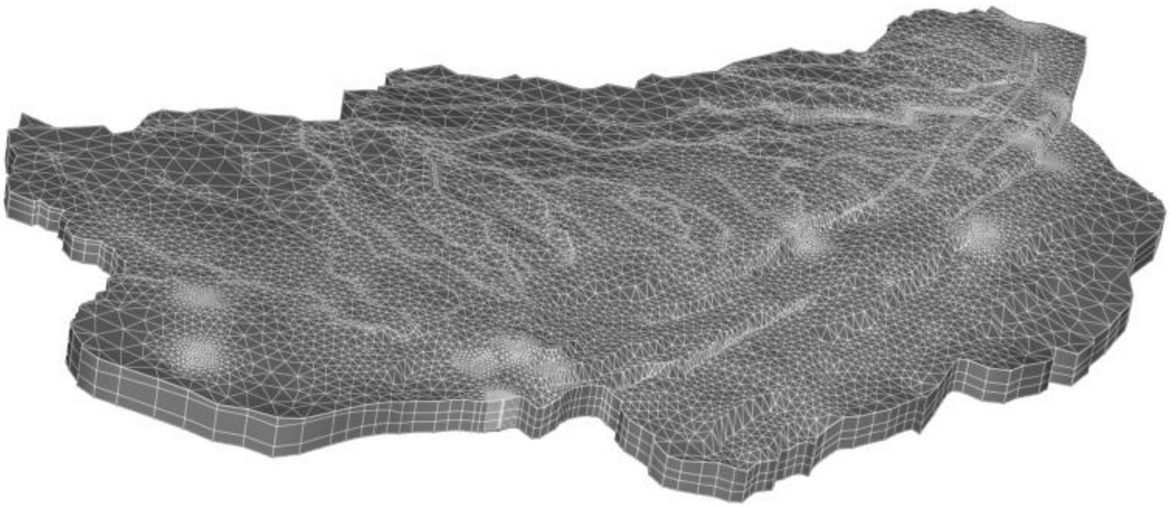
SwRI® Project No. 20-17344

DEVELOPMENT OF A FINITE-ELEMENT METHOD GROUNDWATER FLOW MODEL FOR THE EDWARDS AQUIFER

Final Report



Prepared for

Edwards Aquifer Authority

Prepared by

S. Beth Fratesi, Ronald T. Green, F. Paul Bertetti,
Ronald N. McGinnis, Nathaniel Toll, Hakan Başağaoğlu, and Leslie Gergen
Geosciences and Engineering Division
Southwest Research Institute®

James R. Winterle
Edwards Aquifer Authority

Yoar Cabeza and Jesus Carrera
Institute of Environmental Assessment and Water Research
Spanish Council of Scientific Research in Barcelona, Spain

February 2015

Executive Summary

The Edwards Aquifer Authority relies heavily on groundwater flow models to characterize groundwater flow conditions in the San Antonio segment of the Edwards Aquifer and to serve as the basis for predicting impacts of water-resource management scenarios. Currently, the Edwards Aquifer Authority uses a MODFLOW finite-difference model developed in 2004 by the U.S. Geological Survey to perform these water-resource management analyses. There are recognized limitations and shortcomings in the 2004 MODFLOW model, including questions about the conceptual model on which the numerical model is based.

The Edwards Aquifer Authority undertook two initiatives to reduce uncertainty in models used to perform water-resource management analyses. One initiative was undertaken to advance the 2004 MODFLOW model through a series of recalibration exercises. The second initiative was to develop a second groundwater-flow model that is conceptually independent of the 2004 MODFLOW model. The objective of a second model is not to replace the 2004 MODFLOW model; but to provide an independent numerical tool against which to compare the 2004 MODFLOW model predictions. This report documents the development of the alternative numerical groundwater model of the Edwards Aquifer for the Edwards Aquifer Authority.

Attributes of the alternative model that set it conceptually independent from the 2004 MODFLOW model are:

- Inclusion of the Contributing Zone
- Recharge is calculated directly from precipitation and is not prescribed at the upgradient side of the Recharge Zone
- Western boundary is refined to better define the Kinney Pool
- The Contributing and Recharge Zones are characterized by three layers
- Distinct conduits are included in the Confined Zone
- The alternative model employs a finite-element formulation instead of the finite-difference formulation used in the 2004 MODFLOW model

The fundamental difference between the two models is the manner in which recharge is input in the alternative model. By including recharge as a direct calculation from precipitation over both the Contributing and Recharge Zones, the hydraulic lag between the time of precipitation and the time at which a hydraulic signal is transmitted through the aquifer is captured in the alternative model. Conversely, recharge is a calibrated input parameter in the 2004 MODFLOW model. Although other factors set the alternative model apart from the 2004 MODFLOW model, it is the manner in which recharge is incorporated that establishes the alternative model as conceptually independent from the 2004 MODFLOW model.

Development of the alternative model was considered complete when: (i) the model was tested against the conceptual model (i.e., model cross-checked for internal consistency and consistency with observations); (ii) the conceptual model was determined to be physically reasonable and

representative of the model domain; and (iii) steady-state and transient model predictions of the calibration targets were within the model goals.

The model domain was specified to allow for model boundaries to be no-flow, to the degree possible, with the exception of springs. The model domain is specified to include all groundwater and surface-water basins that contribute water to the San Antonio segment of the Edwards Aquifer. By definition, this domain includes the entire Contributing Zone of the Edwards Aquifer. Designation of no-flow boundary conditions minimizes the uncertainty inherent with determining recharge and discharge associated with specified flux and head dependent boundaries.

A hydrostratigraphic model was developed to establish the boundaries, define distribution of layer thicknesses, represent layers that are offset and locally missing due to slip on the most influential faults, and provide a high-resolution, data- and observation-constrained stratigraphic framework to support the alternative model. This hydrostratigraphic framework model refines major areas of uncertainty in the existing groundwater model, such as the Recharge Zone northern boundary condition, the influence of the western portion of the Edwards Aquifer, and the effect of deformation features (faults, fractures, and layer dip) on groundwater flow.

The major river basins in the Contributing Zone were characterized as hydraulically independent. By doing this, surface water and groundwater flow from each basin to the adjoining basin was minimized. This characterization honored the conceptual model developed for the Contributing Zone in which surface water and groundwater flow in each basin was mostly restricted to each basin. This conceptualization allowed the precipitation/recharge model to be calibrated for each basin (i.e., the recharge model for each basin had its own coefficients).

Comparison of the model against the conceptual model in terms of internal consistency and consistency with observations is discussed in detail in the report. Similarly, the conceptual model developed as part of this numerical model was evaluated to ensure it is physically reasonable and representative of the model domain. Subdomains of the San Antonio segment of the Edwards Aquifer are individually evaluated to ensure the conceptual model is internally consistent, physically reasonable, and representative of the model (sub) domain. Subdomains included Kinney Pool, Uvalde Pool, western San Antonio Pool (Dry Frio, Frio, and Sabinal River watersheds), Medina River watershed, interbasin area between Medina River and Cibolo Creek Basins, Cibolo Creek watershed, Guadalupe River watershed, and Blanco River watershed. To the degree possible, the water budget of each subdomain is explored and evaluated. In those cases where quantitative evaluation is possible, volumetric rates of recharge/discharge of the conceptual model are evaluated and compared with physical assessment and analysis. Elsewhere, the appropriateness of the conceptual model is qualitatively evaluated.

Simulated discharge at 9 springs and hydraulic head at 102 monitoring wells were compared with observations and measurements. Index wells J-17 (Bexar County), J-27 (Uvalde County), Comal Springs, and San Marcos Springs were the most prominent data sources to match in reaching the calibration goals. The calibration period was 11 years, from 2001 to 2011. This calibration period was chosen because it includes two very wet years, 2004 and 2007, and four very dry years, 2006, 2008, 2009, and 2011. Additional justification for this period for calibration was that pumping data and NEXRAD (Next-Generation Radar data provided by the National Weather Service) precipitation data are available, compared with the drought of the 1950s during which pumping and precipitation data would need to be estimated. In addition, water-budget assessments derived from simulations performed with the alternative model were compared with similar assessments based on the conceptual model, U.S. Geological Survey calculations, and model results using Hydrologic Simulation Program FORTRAN.

The alternative model successfully replicated the general response of the Edwards Aquifer. Seven of 14 of the target goals were met by the alternative model. In comparison, the 2004 MODFLOW model met 3 of the 14 target goals. The inability of the alternative model to match high discharge at Comal and San Marcos Springs led to the greatest discrepancy between simulation results and the target goals. The alternative model was more successful in matching low discharge at the two springs. Matching low discharge is recognized to be more important than matching high discharge in model performance. Aside from this discrepancy, simulated heads and spring discharge are in general agreement with observations, as attested by model performance statistics. Agreement between simulations and observations is encouraging when compared with existing models, given that the alternative model has the additional constraint imposed by the recharge model and a decreased degree of freedom due to the fact that recharge is calculated solely on precipitation and is not a specified, calibrated input variable. This feature in the alternative model clearly sets it apart from the 2004 MODFLOW model and substantiates its status as a conceptually independent model. These attributes of the alternative model qualify it for future use to provide the Edwards Aquifer Authority with an independent numerical tool to evaluate aquifer responses to different spatial and temporal patterns of precipitation, recharge, and pumping.

Table of Contents

List of Figures

List of Tables

Acknowledgements

The authors wish to thank Dr. Gary Walter and Dr. David Ferrill for their reviews and insight on the study and the ensuing report. The assistance of Violeta Gonzales and Lucy Gutierrez in report preparation is greatly appreciated. Review comments by and discussions with the Edwards Aquifer Authority's Groundwater Review Advisory Panel members, Mr. James Beach, Dr. William Hutchison, and Dr. Martin Saar were extremely informative during the development of the model and are greatly appreciated. The Edwards Aquifer Authority groundwater modeling staff, Dr. Angang Lui and Mr. Nedko Troshanov, provided significant assistance with their review comments and through discussions to discuss comparisons between the finite-element model and the current version of the 2004 MODFLOW model.

1. Introduction

The Edwards Aquifer Authority (the EAA) relies heavily on groundwater flow models to characterize groundwater flow conditions in the San Antonio segment of the Edwards Aquifer (hereafter referred to as the Edwards Aquifer) and to serve as the basis for predicting impacts of water-resource management scenarios (Figure 1-1). Currently, the EAA uses a finite-difference model developed in 2004 by the U.S. Geological Survey using MODFLOW (Lindgren et al., 2004) to perform these water-resource management analyses. There are recognized limitations and shortcomings in the 2004 MODFLOW model, including questions about the conceptual model on which the numerical model is based. Major conceptualization limitations in the 2004 MODFLOW model were associated with how the western aquifer, the northern boundary, conduit versus diffuse flow, and the recharge zone were incorporated into or accommodated by the model. In addition, there was uncertainty in how and how much recharge is input into the model. For the most part, these limitations can be attributed to unknowns and uncertainties due to lack of data and inadequate conceptual models of the Edwards Aquifer.

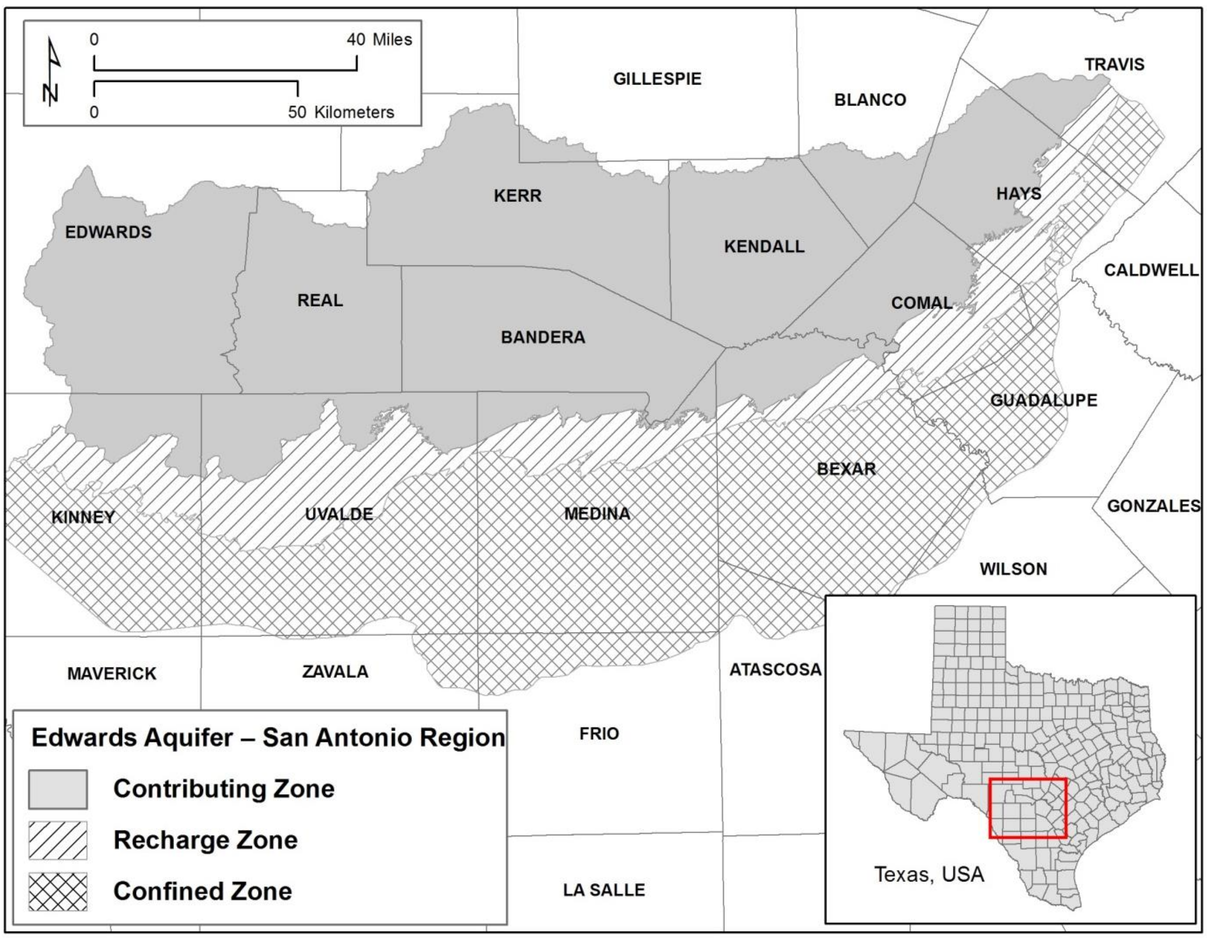


Figure 1-1: Location map of the study area.

The EAA undertook two initiatives to reduce uncertainty in models used to perform water-resource management analyses. One initiative was undertaken to advance the 2004 MODFLOW model through a series of recalibration exercises. The second initiative was to develop a second groundwater-flow model that is conceptually independent of the 2004 MODFLOW model. The objective of a second model is not to replace the 2004 MODFLOW model; but to provide an independent numerical tool against which to compare the 2004 model predictions. The EAA requested that the new alternative model be based on finite-element formulation as part of its desire that the model be fundamentally independent from the existing 2004 finite-difference model (Edwards Aquifer Authority Request for Proposals Letter dated May 2, 2011). This report documents the development of the alternative numerical groundwater model of the Edwards Aquifer for the EAA.

1.1 Scope of Work

The scope of the project was to develop an alternative model of the Edwards Aquifer suitable for the following applications:

- Simulating critical period scenarios
- Simulating regional water-management schemes, including
  - Testing management solutions proposed for the Edwards Aquifer Recovery Implementation Program and the Habitat Conservation Plan
  - Analyzing potential artificial groundwater recharge at different location(s) of the model domain
  - Analyzing potential additional local or regional well pumping redistribution (transfers)
  - Analyzing potential well pumping restriction(s) at certain target(s) (head and/or springflow) conditions
  - Analyzing potential changes of regional groundwater recharge
- Assisting with defining groundwater protection zones (note: while the model can assist with defining groundwater protection zones, groundwater protection zone definition is not included in the scope of work)

The conceptual model for the Edwards Aquifer covers the following domain:

- The southern boundary is defined by an interpreted or assumed no-flow boundary at the 10,000 mg/L salinity surface. The potential impact for pumping of groundwater from aquifers with greater than 10,000 mg/L salinity is not within this scope of work.
- The western boundary is defined as the groundwater divide located between Mud Creek and Pinto Creek in Kinney County.
- The northern boundary is defined by the northernmost extent of the surface watersheds or groundwater basins (i.e., the northernmost boundary of these two is chosen where it is demonstrated that the surface watershed and groundwater basin boundaries are not coincident) that recharge the Edwards Aquifer from the north.
- The eastern boundary is defined as the groundwater divide between San Marcos Springs and Barton Springs.

