61,268	81,200	57,684	75,556	90,496
Recharge rate at 90% Precipitation	0.09	0.9	1.035	0.9	1.71	0.495	0.63	0.225
Recharge at 90% Precipitation	13,474	101,760	69,055	43,248	63,840	34,610	48,821	38,784
Recharge rate at 80% Precipitation	0	0.525	0.645	0.525	1.245	0.165	0.285	0
Recharge at 80% Precipitation	0	59,360	43,034	25,228	46,480	11,537	22,086	0
Recharge rate at 70% Precipitation	0	0.15	0.255	0.15	0.78	0	0	0
Recharge at 70% Precipitation	0	1,837	2,127	300	5,193	0	0	0

Table 8. 2007 Texas State Water Plan Groundwater Availability (acre-feet/year) (Region F and Region J Water Planning Groups water supply analysis, accessed Texas Water Development Board website on May 15, 2010).

County	Basin	TA2010	TA2020	TA2030	TA2040	TA2050	TA2060	Methodology
Crockett	Colorado	636	636	636	636	636	636	50% of recharge
Crockett	Rio Grande	24,824	24,824	24,824	24,824	24,824	24,824	50% of recharge
Kimble	Colorado	23,965	23,965	23,965	23,965	23,965	23,965	50% of recharge
Menard	Colorado	19,000	19,000	19,000	19,000	19,000	19,000	Menard County UWD pumping cap
Schleicher	Colorado	12,204	12,204	12,204	12,204	12,204	12,204	50% of recharge
Schleicher	Rio Grande	3,960	3,960	3,960	3,960	3,960	3,960	50% of recharge
Sutton	Colorado	9,349	9,349	9,349	9,349	9,349	9,349	50% of recharge
Sutton	Rio Grande	11,426	11,426	11,426	11,426	11,426	11,426	50% of recharge
Edwards	Colorado	2,610	2,610	2,610	2,610	2,610	2,610	Edwards-Trinity Plateau Aquifer GAM
Edwards	Nueces	3,480	3,480	3,480	3,480	3,480	3,480	Edwards-Trinity Plateau Aquifer GAM
Edwards	Rio Grande	2,609	2,609	2,609	2,609	2,609	2,609	Edwards-Trinity Plateau Aquifer GAM
Real	Colorado	200	200	200	200	200	200	Edwards-Trinity Plateau Aquifer GAM
Real	Nueces	5,537	5,537	5,537	5,537	5,537	5,537	Edwards-Trinity Plateau Aquifer GAM
Val Verde	Rio Grande	49,607	49,607	49,607	49,607	49,607	49,607	Edwards-Trinity Plateau Aquifer GAM

Table 9. Comparison of calculated recharge, recharge predicted at 90, 80, and 70 percent of average precipitation, recharge values assigned to the 2004 Edwards-Trinity Aquifer GAM, groundwater availability documented in the 2007 Texas State Water Plan, and two potential sets of sustainable yield for use in assigning the 2010 Desired Future Conditions. All values are in acre-feet/year.

	Crockett	Edwards	Kimble	Menard	Real	Schleicher	Sutton	Val Verde
Calculated Recharge	56,140	144,160	95,076	61,268	81,200	57,684	75,556	90,496
Predicted recharge at 90% precipitation	13,474	101,760	69,055	43,248	63,840	34,610	48,821	38,784
Predicted recharge at 80% precipitation	0	59,360	43,034	25,228	46,480	11,537	22,086	0
Predicted recharge at 70% precipitation	0	1,837	2,127	300	5,193	0	0	0
2004 GAM recharge	45,700	96,000	32,300	22,800	32,700	23,800	28,900	99,900
2007 Texas State Water Plan	25,460	8,669	23,965	19,000	5,737	16,164	20,775	49,607
Yield for 2010 DFC - Plan A	14,000	21,600	23,750	15,300	12,200	14,400	18,900	22,500
Yield for 2010 DFC - Plan B	11,200	14,400	19,000	12,200	8,120	11,500	15,100	9,000

Plan A

- Crockett and Val Verde counties are most vulnerable to drought. Set their sustainable yield at 25 percent of average recharge.

Table 9 (continued). Comparison of calculated recharge, recharge predicted at 90, 80, and 70 percent of average precipitation, recharge values assigned to the 2004 Edwards-Trinity Aquifer GAM, groundwater availability documented in the 2007 Texas State Water Plan, and two potential sets of sustainable yield for use in assigning the 2010 Desired Future Conditions. All values are in acre-feet/year.

- Edwards and Real counties benefit from groundwater catchments that extend farther north than the area of their surface watersheds. It has to be recognized that these waters are the principal source of recharge to the western San Antonio segment to the Edwards Aquifer. Set their sustainable yield at 15 percent of average recharge.
- DFC yield for Kimble, Menard, Schleicher, and Sutton counties is set at 25 percent of calculated recharge.

Plan B (More conservative than Plan A)

- Crockett and Val Verde counties are most vulnerable to drought. Set their sustainable yield at 20 percent of average recharge.
- Edwards and Real counties benefit from groundwater catchments that extend farther north than the area of their surface watersheds. It has to be recognized that these waters are the principal source of recharge to the western San Antonio segment to the Edwards Aquifer. Set their sustainable yield at 10 percent of average recharge.
- DFC yield for Kimble, Menard, Schleicher, and Sutton counties is set at 20 percent of calculated recharge.

Appendix A

Bibliography of Documents Related to the Western Edwards-Trinity Aquifer

Alexander, W.H. Jr. and J.H. Patman. 1969. Ground-water resources of Kimble County, Texas. Texas Water Development Board. Report 95. 99 p.

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