The alternative model was required to have certain attributes so as to be useful as a water-resource management tool. These attributes include:

- The software used for the final model must be commercially available and designed to run on a Windows-based desktop computer.
- The timestep interval needs to be one month. This is dictated by pumping data that are reported on a monthly or annual interval.
- The desired model runtime needs to be less than 4 hours for a typical 50-year simulation (with monthly timesteps).

1.2 Conceptual Independence of the Model

The utility of the alternative model would be compromised if it were not sufficiently independent from the existing model. Attributes in the alternative model that are different from the 2004 MODFLOW model are:

- The Contributing Zone is explicitly included.
- Recharge is calculated directly from precipitation and is not prescribed at the upgradient side of the Recharge Zone.
- Western boundary is refined to better define the Kinney Pool.
- The Contributing and Recharge Zones are characterized by three layers.
- Distinct conduits are included in the Confined Zone.
- The alternative model incorporates a finite-element formulation, as opposed to the 2004 MODFLOW model, which uses a finite-difference formulation.

The fundamental difference between the two models is the manner in which recharge is input in the alternative model. By including recharge as a direct calculation from precipitation over both the Contributing and Recharge Zones, the hydraulic lag between the time of precipitation and the time at which a hydraulic signal is transmitted through the aquifer is captured in the alternative model. Conversely, recharge is a calibrated input parameter in the 2004 MODFLOW model. Although other factors set the alternative model apart from the 2004 MODFLOW model, it is the manner in which recharge is incorporated that establishes the alternative model as conceptually independent from the 2004 MODFLOW model.

1.3 Previous Investigations and Research

Previous studies provide the foundation for the investigation of the aquifers in the study area. Foremost are a series of county studies commissioned by the Texas Water Commission in cooperation with the U.S. Geological Survey. These studies include investigations of Kinney (Sayre, 1936; Sayre and Bennett, 1942; Bennett and Sayre, 1962), Uvalde (Welder and Reeves, 1962), Medina (Holt, 1956, 1959), Comal (Guyton, 1979), and Hays (DeCook, 1963) counties. Studies by Maclay and Small (1986), Maclay and Land (1988), Maclay (1995), and Groschen (1996) provide assessments of the Edwards Aquifer. These seminal reports provide comprehensive summaries of the understanding of the aquifer at the time of their publication. Recent investigations by LBG-Guyton Associates (2004), Otero (2007), and Johnson and Schindel (2008) improved the conceptualization of the Comal and San Marcos Springs area.

Early estimates of focused and distributed recharge to the Edwards Aquifer were predicated on an approach originally developed by Lowry (1955), advanced by Petitt and George (1956), and refined by Garza (1962, 1966). This approach was further refined by Puente (1975, 1976, 1978). The Puente approach was used for the next 25 years by the U.S. Geological Survey to estimate recharge of the Edwards Aquifer. The recharge analysis developed by Puente (1975, 1976, 1978) was modified in recent Edwards Aquifer recharge studies conducted by HDR Engineering (2002), LBG-Guyton Associates and Aqua Terra Consultants (2005), and Clear Creek Solutions, Inc. (2009, 2012, 2013).

Rose (1972) and Hovorka et al. (1993, 1996) provided descriptions of the depositional environment of Edwards Aquifer strata in the study area, particularly in terms of how the depositional environment affects the hydraulic properties of the Edwards Aquifer. Some hypotheses suggested that relatively high density of igneous intrusions in the western portion of the study area (Rose, 1972; Ewing, 2004) may affect the groundwater flow regime. Significant analyses of the hydraulic properties have been performed (Small and Maclay, 1982; Mace, 2000; Mace and Hovorka, 2000; Hovorka et al., 1998) leading to a geostatistical assessment of the transmissivity of the San Antonio segment of the Edwards Aquifer by Painter et al. (2002, 2007). The prospect for conduit development in the Edwards Aquifer was investigated by Halihan et al., (2000), Worthington (2004), and Hovorka et al. (2004).

Rose (1972) provided a regional synthesis of the stratigraphy of the Edwards Aquifer. Analysis by Small (1986) provided the structural geologic framework of the Edwards Aquifer. Recent studies by Clark and Small (1997), Clark (2003), Collins (1993, 2000), Collins and Hovorka (1997), Blome et al. (2004, 2005a,b, 2007), Ferrill et al. (2003, 2004, 2005, 2008, 2011), and Ferrill and Morris (2008) provided insight on structural geology in the Edwards Aquifer.

The EAA commissioned and conducted a number of focused studies to address data gaps and conceptual uncertainties that were identified at the conclusion of the 2004 MODFLOW model development. These studies led to reconceptualization of the model domain. An investigation of the hydrogeology of Kinney and Uvalde counties provided insight on the western boundary of the model domain (Green et al., 2006). Evaluation of the role of rivers and streams where they exit the Recharge Zone provided insight on discharge from the Edwards Aquifer associated with the Nueces River (Green et al., 2008b, 2009a), Leona River (Green, 2003; Green et al., 2008b), Frio River (Green et al., 2009b), streams in Medina County (Green et al., 2012b), and Medina River (Green et al., 2012b). Insight of the structure and hydrogeology of the Comal and San Marcos Spring areas were provided by an investigation by LBG-Guyton Associates, (2004), Otero (2007), Johnson and Schindel (2008), Hauwert (2011), and Musgrove and Crow (2012).

The hydraulic interaction between the Trinity and Edwards Aquifers has been recognized as a significant source of uncertainty in characterizing the Edwards Aquifer. Recent work has provided insight on resolving the uncertainty. Multilevel well monitoring by Smith and Hunt (2009, 2010, 2011) provided insight on the hydraulic properties and relationships between the units that comprise the Edwards and Trinity Formations. Tracer tests at Panther Springs Creek and near Comal Springs have provided insight into the role of faults as barriers or avenues of groundwater flow in the Balcones Fault Zone (Johnson et al., 2009, 2010, 2012). Gain-loss studies upgradient from the Edwards Aquifer Recharge Zone (Green et al., 2011) highlighted the importance of recharge in the Contributing Zone. Gary et al. (2011) recognized the spatial variability in the hydraulic relationship between the Edwards and Trinity Aquifers, particularly across the 180-mile span of the model domain. Clark et al. (2009) developed high resolution geologic maps of the Glen Rose Formation in Bexar County; however, this level of mapping is not yet available across the entire Contributing Zone of the model domain.

1.4 Previous Models

Klemt et al. (1979) developed the first comprehensive groundwater model of the Edwards Aquifer using the U.S. Geological Survey simulator GWSIM, Groundwater Simulation Program, based on the groundwater simulation program developed by Prickett and Lonnquist (1971) (Figure 1.4-1).

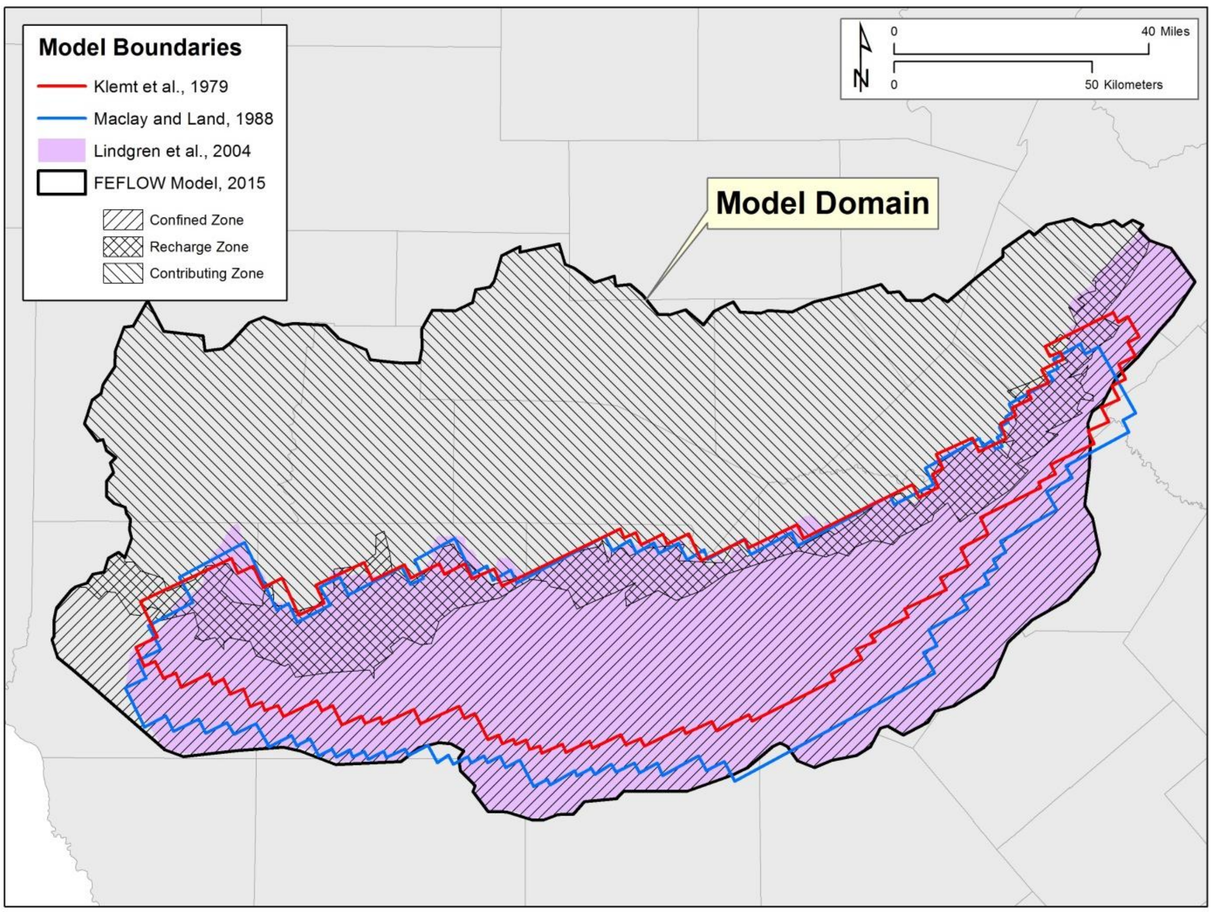


Figure 1.4-1. Map illustrating the domains of the Klemt et al. (1979), Maclay and Land (1988), Lindgren et al. (2004), and FEFLOW models.

The Klemt et al. (1979) model domain extended from a groundwater divide located near Brackettville in Kinney County on the west to a groundwater divide located near the Blanco River in Hays County on the east (Figure 1.4-1). The northern boundary was the upgradient edge of the Edwards Aquifer Recharge Zone and the southern boundary was designated as the downdip edge of freshwater in the Edwards Aquifer, which was defined as less than 1,000 mg/l dissolved solids. Thorkildsen and McElhaney (1992) reevaluated the Klemt et al. (1979) model using refined water levels and spring flows. The model domain remained the same as the Klemt et al. (1979) model.

Maclay and Land (1988) developed an independent groundwater flow model that relied on a different groundwater flow simulator (Trescott et al., 1976). The southern boundary of their model domain was essentially the same as that designated in the Klemt et al. (1979) model (Figure 1.4-1); however, the northern boundary was modified based on a refined interpretation of the Recharge Zone (Puente, 1978). In particular, the northern limit of the Recharge Zone was extended to include more area in eastern Kinney County and most of Uvalde County. The remainder of the Recharge Zone in Bexar, Comal, and Hays counties remained the same as that defined by Klemt et al. (1979). A regional-scale finite-element model that included the Edwards, Trinity, and Edwards-Trinity Aquifers was developed to provide a large-scale assessment of the three aquifers (Kuniansky, 1994; Kuniansky and Holligan, 1995).

The EAA commissioned a groundwater flow model of the Edwards Aquifer that was completed in 2004 (Lindgren et al., 2004). The northern boundary of the model domain was essentially the same as that defined by Maclay and Land (1988). The location of the southern boundary at the fresh water/saline water interface was revised from 1,000 mg/l to 10,000 mg/l, thereby extending the model domain farther south (Figure 1.4-1). MODFLOW (Harbaugh and McDonald, 1996; Harbaugh et al., 2000) was the flow simulator.

Fundamental similarities among the Klemt et al. (1979), Maclay and Land (1988), and Lindgren et al. (2004) models were treatment of the northern model boundary and how recharge was incorporated. None of these models included the Edwards Aquifer Contributing Zone. In all three models, recharge from the Contributing Zone was input into the upstream boundary of the Edwards Aquifer Recharge Zone as a spatially and temporally varied flow. It was common to treat the recharge rate as a variable, which was adjusted during calibration. Recharge rates were based on surface-flow measurements and analyses provided by the U.S. Geological Survey.

The 2004 MODFLOW model (Lindgren et al., 2004) incorporated focused high-transmissivity zones to represent conduit flow, as conceptualized in the Edwards Aquifer by Hovorka et al. (2004) and Worthington (2004). The 2004 version of the MODFLOW model was used for a series of assessments of recharge and recirculation scenarios (Todd Engineers, 2004, 2005, 2008). Lindgren (2006) modified the 2004 MODFLOW model by replacing the high transmissivity representations of conduits with a diffuse flow conceptualization. The 2006 version of the MODFLOW model was used for additional simulations of the Edwards Aquifer (Lindgren et al., 2009).The EAA continues to refine the 2004 MODFLOW version by recalibrating the model with recent data.

1.5 Model Objectives

An objective of the model was to incorporate conceptual model enhancements and refinements that have become available subsequent to development of the 2004 MODFLOW groundwater availability model (Lindgren et al., 2004). Motivation for this reconceptualization was to make the alternative groundwater availability model as defensible as possible. Following is a summary of the key documents used to refine the conceptual model used in development of the alternative groundwater flow model. Recent studies in geologic structure that were incorporated in development of the hydrostratigraphic framework model include Clark (2003), Blome et al. (2004, 2005a,b, 2007), Ferrill et al. (2003, 2004, 2005, 2008, 2011), Ewing (2004, 2005), Clark et al. (2006, 2009, 2013), and Ferrill and Morris (2008).

Insights on the hydraulic relationship between the Trinity and Edwards Aquifers included Green et al. (2011), Smith and Hunt (2009, 2010, 2011), Johnson and Schindel (2009, 2010, 2012), Schindel and Johnson (2011), Gary et al. (2011), and Wong et al. (2013). Refinements in the boundary conditions and hydrogeology of the western portion of the Edwards Aquifer were drawn from Green et al. (2006). Evaluation of the hydraulic relationship of rivers and streams and the Edwards Aquifer was documented in studies by Green (2003), Green and Bertetti (2010) and Green et al. (2008a, 2009a,b, 2012b, 2014). The effect of faulting on groundwater flow, particularly in Medina County, was evaluated based on work by Clark and Journey (2006) and Green et al. (2012b). Improved characterization of the Comal, Hueco, and San Marcos springs area is documented by LBG-Guyton Associates (2004), Otero (2007), Johnson and Schindel (2008), Hauwert (2011), and Musgrove and Crow (2012).

Development of the alternative model had the following objectives: (i) the model was tested against the conceptual model (i.e., model cross-checked for internal consistency and consistency with observations); (ii) the conceptual model was determined to be physically reasonable and representative of the model domain; and (iii) steady-state and transient model predictions were within the model goals. Model goals were a topic of the EAA’s Groundwater Model Review Panel meetings. Model goals were identified during these discussions as desirable targets.

Comparison of the alternative model with the conceptual model is discussed in detail in Chapter 2. Similarly, the conceptual model developed as part of this numerical model was evaluated to ensure it is physically reasonable and representative of the model domain. This evaluation also is addressed as part of Chapter 2. Subdomains of the Edwards Aquifer are individually evaluated to ensure the conceptual model is internally consistent, physically reasonable, and representative of the model (sub) domain. To the degree possible, the water budget of each subdomain is explored and evaluated. In those cases where quantitative evaluation is possible, volumetric rates of recharge/discharge of the conceptual model are evaluated and compared with physical assessment and analysis. Elsewhere, the appropriateness of the conceptual model is qualitatively evaluated.

Development of the numerical model, including property value assignments and data input, is described in Chapter 3. Model output, including steady-state and transient model predictions, is included in Chapter 4. Also included in Chapter 4 is evaluation of model performance in terms of model predictions compared with calibration targets. Lastly, model limitations and recommended work to be done are described in Chapters 5 and 6, respectively.

2. Conceptualization of the Model Domain

2.1 Hydrologic Setting

The study area is located across the Balcones Fault Zone, which marks the transition between the Edwards Plateau region and the Gulf Coastal Plain (Rose, 1972) (Figure 2.1-1). The major depositional provinces of the Edwards Group are illustrated in Figure 2.1-2.

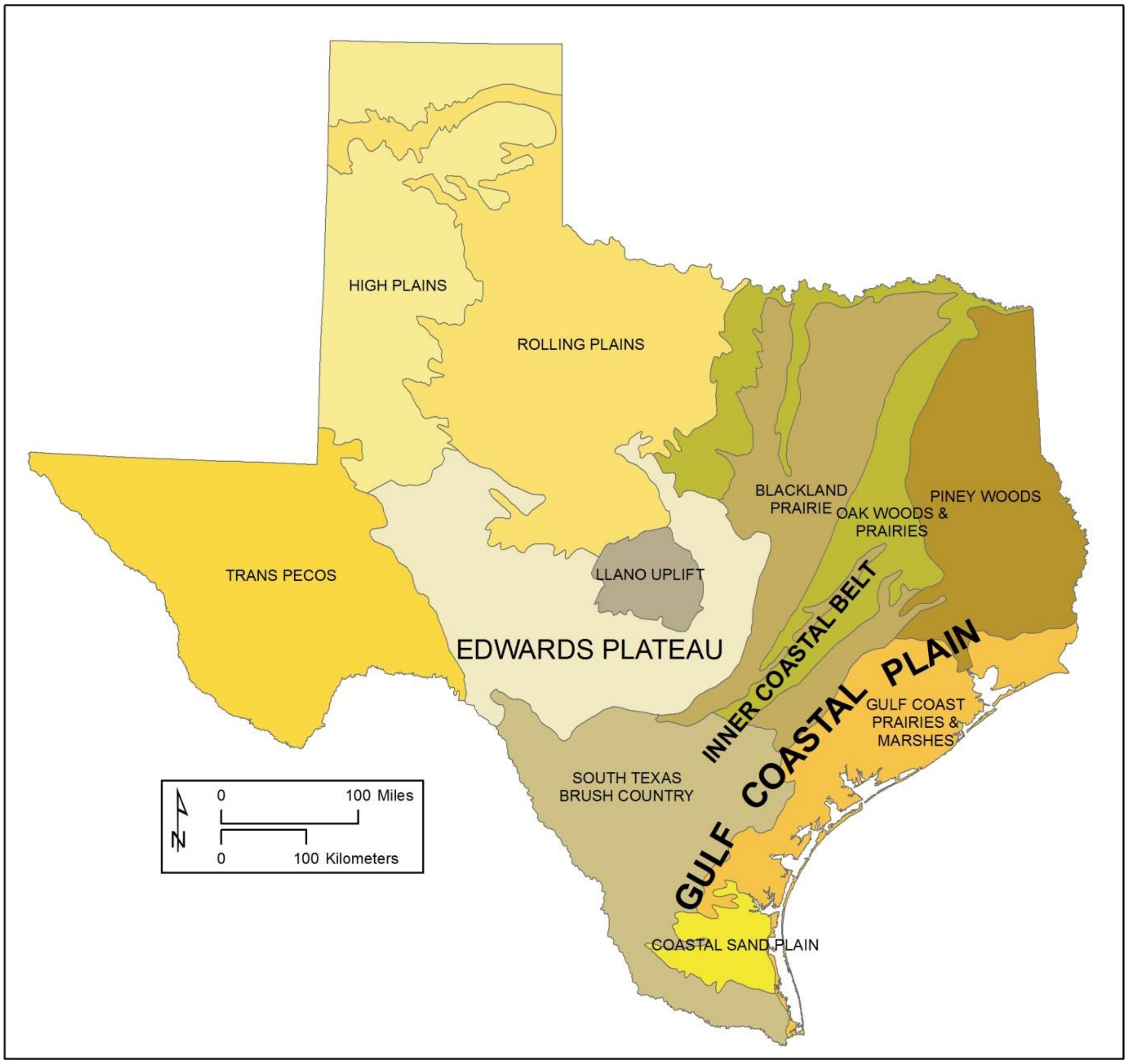


Figure 2.1-1. Major physiographic regions in Texas. Data from Texas Parks and Wildlife Department (http://tpwd.texas.gov/gis/data).

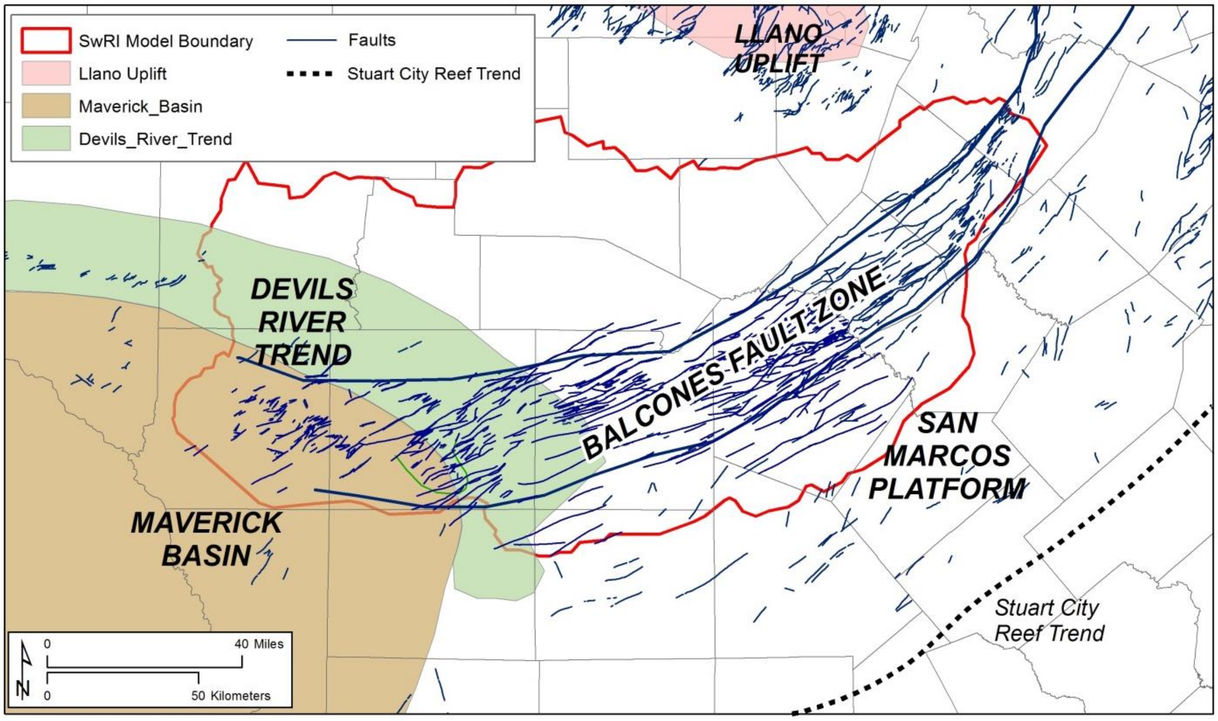


Figure 2.1-2. Major depositional provinces of the Edwards Group in the Edwards Aquifer region Locations of major features derived from Maclay and Land (1988). Fault data from Geologic Database of Texas (Pearson, 2007; http://tnris.org/data-catalog/geology/geologic-database-of-texas/).

To the north, the more massive and resistant carbonate members of the Edwards Group form the uplands of the Edwards Plateau. To the south, the Inner Coastal Belt of the Gulf Coastal Plain extends toward the Gulf of Mexico. The Inner Coastal Belt is mostly covered with younger alluvial materials that originate from the erosion of the Edwards Plateau with occasional outcrops of Upper Cretaceous Formations. The Inner Coastal Belt is characterized by black soils that extend discontinuously through the study domain south of the Balcones Fault Zone (Rose, 1972) (Figures 2.1-1 and 2.1-2).

Major drainage basins cross the area (Figure 2.1-3). From east to west across the northern extent of the Contributing Zone, dominant rivers within these drainage basins include the Blanco, Guadalupe, Cibolo, Medina, Sabinal, Frio-Dry Frio, and Nueces-West Nueces Rivers. There are additional watersheds in the south of the model domain that do not extend to the northern model boundary, including the Upper and Lower San Antonio River Basins located between the Cibolo Creek and Medina River Basins, and the Hondo Basin between the Medina and Upper Frio River Basins.

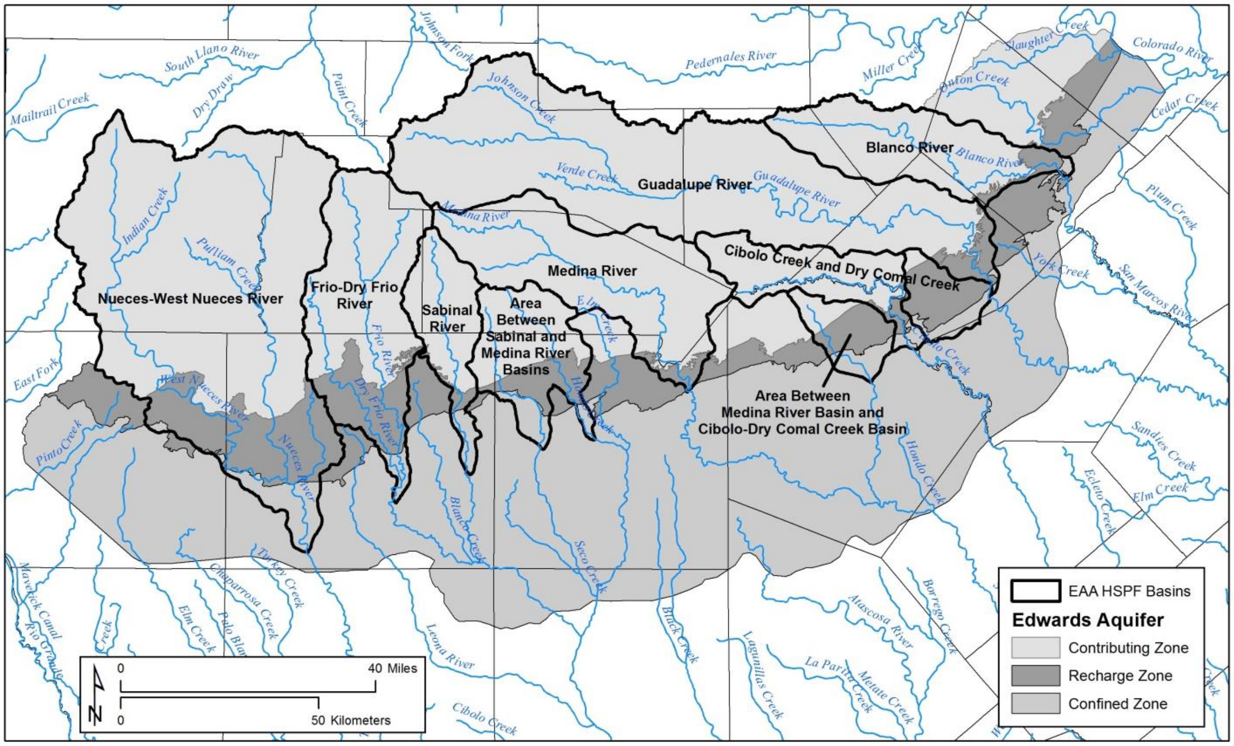


Figure 2.1-3. Major drainage basins in the study area.

The climate in the study area is described as subhumid. Average annual rainfall for the period 1950 to 2000 varies from 30.5 inch/yr in Hays, Blanco, Kendall, and Kerr counties in the east to 25.1 inch/yr in Real, Uvalde, and Edwards counties in the west (LBG-Guyton Associates and Aqua Terra Consultants, 2005) (see map of annual precipitation for 1960 to 1990 in Figure 2.1-4).

Surface-water flow in each of the major watersheds is dominated by the major river for which it is named. Each main river has a number of contributing tributaries, some of which are named and most are ephemeral. The topographic boundary between adjoining basins is typically distinct. Less apparent are the boundaries between the groundwater basins aligned with each surface watershed. Groundwater basin boundaries are typically assumed to align with surface watershed boundaries, unless site specific data on the extent of the groundwater basin are available and distinctions between the extents of the surface watersheds and the groundwater basins are noted. This generalization that the surface watershed is coincident with the groundwater basin is often known to fail, especially in karst terrains (Ford and Williams, 1989; White and White, 2001; White, 2006).

Rivers and streams in the model domain vary significantly, both in terms of physical attributes and in the surface-water features (gain-loss distribution) represented in the model. This variance in attributes has profound implications on how the Edwards Aquifer is recharged by the rivers as they traverse the Contributing and Recharge Zones.

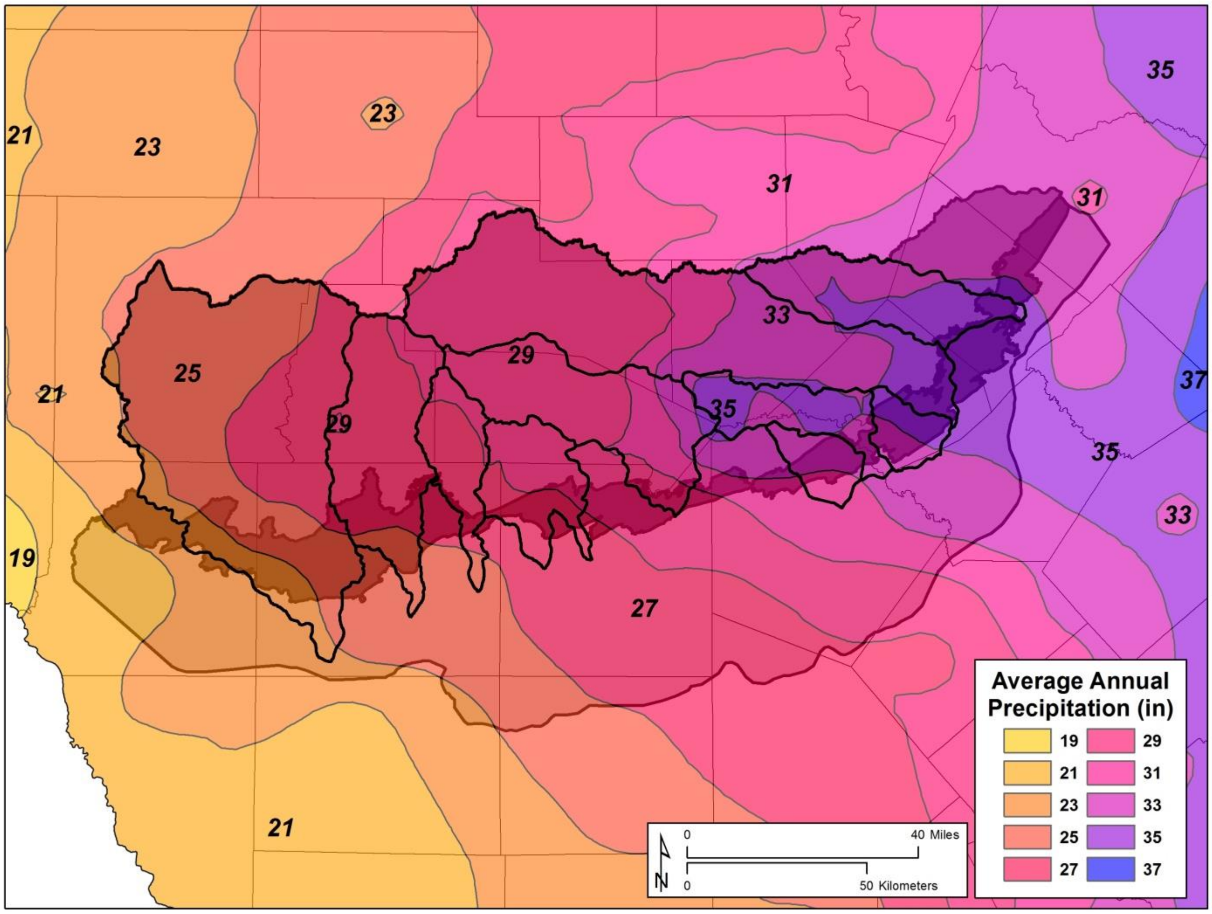


Figure 2.1-4. Average annual precipitation in the study area for the period 1960–1990. Basin outlines and aquifer zones also are shown.

Most rivers that originate in the upper reaches of the Contributing Zone are ephemeral in the upper reaches of the Contributing Zone, increase in surface flow via spring discharge over the middle reaches of the Contributing Zone, and decrease in flow as the streams and rivers approach and enter the Recharge Zone. Rivers with this character include the West Nueces, Nueces, Dry Frio, Frio, Sabinal, and Cibolo. This is a generalization of flow in these rivers because essentially all rivers exhibit reaches that gain or lose over short spans.

Of the rivers that originate in the upper reaches of the Contributing Zone, only the Guadalupe and Blanco Rivers exhibit continuous flow where they exit the Recharge Zone. The West Nueces, Nueces, Dry Frio, Frio, Sabinal, and Cibolo Rivers are ephemeral where they exit the Recharge Zone. This distinction is interpreted to indicate that the Guadalupe and Blanco Rivers do not provide recharge in the Contributing Zone to the degree as do the rivers that are ephemeral in the Recharge Zone. River gauging and gain-loss studies provide insight on how much or how little water is recharged by the perennial and ephemeral rivers; however, these rates are variable and are not well constrained (Slade et al., 2002).

The Edwards Group and Glen Rose Formation mantles most of the Contributing Zone. The exceptions are in river channels, which have Quaternary sediment deposits. The Edwards Group is thickest in the western and southwestern portion of the Contributing Zone and is thin or absent in the eastern portion of the Contributing Zone. As will be discussed in greater detail, the permeability of the Glen Rose Formation is quite variable. The Upper Glen Rose Formation tends to be more hydraulically similar to the Edwards Group than it is to the Lower Glen Rose Formation. This tendency has important implications, particularly when characterizing groundwater flow in the down-gradient Contributing and Recharge Zones.

Rivers and streams in the study area that do not originate in the upper reaches of the Contributing Zone exhibit different characteristics than rivers that do originate in the upper reaches of the Contributing Zone. The Leona, Medina, and San Antonio Rivers and a number of streams from D'Hanis on the west to Quihi on the east in Medina County are in this category (Figure 2.1-3). The principal sources of water for this category of rivers and streams are interpreted to be paleo springs located down-dip to normal faults that expose the formations providing the spring discharge. The river channels up-gradient from the paleo-springs are mostly ephemeral. Additional recharge can be derived from these upland reaches; however, the volume of the flow is much less than what is derived from the paleo-stream channels. The up-gradient fault blocks from which the springs issue are typically composed of the Austin Chalk and Buda Limestone (Green et al. 2008a, 2009a, 2012b). The Leona Formation that comprises the paleo-stream channels was deposited during the Pleistocene Epoch, the end of which corresponds with the end of the last glacial period. The Leona Formation tends to be highly permeable in many locations; therefore, paleo-springs and the associated downstream paleo-stream sediments composed of these gravels can possibly convey relatively large volumes of water in the subsurface (Green et al., 2008a, 2009a, 2012b).

Paleo-stream channels located in the Leona and Medina Rivers are the most prolific of this category of river-channel deposit flows (Green et al., 2008a, 2012b). At both locations, the downstream paleo-stream channel deposits and groundwater flow do not appear to be in hydraulic communication with river flow in each respective river channel. The paleo-spring in the Leona River channel is sourced by water from the Austin Chalk and Buda Limestone at locations where these two formations are in hydraulic communication with the Edwards Aquifer (Green et al., 2008a). The source of water discharged at the Medina River paleo-spring is not as well characterized, but is interpreted to be sourced from the Edwards Aquifer (Green et al., 2012b).

The Austin Chalk is the source of water discharged to paleo-springs and streams of this category in Medina County. The hydraulic head in the Austin Chalk is approximately 80 ft above the hydraulic head in the Edwards Aquifer at these locations, thus it is unlikely that water discharged via these streams originated in the Edwards Aquifer (Green et al., 2012b). This source of discharge is in contrast with discharge to the paleo-spring in the Medina River channel, which is sourced from the Edwards Aquifer and occurs at a lower elevation.

2.2 Model Domain

The model domain was specified to allow for model boundaries to be natural no-flow boundaries, to the degree possible (Figure 1.4-1). The model domain is specified to include all groundwater and surface-water basins that contribute water to the San Antonio segment of the Edwards Aquifer (hereafter called Edwards Aquifer). By definition, this domain includes the entire Contributing Zone of the Edwards Aquifer. Designation of no-flow boundary conditions minimizes the uncertainty inherent with determining recharge and discharge associated with specified flux and head dependent boundaries.

2.2.1 Western Boundary

Previous conceptual models of the Edwards Aquifer flow regime in the western Edwards Aquifer were based on studies by Sayre (1936), Sayre and Bennett (1942), Bennett and Sayre (1962), and Welder and Reeves (1962). Bennett and Sayre (1962) provided contour maps of the piezometric surface of the Edwards Aquifer for the period 1937 to 1940, January 1952, and August 1956. The general features of the piezometric surfaces did not change even during the drought of the 1950s. All historical maps are consistent in that the piezometric surface exhibits a 1,100-ft mean sea-level (msl) contour line near Brackettville, a north-south gradient of about 10 ft/mi, a general concave shape to the piezometric surface, an eastward component in the hydraulic gradient near Uvalde County, and a westward component to the hydraulic gradient near Val Verde County. Sayre and Bennett (1942) and Bennett and Sayre (1962) interpreted this general concave shape and a subtle north-trending groundwater ridge (i.e., approximately 1,100 ft msl at Las Moras Springs, 950 ft msl to the west at San Felipe Springs, and 850 ft msl to the east at Leona Springs) as a groundwater divide in the vicinity of Brackettville in Kinney County.

Subsequent studies also placed the groundwater divide and western boundary of the Edwards Aquifer near Brackettville (Bush et al., 1992; Hovorka et al. 1993; LBG-Guyton Associates, 1995; Maclay, 1995; Groschen, 1996; Khorzad, 2002, 2003; Snyder, 2004), although the specific location of the groundwater divide varied somewhat in the different studies. Similarly, most numerical models of the Edwards Aquifer prescribed a groundwater divide in central Kinney County as the western boundary (Klemt et al., 1979; Maclay and Land, 1988; Thorkildsen and McElhaney, 1992; Lindgren et al., 2004), with the possible exception of regional Edwards–Trinity Aquifer models by Kuniansky (1994), Kuniansky and Holligan (1994), and Anaya and Jones (2004, 2009), in which the Brackettville groundwater divide was hardly perceivable. In general, the groundwater divide near Brackettville has been historically accepted as the western boundary of the Edwards Aquifer (Lindgren et al., 2004; Edwards Aquifer Authority, 2009). Regional maps of the piezometric surface by Bush et al. (1992) and Kuniansky and Holligan (1994) are consistent with this conceptualization.

Based on these studies, the western boundary of the model domain is designated as the surface water divide located between Mud and Pinto Creeks. This boundary is designated as a no-flow boundary. Placement of the western boundary of the Edwards Aquifer at this location results in most of Kinney County being included in the model domain, even though recent studies indicate this section of the Edwards Aquifer in Kinney County acts as a separate pool (Green et al., 2006; Edwards Aquifer Authority, 2007, 2009). Including most of Kinney County and the associated Contributing Zone in the model domain allows for: (i) in-depth examination of the water budget of western Edwards Aquifer and (ii) adjustment of the structural hydraulic boundary separating the Edwards Aquifer in Kinney County from the Edwards Aquifer in Uvalde County.

2.2.2 Southern Boundary

The southern boundary of the Edwards Aquifer in the study area is designated as the 10,000 ppm total dissolved solids (TDS) transition from fresh to saline water. Wells to the south of this boundary are high in TDS (>10,000 ppm), sulfate, and chloride. This saline-water zone also is known as the bad-water zone. Bennett and Sayre (1962) and Welder and Reeves (1962) delineated the approximate boundary of the saline-water line (water free from hydrogen sulfide to the north of this line) along a trend similar to the track of U.S. Highway 90 in Kinney County and continuing across the southern portion of Uvalde and Medina Counties(Holt, 1956). The southern extension of the freshwater zone in western Medina County was added in the 2004 MODFLOW model (Lindgren et al., 2004).

Although not technically a no-flow boundary, there is negligible interchange of water across the 10,000-ppm TDS interface. The 10,000-ppm TDS interface effectively acts as a no-flow boundary. There is discharge occurring from surface (i.e., Mud, Pinto, Las Moras, Leona, San Antonio, San Pedro, Hueco, Comal, and San Marcos) and subsurface (i.e., Leona and Medina) springs (Green, 2003; Green et al, 2008a, 2012b) near the southern boundary, but they are not considered part of the boundary.

Previous estimates of discharge rates through Leona Springs and the Leona River floodplain (summarized in Lindgren et al., 2004; Tremallo et al., 2014) were refined in investigations by Green (2003) and Green et al. (2008a) based on geophysical survey and aquifer test results. Discharge as surface and groundwater flows in the Medina River channel was characterized by Green et al. (2012b). Hydrogeology of the eastern springs (Hueco, Comal, and San Marcos) was characterized by LBG-Guyton Associates (2004), Otero (2007), Johnson and Schindel (2008), Hauwert (2011), and Musgrove and Crow (2012).

Clement and Sharp (1988) and Oetting et al. (1996) reported on water types within the saline-water zone of the Edwards Aquifer. They noted the water type of the saline-water zone in southern and southwestern Kinney County is distinctly different than the water type in the saline-water zone of southern Uvalde County. Notably, the Kinney County saline waters are high in sulfate and low in chloride and sodium, whereas the Uvalde County saline waters are high in chloride and sodium as well as sulfate. This water type continues to the eastern Edwards Aquifer. Clement and Sharp (1988) suggested that chloride was flushed from the aquifer rocks and thus was found in low concentrations in groundwater from the Kinney County saline-water zone.

Maclay (1995) noted that although rocks in the saline-water zone are generally more porous than rocks in the fresh-water zone, the pores are not well connected. It seems likely that the high sulfate in the Kinney County samples is due to the much greater content of gypsum and anhydrite in the Maverick Basin rocks of Kinney County, and the low chloride is due to the low connectivity of primary porosity in those rocks. That is, rather than being flushed, the chloride in primary pore spaces is not yet accessible. Rocks of the eastern Maverick Basin and the Devils River Trend in the Edwards Aquifer saline-water zone of Uvalde County originally had fewer sulfate minerals and had undergone greater dissolution and dedolomitization. Thus, more chloride is available to enter solution and less sulfate is derived from remaining gypsum and anhydrite. Oetting et al. (1996) concluded the increased amount of chloride in the saline-water zone of the eastern Edwards Aquifer was a result of mixing of fresh water with deep Edwards Aquifer brines and leakage of high chloride waters upward from underlying stratigraphic units. Oetting et al. (1996) noted the saline-water zone of southern Kinney County occurs in rocks that are isolated from underlying aquifers due to the absence of significant faulting and igneous intrusions; thus, this portion of the saline-water zone does not have a source for high chloride content. The saline-water line was additionally constrained by subsequent investigations (e.g., Harden, 1968; Maclay et al., 1980; Schultz, 1994).

2.2.3 Northern Boundary

The northern boundary of the model domain is designated as no flow. The extent of surface watersheds on the northern boundary of the model domain is based on mapped topography (Figure 2.1-3). The northern surface-watershed boundary encompasses the upper reaches of the West Nueces, Nueces, Dry Frio, Frio, Guadalupe, and Blanco River watersheds.

Groundwater basin boundaries in the model domain, however, are more difficult to determine. Using techniques, such as dye tracing, cave surveying, water-chemistry sampling and assessment, potentiometric maps based on synoptic data, and the full use of local geology and water-budget analysis, can provide insight on groundwater basin extent and location; however, these data are not usually available at a resolution needed to be useful (Schindel et al., 1994; White, 2006). In practice, groundwater basin boundaries are commonly approximated by the overlying surface watershed area. This approximation is not always valid, particularly in carbonate aquifers (Ford and Williams, 1989; White and White, 2001; White, 2006). 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 (Green et al., 2014). 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 the geographical boundary of a groundwater basin is not coincident with the overlying surface watershed (Ford and Williams, 1989; 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.

Water-budget analysis was used to delineate the Nueces-West Nueces and Dry Frio-Frio River groundwater basins in the absence of supplemental information. Recharge calculations for the Colorado-Llano RiverBasins and the Nueces-West Nuces and Dry Frio-Frio River Basins provide the basis to estimate the northern extent of the Nueces-West Nueces and Dry Frio-Frio River groundwater basins. Calculation of the extent of groundwater basins is predicated on the assumption that recharge is uniform over regions that exhibit similar geology, precipitation duration and intensity, temperature, solar radiation, wind, slope, soil type, antecedent moisture conditions, and vegetation. The contours of constant precipitation (i.e., isohyets) in the Nueces and Dry Frio-Frio River watersheds are roughly north-south trending, and the remaining factors that influence recharge are essentially uniform (Figure 2.1-4). Thus, differences in calculated recharge within areas of equal precipitation indicate an additional hydrogeological mechanism is at play. This mechanism is interpreted to be groundwater piracy.

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 260,000 acres, the annual recharge would be 2 inches. Long (1958) suggested this estimate of recharge was probably low because precipitation is less in winter than during summer. Conversely, increased evapotranspiration in the summer, however, could reduce summer recharge.

Recharge in the Upper Frio watershed was calculated using river-discharge measurement data (Green and Bertetti, 2010a; Green et al., 2012a). Fortunately, relatively long-term, river-discharge data have been recorded near the headwaters of surface watersheds in the study area by the U.S. Geological Survey (Figure 2.2.3-1). River discharge can be characterized as having two flow components; baseflow and storm surge. Baseflow can be considered to be the groundwater contribution to stream flow and is interpreted to equal recharge (Arnold et al., 1995; Arnold and Allen, 1999; White and White, 2001; Szilagyi et al., 2003; 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 (Ford and Williams, 1989). Conceptualization that river discharge equates to recharge is only valid if rivers are gaining. This assumption is mostly valid in the upper reaches of the Nueces-West Nueces and Frio-Dry Frio River watersheds (Slade et al., 2002).

Recharge in the Frio-Dry Frio River Basins was calculated by separating baseflow from river flow measured at U.S. Geological Survey gauge 8195000, located at Concan. The baseflow fraction was 0.75, calculated using flow data that dated back to 1923 (Green and Bertetti, 2010a; Green et al., 2012a). Average flow was 90,862 acre-ft/yr over this period. This equates to 4.45 inch/yr when averaged over the 245,120-acre watershed located upstream of the flow gauge. Of this, 3.34 inch/yr is calculated using the baseflow fraction to be recharge. This estimate for recharge is greater than the 1.4 inch/yr estimate for recharge in Real County (Long, 1958) and the 2.0 inch/yr estimate for Edwards County (Long 1962, 1963). The 3.34 inch/yr of recharge estimate is interpreted as an indication that the groundwater basin of the Frio River extends farther north than the surface watershed. In this manner, an average recharge rate of 2.95 inch/year was assigned to the combined watersheds of the Upper Frio and South Llano Rivers.

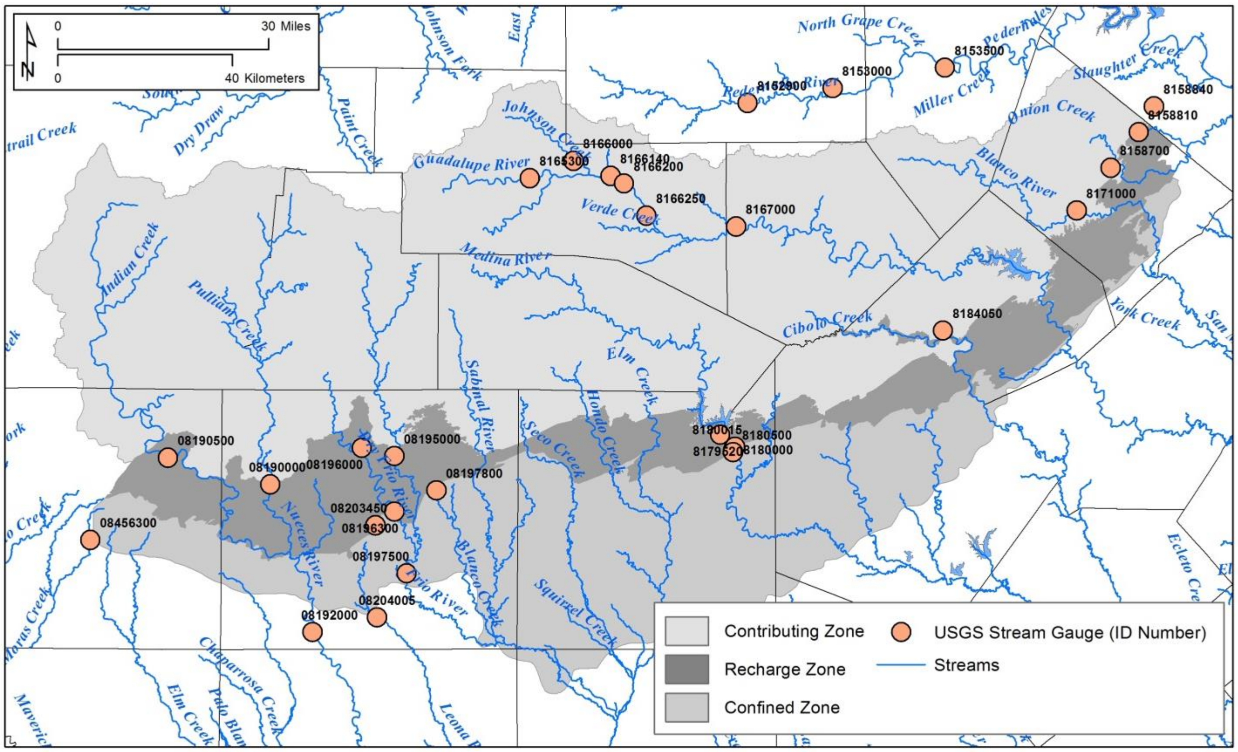


Figure 2.2.3-1. Locations of U.S. Geological Survey stream gauges in the study area.

Recharge in the South Llano River watershed was similarly calculated. 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 downstream of 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 1.45 inch/yr for the watershed. When corrected for a baseflow fraction of 0.64, recharge is calculated as 0.93 inch/year, significantly less than the recharge rate of 3.34 inch/yr calculated for the Frio River.

Recharge in the Nueces-West Nueces Rivers and South Llano watersheds also was calculated using river discharge measurement data (Green and Bertetti, 2010a; Green et al., 2012a). Distributed recharge was estimated by averaging the calculated values for recharge along isohyets for areas with uniform precipitation. Because the isohyets are essentially north trending in the western portion of the study area, uniform recharge rates also should be north trending. Following this reasoning, recharge was averaged across the South Llano and Northern Nueces-West Nuces River watersheds. The resulting average recharge rates were weighted relative to area to conserve mass (Green and Bertetti, 2010a; Green et al., 2012a).

The Nueces-West Nueces and South Llano River watersheds both receive comparable precipitation. The combined area of the two watersheds is 601,600 acres (South Llano River watershed) plus 471,680 acres (Nueces-West Nueces River watersheds) or 1,073,280 acres. The combined average annual recharge is 2.16 inch/yr over 471,680 acres plus 1.2 inch/yr over

601,600 acres for a total of 145,062 acre-ft per year. This equates to an annual recharge rate of 1.62 inch/yr when averaged over the 1,073,280 acres. The groundwater capture area for the Upper Nueces River is the area that equates to 84,662 acre-feet/year or 1.62 inch/yr. This implies the groundwater capture area for the Upper Nueces River is 604,729 acres. This area exceeds the surface area of the Nueces-West Nueces River watersheds by 133,048 acres. 133,048 acres accounts for approximately 22 percent of the South Llano River watershed. The revised Nueces-West Nueces River groundwater basin boundaries have to encroach into approximately 22 percent of the South Llano River watershed for recharge to be equal over the area of equal precipitation.

If the contact between the Nueces-West Nueces and Dry Frio-Frio River watersheds and the South Llano River watershed is approximately 22 miles wide, then the actual groundwater basin boundary extends approximately 9–10 miles north of the surface water divide at the north end of the Nueces River watershed. The blue dashed line in Figure 2.2.3-2 denotes the approximate location of the groundwater basin boundary between the South Llano and the Nueces-West Nueces groundwater basins.

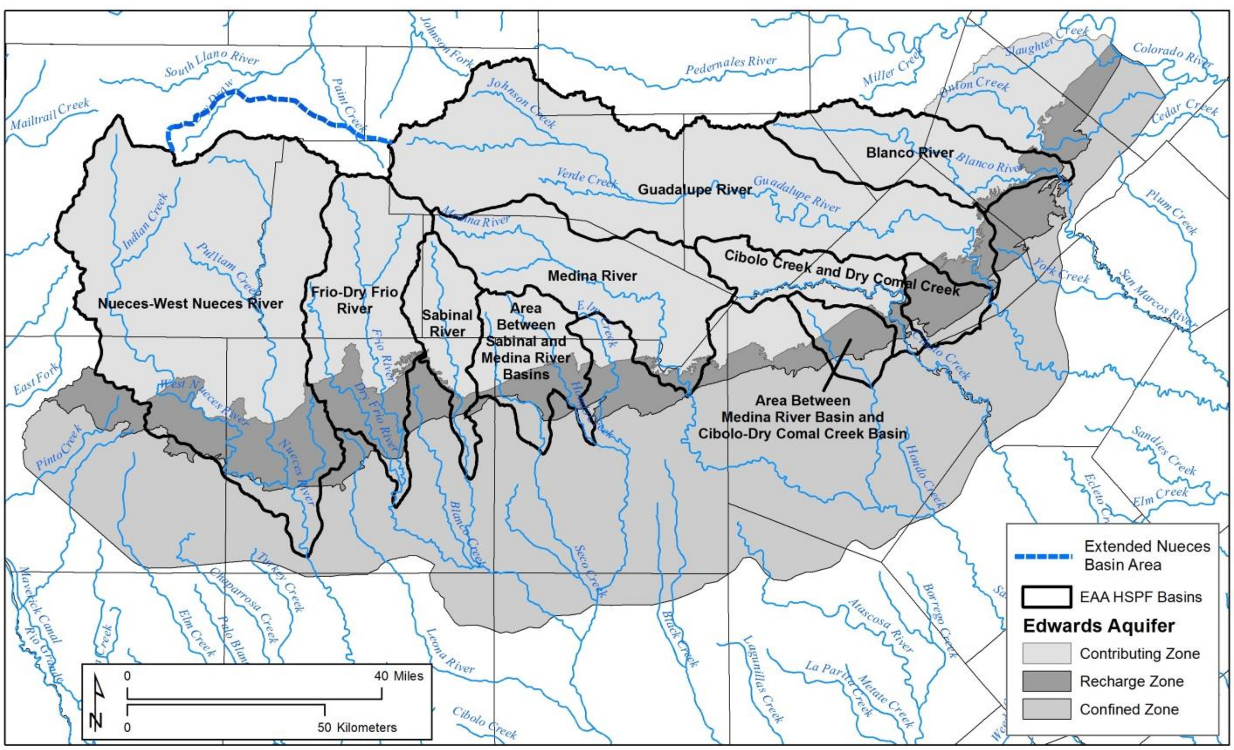


Figure 2.2.3-2. Designation of the upstream boundary of the Nueces River groundwater basin.

The Nueces-West Nueces and Dry Frio-Frio River watersheds were the only basins where sufficient recharge-discharge data were available to support groundwater basin delineation using a water-budget analysis. Elsewhere, the Guadalupe and Blanco River groundwater basins in the Contributing Zone are assumed to occupy the same boundaries as the overlying surface watersheds.

2.2.4 Eastern Boundary

Barton Springs was initially designated as the eastern boundary of the model domain. The eastern boundary was effectively revised westward to the groundwater divide that separates the San Marcos Springs Basin from the Barton Springs Basin by designating a very low hydraulic condutivtivity to this area. This revision was necessitated when calibration of this northeastern segment proved to be elusive in the absence of pumping records for the region. By moving the eastern boundary to the groundwater divide near Onion Creek, the model lost the capacity to migrate the groundwater divide in response to changes in groundwater stage. This revision was determined to be of secondary relevance to model performance.

2.3 Hydrostratigraphic Framework

A hydrostratigraphic framework model was developed to set the boundaries, define distribution of layer thicknesses, represent layers that are offset and locally missing due to slip on the most influential faults, and to provide a high-resolution, data- and observation-constrained stratigraphic framework to support the alternative model. This hydrostratigraphic framework model refines major areas of uncertainty in the existing groundwater model, such as the Recharge Zone northern boundary condition, the influence of the western portion of the Edwards Aquifer, and the effect of deformation features (faults, fractures, and layer dip) on groundwater flow. To reduce these uncertainties and develop an improved groundwater flow model (i.e., with fewer inaccuracies and less uncertainty), it is important to have a data-constrained hydrostratigraphic framework model.

The hydrostratigraphic model was created using the currently available data, including published geologic, structure, and topographic maps; stratigraphic-horizon picks from wells; and structural and stratigraphic interpretations. The hydrostratigraphic model was structured into nine hydrostratigraphic layers, although not all layers were ultimately included in the numerical model. By developing a more detailed hydrostratigraphic model, additional layers can be incorporated into the numerical model without having to redevelop a new hydrostratigraphic model. As new data become available, this model can be efficiently modified in an iterative fashion to keep the hydrostratigraphic framework up-to-date for use as the basis for increasingly refined groundwater flow and availability modeling if the Edwards Aquifer Authority (the EAA) elects to refine the alternative model in the future.

2.3.1 Framework Model

2.3.1.1 Framework Model Software

Three primary software programs were used to develop the hydrostratigraphic framework model: (i) Microsoft Excel 2010, (ii) ESRI ArcGIS 10.0, and (iii) Schlumberger PETREL 2012.1. These programs were used to organize tabulated data, assemble and analyze geographically distributed data and interpretations, and for three-dimensional hydrostratigraphic framework modeling, respectively.

Microsoft Excel 2010 was used to compile well data including locations, wellhead elevation, stratigraphic picks, and thickness information. Well data were provided by the EAA at the onset of the project. A spreadsheet of formation thicknesses across the model domain and a quality controlled database of well picks were compiled using this information.

ESRI ArcGIS 10.0 was used to assemble topography, geologic maps, structural data, and other geographically distributed data. These data were used as the basis for defining the model domain and collecting data to be used in hydrostratigraphic framework modeling. All digital data used to create the model are in a georeferenced map package (.mpk), and all well picks were evaluated using published maps and point shapefiles.

PETREL 2012.1 was used to construct the hydrostratigraphic framework model. PETREL is a Windows PC software package that is used primarily by the oil and gas industry. This software package allows surface and subsurface data to be assimilated from multiple sources and perform stratigraphic and structural geologic interpretations. This integrated software package was selected because of its flexibility in data handling, interpretation, and model development and manipulation, which eliminates the need for multiple highly specialized tools, which would otherwise be required. PETREL has a wide range of export options that facilitate inputting model results into other software programs.

The hydrostratigraphic framework model was developed in Universal Transverse Mercator (UTM) coordinate system with respect to the North American Datum of 1983 (NAD83). The entire model domain is within UTM Zone 14. Vertical positions are in feet with respect to mean sea level.

2.3.1.2 Physical Geology Database

Data sources include U.S. Geological Survey topographic data (digital elevation models), published geologic maps, published fault maps, stratigraphic measured sections, stratigraphic fence diagrams, cross sections, stratigraphic thicknesses, and well data. Surface-elevation data were downloaded from the U.S. Geological Survey National Map Viewer. The data have vertical accuracy of 8 ft, and horizontal data spacing of 1/3 arc-second or 31.4 ft. These data were upscaled to 160-ft, horizontal-data spacing and then to a final grid size of 640 ft.

Published geologic maps were used to extract elevations for mapped geologic contacts that define hydrologic boundaries in areas of limited or no well data. Geologic maps used in this fashion included maps published by the Bureau of Economic Geology (Barnes, 1977, 1983; Fisher, 1983; Collins and Hovorka, 1997; Collins, 2000) and the U.S. Geological Survey (Blome et al., 2005a,b).

Fault interpretations produced by the U.S. Geological Survey (Blome et al., 2005a,b) and the Bureau of Economic Geology (Barnes, 1977, 1983; Fisher, 1983; Collins and Hovorka, 1997; Collins, 2000) were evaluated and compared as part of the data assimilation process. Because there are differences between the U.S. Geological Survey and Bureau of the Economic Geology interpretations, information from both agencies was used to generate a revised fault map for the hydrostratigraphic framework model. In addition, all available digital data were collected in a single ArcGIS project. Stratigraphic data were collected from a wide range of sources. These sources were used to construct a formation thickness database and were derived from measured sections described in the literature.

2.3.1.3 Well Database

The well database provided by the EAA included data from 14,669 wells across the model domain; however, only 11,460 of the wells had geographic coordinates. Of the wells that had geographic coordinates, 3,923 wells contained elevations of formation tops (i.e., well picks). The well picks were used to construct an initial hydrostratigraphic framework model.

Close inspection of the initial model indicated a significant number (> 100) of bad data on the top of the Edwards Group surface. Bad data are those with errors in picking correct unit intersections or geological surfaces from well logs. The following procedure was used to evaluate the 3,923 well picks provided by EAA staff:

- Eliminate well picks inconsistent with the surface geology using published geologic maps
- Eliminate well picks that had significantly different elevations from surrounding wells or that could not be justified by faulting
- Assuming all the faults are normal, determine if well picks close to faults should be on hanging wall (lower elevation than wells on footwall), footwall (higher elevation than wells on hanging wall), or along fault trend
- Verify the formation thicknesses based on well picks

Based on this evaluation, 532 (14 percent) of the 3,923 well picks were eliminated from the data set. In addition, nearly every fault was reinterpreted and numerous faults were added to the fault database.

2.3.2 Hydrostratigaphy

Geology of the model domain consists of Cretaceous carbonate and clastic-rock layers, resting unconformably on folded and thrust-faulted Paleozoic sedimentary and metasedimentary strata of the Ouachita fold and thrust belt, and Precambrian basement (Flawn et al., 1961). The Cretaceous strata are structurally deformed by faults of the Balcones fault zone—a primarily down-to-the-coast normal fault system that cuts the Cretaceous strata.

The hydrostratigraphic framework was initially developed with nine model units.

- Leona Formation gravel
- Austin Chalk
- Eagle Ford Formation (confining unit)
- Buda Limestone
- Del Rio Clay (confining unit)
- Upper Edwards Aquifer
- Lower Edwards Aquifer (confining unit in the Maverick Basin, aquifer elsewhere)
- Upper Glen Rose Aquifer
- Lower Glen Rose Formation (basal confining unit)

The numerical model was initially represented with one model unit, the Edwards Aquifer. During development, the model was expanded to three mappable units with an overlying confining layer where appropriate. These units are defined (from bottom up) as (i) Lower Trinity up to and including the Lower Glen Rose Unit, (ii) Upper Glen Rose Unit, (iii) Edwards Unit, and (iv) Del Rio Formation and above Confining Unit.

The Trinity Aquifer consists of: (i) an upper part consisting of the upper member of the Glen Rose Formation, (ii) a middle part consisting of the lower member of the Glen Rose Formation and the Cow Creek Limestone, which are separated by the Hensell Sand or Bexar Shale, and (iii) a lower part consisting of the Hosston Formation and overlying Sligo Formation that is separated from the Cow Creek Limestone by the intervening Hammett Shale (Mace et al., 2000). The Lower Glen Rose Unit includes the entire stratigraphic section from the Upper-Lower Glen Rose Boundary, marked by the “Corbula bed” (Lozo and Stricklin, 1956; Stricklin, et al., 1971), to the top of Precambrian basement–this unit effectively represents the lower confining unit for the Edwards Aquifer. The Upper Glen Rose Unit includes the Upper Glen Rose Formation. This unit is separated from the Lower Glen Rose Unit because the Upper Glen Rose Unit is recognized to be more hydraulically similar to the Edwards Aquifer than it is to the Lower Glen Rose Formation (Smith and Hunt, 2009, 2010, 2011). Thus, the rest of the Trinity Aquifer and the Upper Glen Rose Unit are designated as separate layers in the model. The stratigraphic column is illustrated in Figure 2.3.2-1.

The Edwards Aquifer or Group is represented by three regionally distinct facies in the study area (Figure 2.1-2). To the west, in the Maverick Basin facies, the Edwards Aquifer consists of (from youngest to oldest) the Salmon Peak, McKnight, and West Nueces Formations. The Devils River Trend is composed of a basal nodular unit and the overlying undifferentiated rocks of the Devils River Formation (Clark, 2003). The Upper Devils River Formation tends to be the most permeable section in the Devils River Trend facies of the Edwards Aquifer. The Lower Devils River Formation is less permeable than the upper section and is typically not a significant source of groundwater (Maclay, 1995; Clark 2003). Rocks of the Devils River Trend are more permeable than rocks of the Maverick Basin but less permeable than rocks of the San Marcos Platform (Maclay, 1995). The Edwards Group within the San Marcos Platform has been characterized as the Kainer and Pearson Formations overlain by the Georgetown Formation (Maclay, 1995).

The Edwards Model Unit includes a range of different named formations that collectively make up the Edwards Aquifer. The Segovia, Salmon Peak, Upper Devils River, and Person Formations are considered laterally equivalent units across the multiple facies zones of the model domain (Rose, 1972; Smith, et al., 2000). Similarly, the Fort Terrett, McKnight, West Nueces, Lower Nueces, and Kainer Formations are considered laterally equivalent units (Rose, 1972; Smith et al., 2000). The Georgetown Formation is extended across the entire model domain marking the upper part of the Edwards Aquifer. The upper confining unit of the Edwards Aquifer includes the overlying Del Rio Clay and other shallow units.

Alluvial sediments of the Leona Formation form significant local aquifers in the Leona and Medina River watersheds (Green, 2003; Green et al., 2008a, 2012b). The sands and gravels of the Leona Formation were deposited in paleo-stream channels embedded in silt and clay deposits. These sediments are underlain by a basal clay layer. Leona Formation gravels are found in lesser amounts elsewhere in the model domain (i.e., downgradient from the Austin Chalk Recharge Zone in Medina County); however, these occurrences are not significant and the Leona Formation gravels at these locations do not convey significant groundwater (Green et al., 2012b).

Even though alluvial sediments convey large volumes of water, particularly in the Leona and Medina River watersheds, they are not included as mappable units in the numerical model. This designation is justified because these two hydrostratigraphic features are located downgradient from points of discharge in the model domain. Once groundwater enters the paleo-stream channels in the Leona and Medina River Floodplains, that groundwater is lost from the Edwards Aquifer.

2.3.3 Balcones Fault Zone

The Balcones Fault Zone is a broad *en echelon* system of mostly south-dipping normal faults that formed during the middle to late Tertiary (Murray, 1961; Young, 1972; Ferrill et al. 2004; Ferrill and Morris, 2008) (Figure 2.3.3-1). The arc-shaped zone trends east-northeast and spans much of central Texas. The 16- to 19 mi-wide Balcones Fault Zone has a maximum total displacement of 1,200 ft (Weeks, 1945) and defines the transition from structurally stable flat-lying rocks of the Edwards Plateau to gently coastward-dipping sediments of the subsiding Gulf of Mexico. Offset of carbonate strata across the Balcones Fault Zone resulted in a broad, weathered escarpment of vegetated limestone hills rising from the predominantly clastic coastal plains to the uplands of the Edwards Plateau. Within the fault system, the dip of bedding varies from gentle coastward to nearly horizontal, with occasional localized dip of hanging-wall beds northward into some faults and parallel to fault strike in relay ramp structures (Collins and Hovorka, 1997).

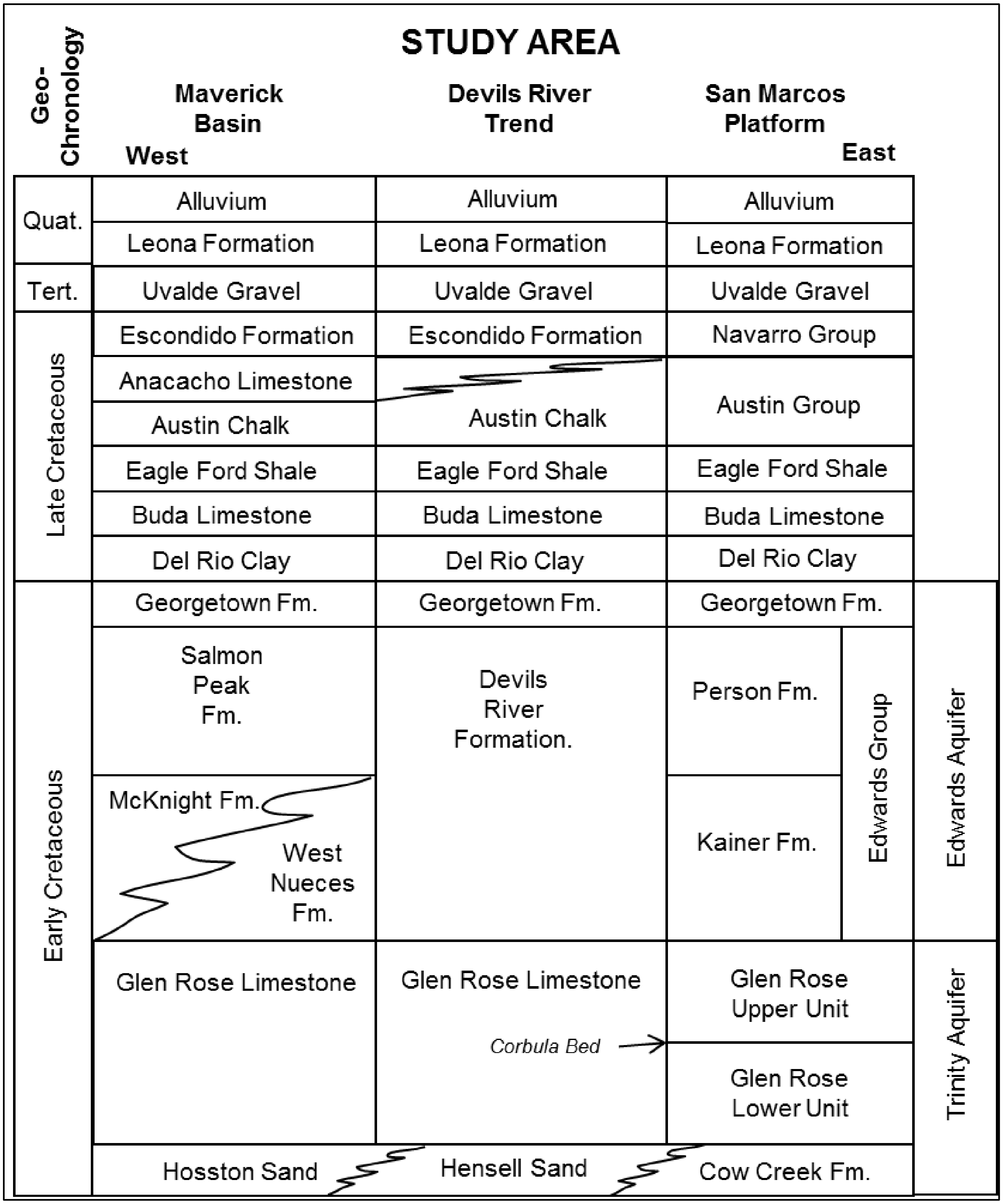


Figure 2.3.2-1. Generalized Cretaceous stratigraphy and selected younger units of south-central Texas.

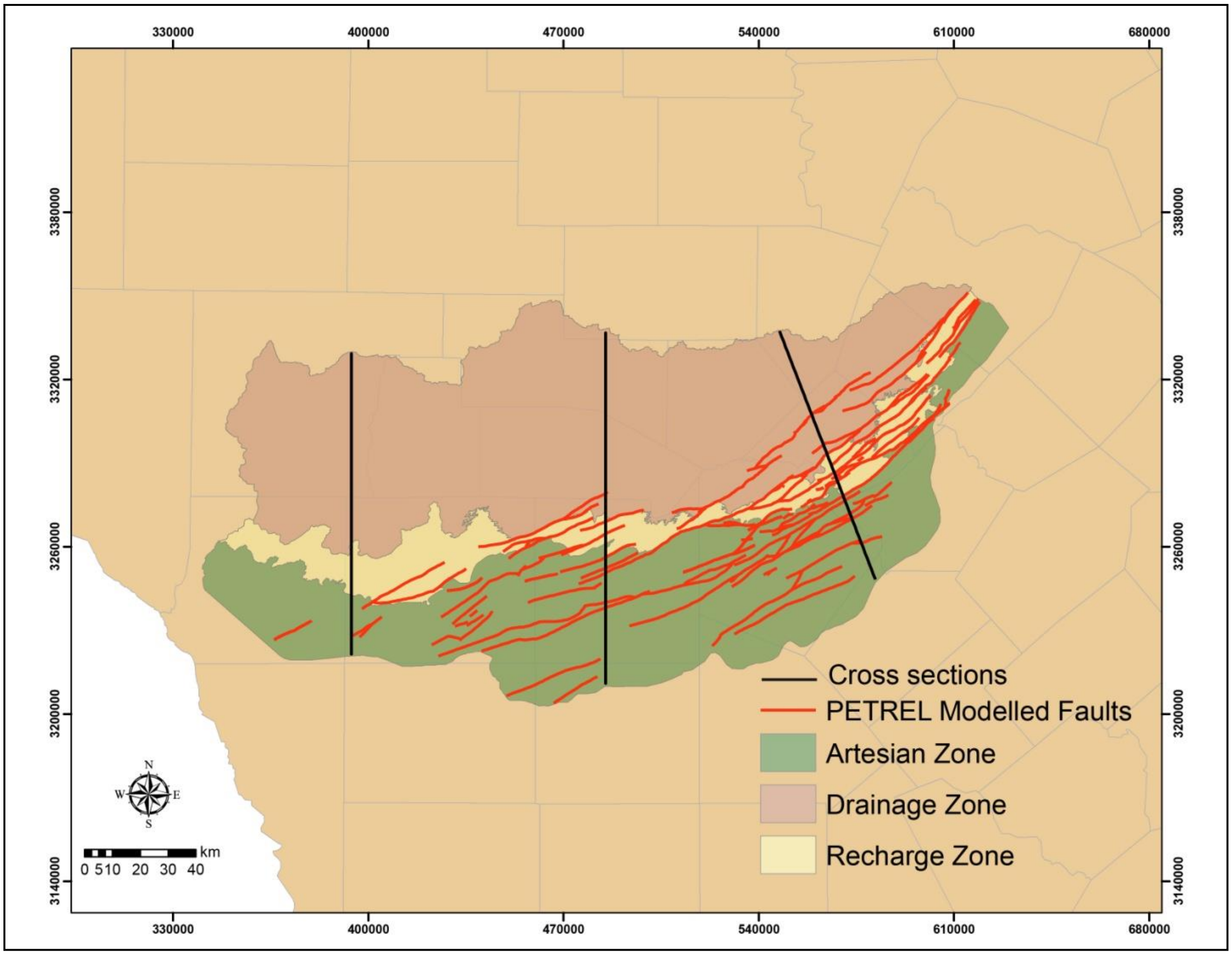


Figure 2.3.3-1. Locations of three vertical hydrostratigraphic cross sections that illustrate the structural variability of the Balcones Fault Zone.

Conveyance of water from the Contributing Zone to the Recharge and Confined Zones of the Edwards Aquifer follows a somewhat tortuous route. Both the Edwards and Trinity Formations are exposed at the surface in the Contributing Zone. Typically, the Edwards Group is found at hill tops and other higher elevation locations while the Trinity Formation is exposed in river channels and other locations where the Edwards Plateau and Balcones Fault Zone have been incised by erosion.

The complex geologic structure results in a complicated path of groundwater flow through the hydrostratigraphic geologic units in various juxtaposition relations due to faulting. Lateral changes in aquifer geometry and fault juxtaposition are illustrated in three vertical geologic cross sections extracted from the hydrostratigraphic framework model (Figures 2.3.3-2, 2.3.3-3, and 2.3.3-4). The cross sections illustrate the geologic structure of the Balcones Fault Zone at three locations within the model domain (see Figure 2.3.3-1 for cross section locations) to illustrate the structural variability of the Balcones Fault Zone.

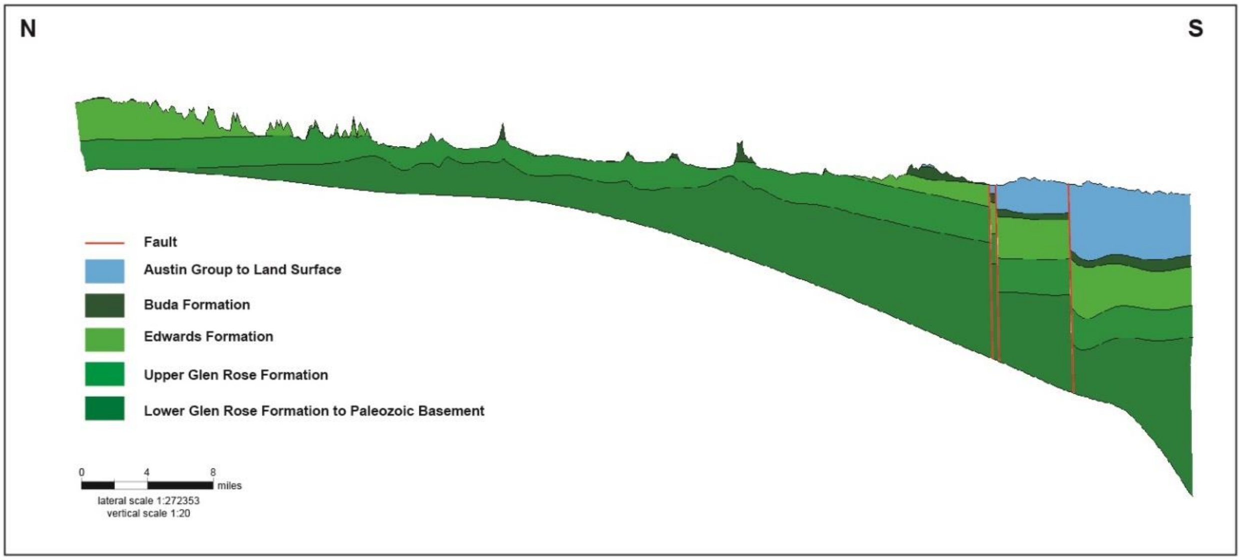


Figure 2.3.3-2 Vertical cross section of the geologic structure in the western model domain.

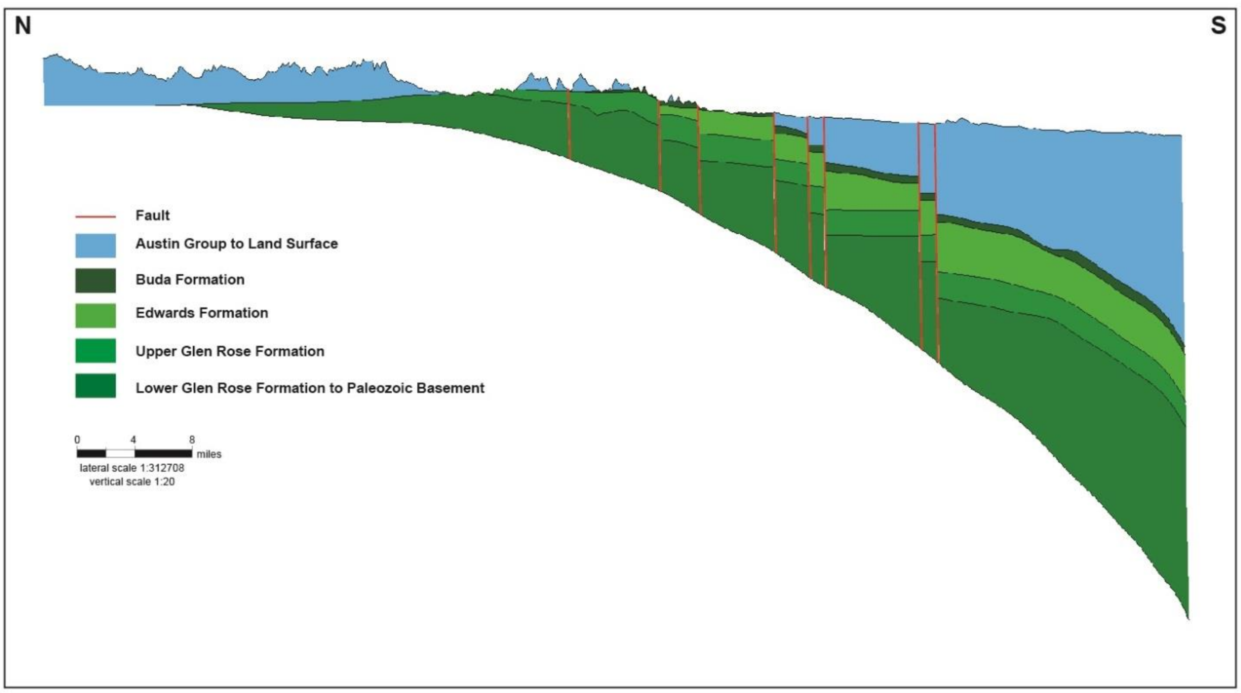


Figure 2.3.3-3 Vertical cross section of the geologic structure in the central model domain.

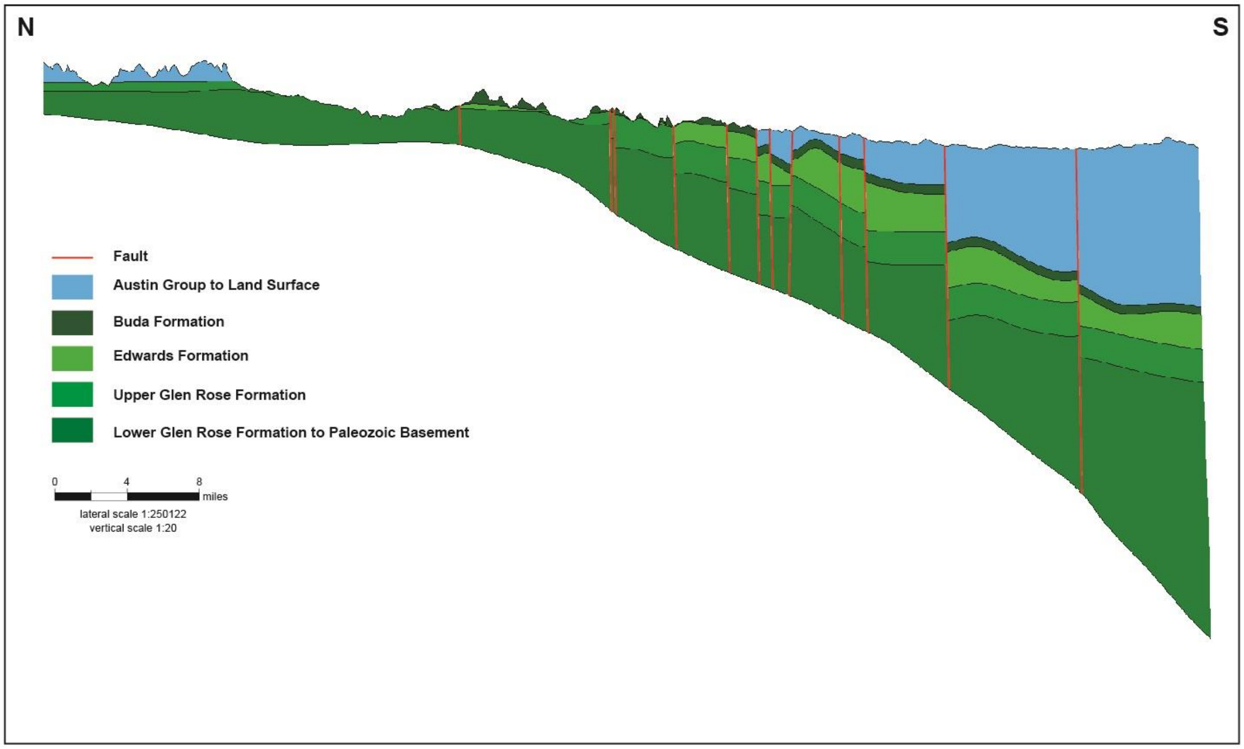


Figure 2.3.3-4 Vertical cross section of the geologic structure in the eastern model domain.

The Trinity, Edwards, Buda Limestone, and Austin Chalk Aquifers that comprise the rocks of the Balcones Fault Zone are complex karst limestone aquifer systems that have permeability architectures that include a combination of host rock permeability, fractures and fault zones, and dissolution features (Maclay et al., 1981; Maclay and Small, 1983). Although the strata that make up the Edwards Aquifer are younger and stratigraphically overlie the strata of the Trinity Aquifer (Figure 2.3.2-1), displacement along faults of the Balcones Fault Zone has placed the Edwards Aquifer laterally against (side-by-side with) the Trinity Aquifer in parts of the study area. The location and amount of fault juxtaposition are sensitive to the location, geometry, and displacement on faults (Ferrill et al., 2005, 2008). Along faults that define the structural interface between the Edwards and Trinity Aquifers, caves and some fault zones provide conduits for groundwater flow and potential pathways for interaquifer communication. The occurrence of and degree to which interaquifer communication occurs are not well defined, although various hydrologic and hydrochemical studies have attempted to place constraints on the amount of water that the Trinity Aquifer contributes to the Edwards Aquifer (e.g., LBG-Guyton Associates, 1995).

Rocks of the Trinity Aquifer crop out in the Edwards Plateau region, and their southern and eastern outcrop boundary is within the Balcones Fault Zone, a zone of Tertiary age, down to the southeast, normal faulting (Foley, 1926; Maclay and Small, 1983, 1984; Stein and Ozuna, 1996; Clark, 2003; Collins, 2000). South and east of the Balcones Fault Zone, the Edwards Aquifer is confined beneath younger sedimentary rocks. Recharge of the aquifer occurs primarily by streamflow loss and infiltration in porous parts of the unconfined Edwards Aquifer Contributing and Recharge Zones, responding to precipitation in both Contributing and Recharge Zones. Water in the unconfined aquifer moves down the hydraulic gradient, in many places following tortuous flowpaths controlled by the Balcones Fault Zone. Natural discharge sites for the Edwards Aquifer include springs associated with the Balcones Fault Zone.

After precipitation lands on the Contributing Zone, water that is not returned to the atmosphere by evapotranspiration is recharged to the subsurface or flows overland to river channels. Both surface water and groundwater gradients within the Contributing Zone of the Edwards Aquifer are to the south and east toward the Recharge and Confined Zones (Figure 2.3.3-5). As illustrated in Figures 2.3.3-2, 2.3.3-3, and 2.3.3-4, although the Edwards Formation is present throughout most of the Contributing Zone, it is frequently absent in the zone immediately upgradient from the Recharge Zone (Figure 2.3.3-6). In addition, the Upper Glen Rose Formation thins and is even absent in this same zone adjacent to the Recharge Zone.

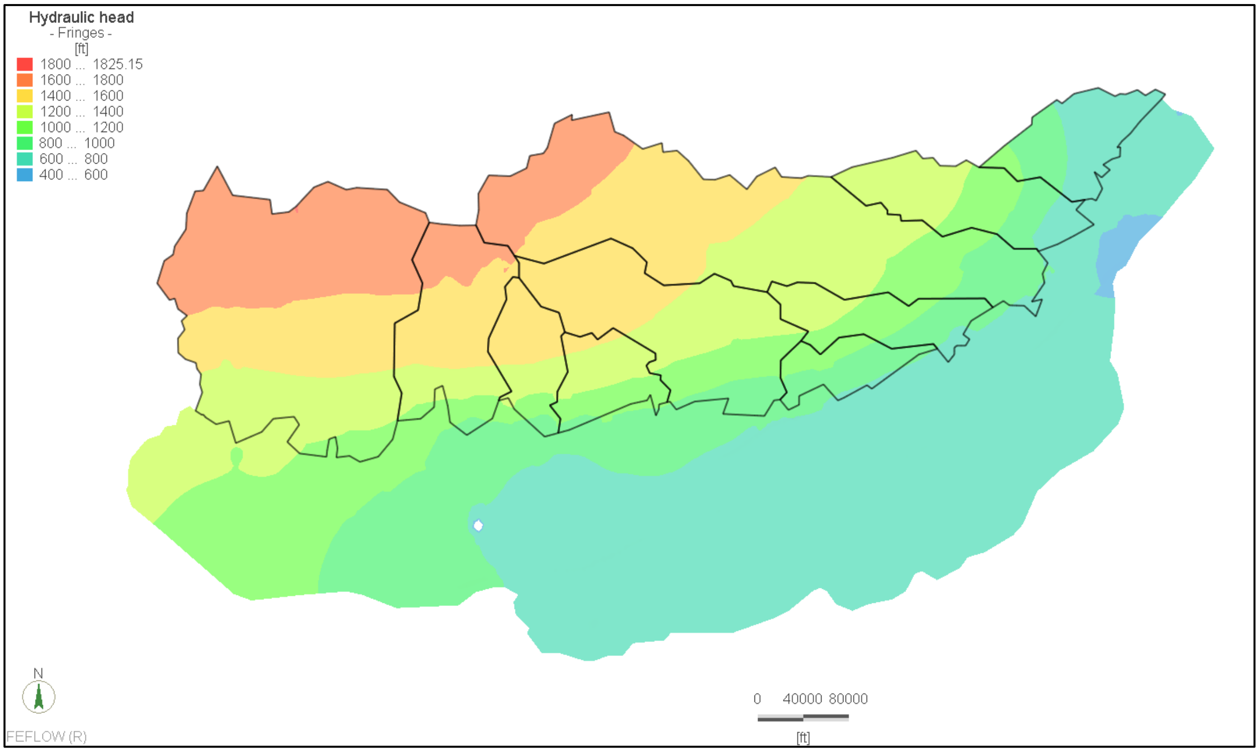


Figure 2.3.3-5. Map showing the piezometric surface in the model domain used as the initial conditions. Head distribution was generated using the average recharge and pumping rates for the 11-year calibration period 2001–2011.

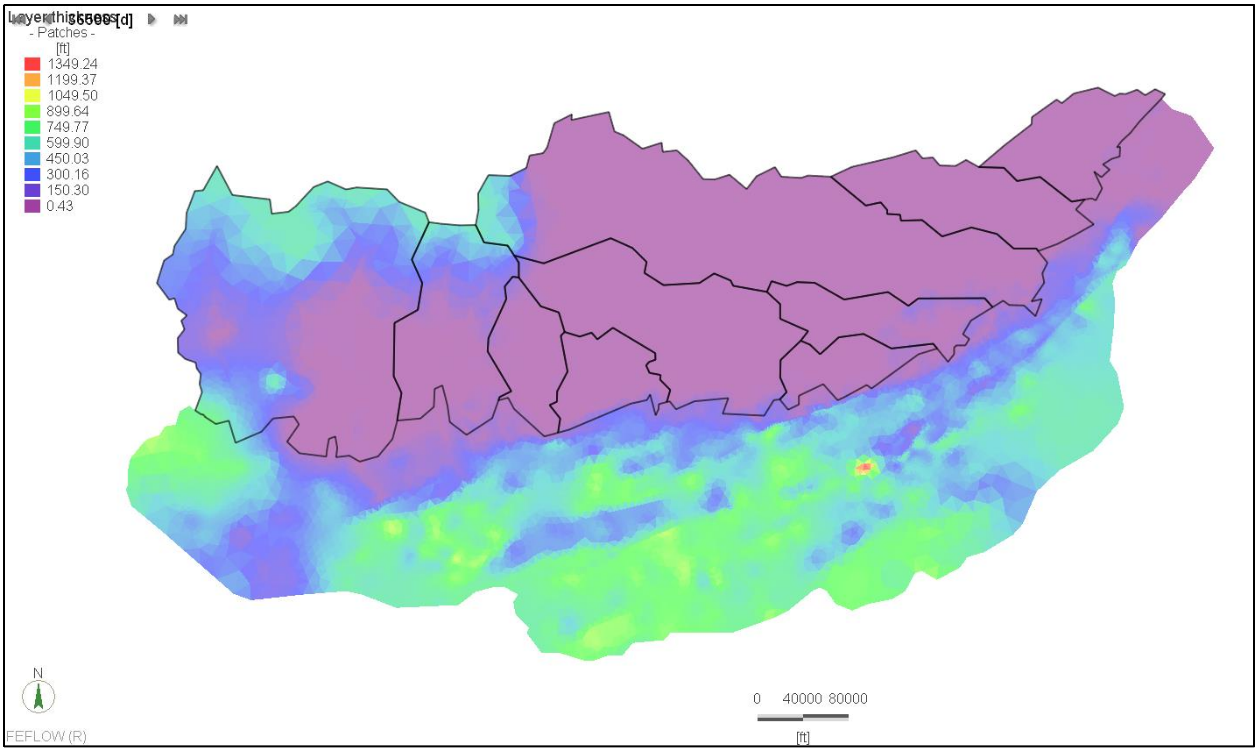


Figure 2.3.3-6. Thickness of the Edwards Aquifer in the model domain (ft).

Thinning or absence of the Edwards Aquifer and the Upper Glen Rose Formation in this zone can impede the flow of groundwater from the upper reaches of the Contributing Zone to the Recharge Zone. This impedance to flow can be exacerbated if groundwater elevations are sufficiently low that the more permeable units (i.e., Edwards Aquifer and Upper Glen Rose Formation) are not active in conveying groundwater and that groundwater flow is mostly (or totally) conveyed via formations with lower permeability, such as the Lower Glen Rose Formation and other lower units in the Trinity Aquifer.

It is possible that groundwater is conveyed from the Contributing Zone, across the zone where the Edwards and Upper Glen Rose are reduced or absent, via high preferential flow zones (i.e., conduits or simply zones of enhanced permeability) that may have developed concurrent with river channels. Although the development of preferential flowpaths is observed in river channels in the karstic limestones of the western Edwards Plateau (Woodruff and Abbott, 1979, 1986; Green et al., 2014), the presence of similar high permeability zones in the river channels of the Edwards Aquifer Contributing Zone have not been observed or discerned.

A groundwater model that includes the Contributing, Recharge, and Confined Zones is useful in constraining which conceptual model(s) of flow from the Contributing Zone to the Recharge Zone is (are) feasible and reasonable. The range of possible conceptual models of flow mechanisms in the Contributing Zone is not well constrained because of an absence of hydraulic information (i.e., potentiometric measurements) in the Contributing Zone. The alternative groundwater model developed in this project illustrates that even if such information becomes available, it is important to know if the head data are representative of the Austin Chalk, Buda Limestone, Edwards, Upper Glen Rose, Lower Glen Rose, or another hydrostratigraphic unit. In the absence of these data, uncertainty in the conceptual model of flow in the Contributing Zone remains high.

2.3.4 Role of Faults

The role of faults in the model domain has been explored and evaluated in recent years (Ferrill et al. 2004; Clark and Journey, 2006; Ferrill et al., 2008; Johnson et al., 2009, 2010, 2012; Schindel and Johnson, 2011; Green et al., 2012b). Results from tracer tests in Bexar County demonstrated that faults in the Balcones Fault Zone, at least in Bexar County, do not act as barriers to flow (Johnson et al., 2009, 2010, 2012; Schindel and Johnson, 2011). These studies support the hypothesis that most faults in the model domain do not impede cross-fault flow. Exceptions are the Haby Crossing Fault in Medina and Bexar Counties (Figure 2.3.4-1) and four faults associated the Comal and San Marcos Springs areas (Johnson et al., 2009) (Figure 2.3.4-2).

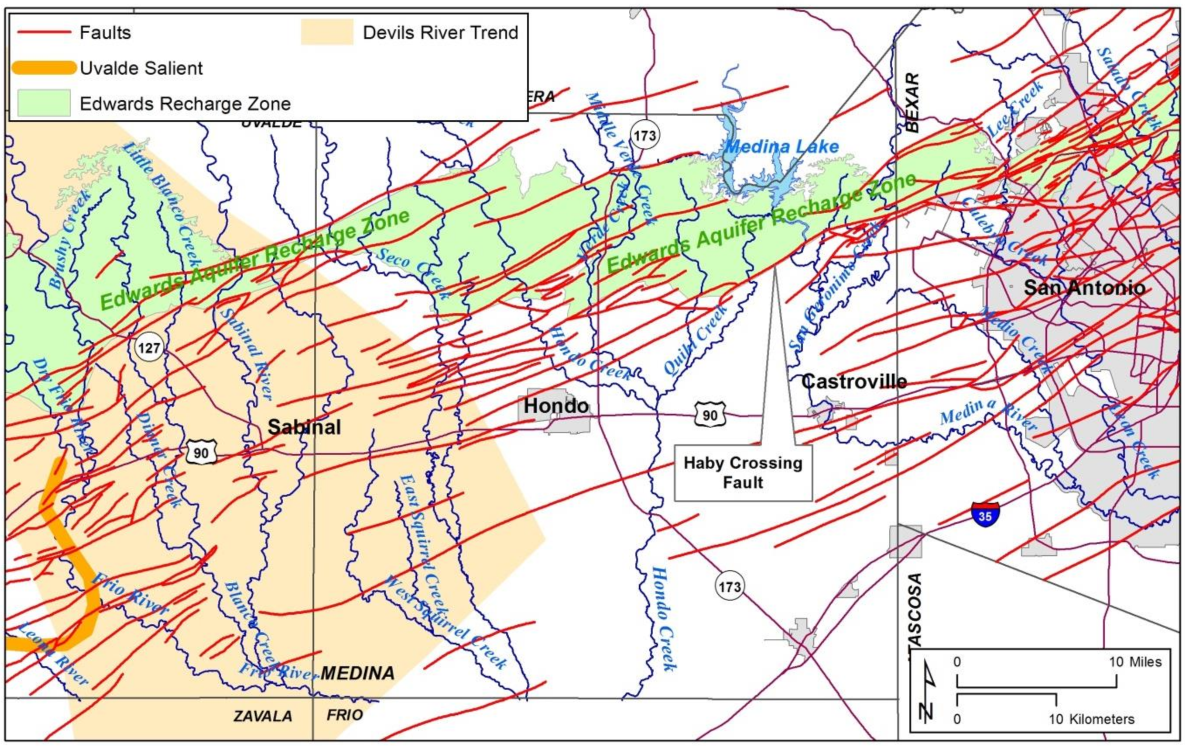


Figure 2.3.4-1. Geological structure map of Medina County illustrating Balcones Fault Zone.

The ability of faults to act as both conduits and barriers to flow within the Edwards Aquifer has been acknowledged by virtually all workers over the last century; however, since the 1950s, the concept of barrier faults that partition the aquifer has become increasingly popular (e.g., Holt, 1956, 1959; Maclay and Small, 1983; Maclay, 1989, 1995; Clark and Journey, 2006). It also has been noted that a fault that acts as a barrier to cross-fault flow also may also serve to accentuate along-fault flow (Sharp and Banner, 1997; Ferrill and Morris, 2003; Ferrill et al., 2004). Faults are acknowledged to exert fundamental control on the groundwater flowpaths within the Edwards Aquifer in the following ways (Figure 2.3.4-3):

- As both horizontal and vertical flow conduits because fault zones are often preferentially dissolved.
- As barriers to flow, especially where displacement is sufficient to juxtapose the Glen Rose Formation (generally regarded as having lower permeability) in the upthrown block with Edwards limestones in the downthrown block; or Edwards limestones in the upthrown block with Del Rio Clay in the downthrown block.
- As both barriers and conduits depending on the nature of the fault.

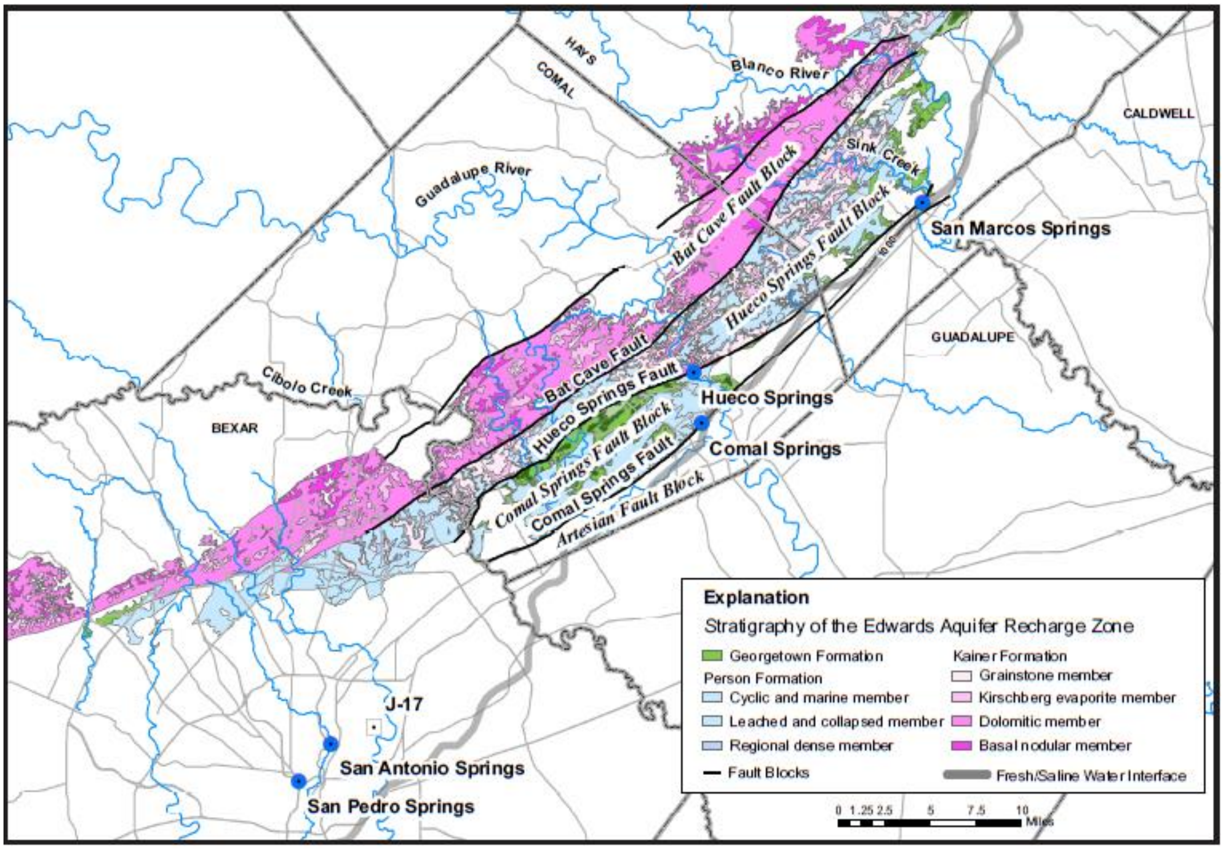


Figure 2.3.4-2. Geologic structure in eastern Bexar, Comal, and western Hays counties (from Johnson and Schindel, 2008).

The objective of this characterization was to include faults that have sufficient throw (vertical component of displacement) to be significant. A throw of 65 ft or greater that is confirmed by surface mapping and/or subsurface data was selected as the criterion as to whether the fault was significant. Over 1,500 fault interpretations that came from structure contour maps (Collins and Hovorka, 1997), geologic maps (Barnes, 1977, 1983; Fisher, 1983; Collins 2000), well data (well picks), and SwRI-led projects (Ferrill and Morris, 2008; Ferrill et al., 2003, 2004, 2005, 2008, 2011) were examined. Of the 1,500 fault interpretations, only 130 met the criteria of 65 ft or greater throw. The 130 faults that met the criteria were included in the model as discrete surfaces that cut through all layers (Figure 2.3.3-1). All smaller faults were included in the model as discontinuities.

Holt (1956) and Maclay (1995) interpreted that a major fault in Medina County impedes cross-fault flow. Clark and Journey (2006) identified additional faults in Medina County that may impede flow and establish a number of individual flow paths. Green et al. (2012b) used water chemistry analysis to limit the number of flow paths and faults that impede cross-fault flow in Medina County. There are four faults near Comal and San Marcos Springs that have been characterized as barriers to cross-fault flow (Johnson and Schindel, 2008). The intervening fault blocks are named consistent with the faults (Figure 2.3.4-2).

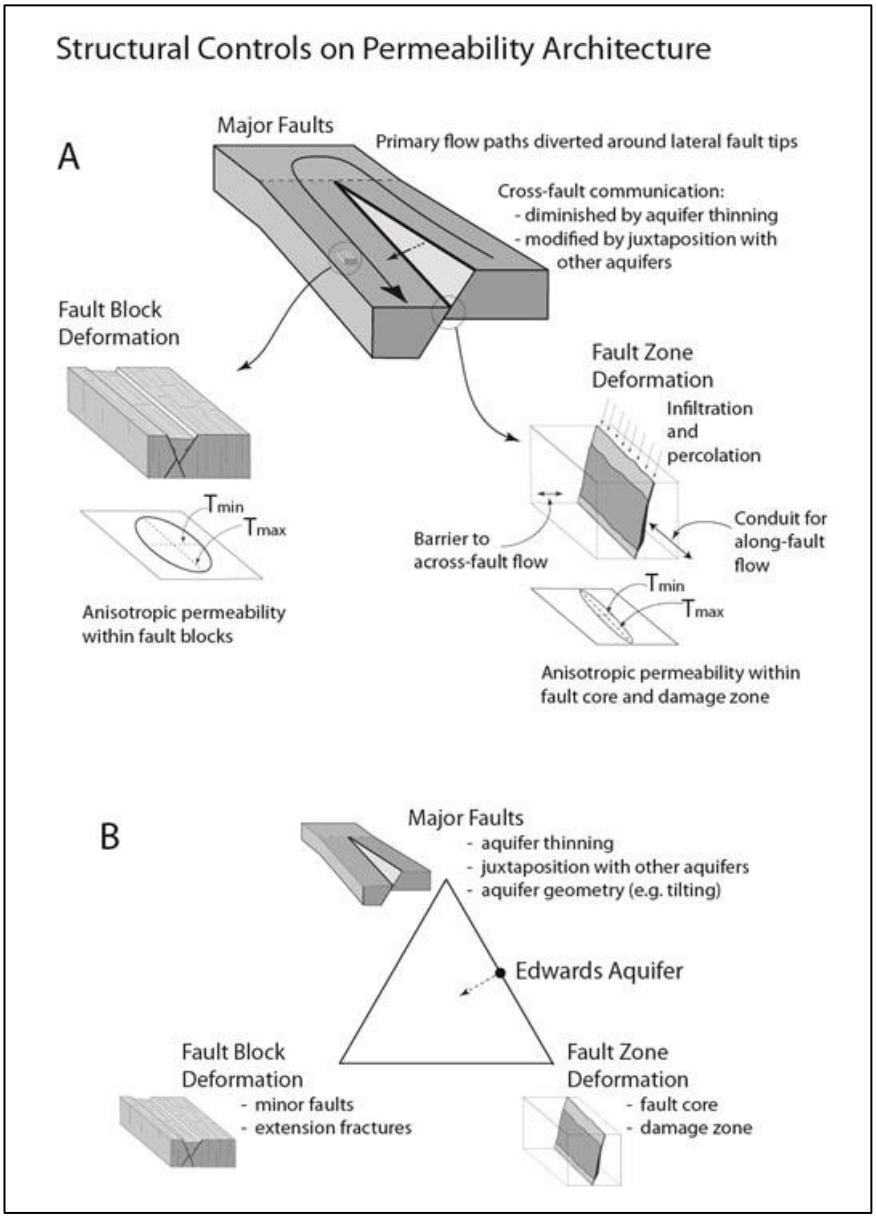


Figure 2.3.4-3. Schematic of faults that act as conduits, barriers, and both as conduits and a barrier (Ferrill et al., 2004).

The Bat Cave and Hueco Springs Fault blocks are separated by the Bat Cave Fault. The Hueco and Comal Springs Fault blocks are separated by the Hueco Springs Fault. The Hueco Springs

Fault extends to San Marcos Springs where it is referred to as the San Marcos Springs Fault. The Comal Springs and Artesian Fault blocks are separated by the Comal Springs Fault. The fault on the northwest side of the Bat Cave Fault block is not named in Johnson and Schindel (2008).

The Bat Cave Fault block consists of the Dolomitic member and Basal Nodular member with small outcrops of the Kirschberg member of the Edwards Group. Most wells in the Bat Cave Fault block are in the Glen Rose Aquifer because the Edwards Aquifer is mostly dewatered. The Bat Cave Fault has 350 ft displacement. The middle members of the Edwards crop out in the Hueco Springs Fault block. These are the Leached and Collapsed, the Regional Dense, and the Grainstone members. The Kirschberg and lower members of the Edwards are exposed along the Guadalupe River and other streams. Enough of the Edwards Aquifer in parts of the Bat Cave Fault block is saturated to support wells. The Hueco Springs Fault is a normal fault with approximately 300 ft of displacement (Johnson and Schindel, 2008).

The upper members of the Edwards Group crop out in the Comal Springs Fault block. These include the Cyclic and Marine members. The Georgetown, Del Rio Clay, Buda Limestone, Eagle Ford Group, and Austin Group also crop out in the Comal Springs Fault block. The Comal Springs Fault has 400 to 600 ft of displacement. Comal Springs Fault is a normal fault with 200 to 300 ft of displacement near the Bexar-Comal County line and more than 800 ft of displacement at Comal Springs. The Comal Springs fault block is 4-miles wide at Comal Springs narrowing to ½-mile wide at San Marcos Springs. The top of the Edwards Group is 150 to 600 ft below ground surface in the Artesian Fault block. The southern limit of the Edwards Aquifer, if defined by the 1,000 mg/l interface, is within the Artesian Fault block (Johnson and Schindel, 2008).

2.3.5 Role of Conduits

The Edwards Aquifer is well recognized as a karst-limestone aquifer. With 500 named caves in Bexar County, the degree of karstification is significant (Veni, 1988). Conduit development also is believed to be significant; however, conduits in the San Antonio Pool are deep and not well located or characterized (Woodruff, 1974; Woodruff and Abbott, 1979, 1986; Maclay, 1985). Biological surrogates are useful in demonstrating connectivity of conduit-like flow pathways (Krejca, 2005). In the absence of definitive data, such as the extensive dye tracing conducted at Barton Springs (Hauwert et al., 2002, 2004) or biological surrogates for demonstrating connectivity of conduit-like flow pathways (Krejca, 2005), actual conduit flow paths in the Edwards Aquifer only can be discussed in general terms. Approximate locations of conduits in the Edwards Aquifer have been postulated using groundwater troughs and related information (Worthington, 2004; Hovorka et al., 2004). It is recognized that these estimates only approximate general locations and do not characterize conduit size, depth, or other physical attributes.

Representation of the hydraulic response of a karst aquifer requires accommodation of the flashy response of the aquifer when subjected to large precipitation events that lead to flashy recharge impulses to the aquifer. Any attempt to replicate rapid-response (high-frequency) hydrographs within a karst aquifer necessitates inclusion of a fast-flow component associated with karst conduit flow. Because the model is limited to monthly stress period, it is not clear whether actual incorporation of conduits and conduit flow in the alternative model is necessary. This question is addressed during calibration.

The dilemma of whether and how to incorporate conduit flow into a numerical groundwater flow model of a karst aquifer was encountered during development and implementation of the 2004 MODFLOW model (Lindgren et al., 2004, 2009; Lindgren, 2006). The modeling software used in this alternative model (FEFLOW) was selected, in part, due to its facility to incorporate discrete features into the flow regime. The use of discrete features and high transmissivity zones was evaluated to ascertain which approach for incorporating conduit flow would best achieve the desired performance of the model, while at the same time avoiding over-parameterization of the model domain. Both discrete feature and high transmissivity zones were needed to represent conduit flow in the model.

2.4 Hydrogeology of the Model Domain

2.4.1 Potentiometric Surface

Piezometric contour maps for the study area illustrate the general groundwater-flow patterns within the Edwards Aquifer. Water is recharged from river basins located in the Edwards Aquifer Contributing and Recharge Zones to the north. Groundwater flow in the Contributing and Recharge Zones generally follows the alignment of the river basins which is north-south in the west of the model domain and transitions to west-east in the east. After entering the Confined Zone, the direction of flow is generally from west to east. The piezometric surface map by Maclay and Land (1988) for the winter of 1973 is commonly cited as representative for “normal precipitation” periods in the Edwards Aquifer. A potentiometric map of the Edwards Aquifer was prepared using initial hydraulic head values determined by running a pseudo-steady-state simulation for 100 years with pumping and recharge conditions set to the average of the 11-year calibration period (Figure 2.3.3-5).

Groundwater elevation data for the Contributing Zone were extracted from the Texas Water Development Board database to provide a physical basis for the Contributing Zone. These data are not representative of a synoptic measurement exercise and only are intended to be indicative of general hydrogeological conditions. Groundwater elevation data in the Contibuting Zone were used to constrain the model during calibration, however these data were not included in the calibration statistics.

2.4.2 Western Hydrogeology

2.4.2.1 Kinney Pool

A conceptual model of the groundwater flow regime in the western Edwards Aquifer that differs from the conceptual model represented in the 2004 MODFLOW model (Lindgren et al., 2004) was developed. In this new conceptual model, the portion of Edwards Aquifer in Kinney County is conceptualized as a separate segment or pool. The pool extends from the groundwater divide between the Pinto and Mud Creeks in the west to eastern Kinney County in the east (Figure 2.4.2.1-1). This segment is referenced here as the Kinney Pool. A schematic of Kinney Pool is illustrated in Figure 2.4.2.1-2.

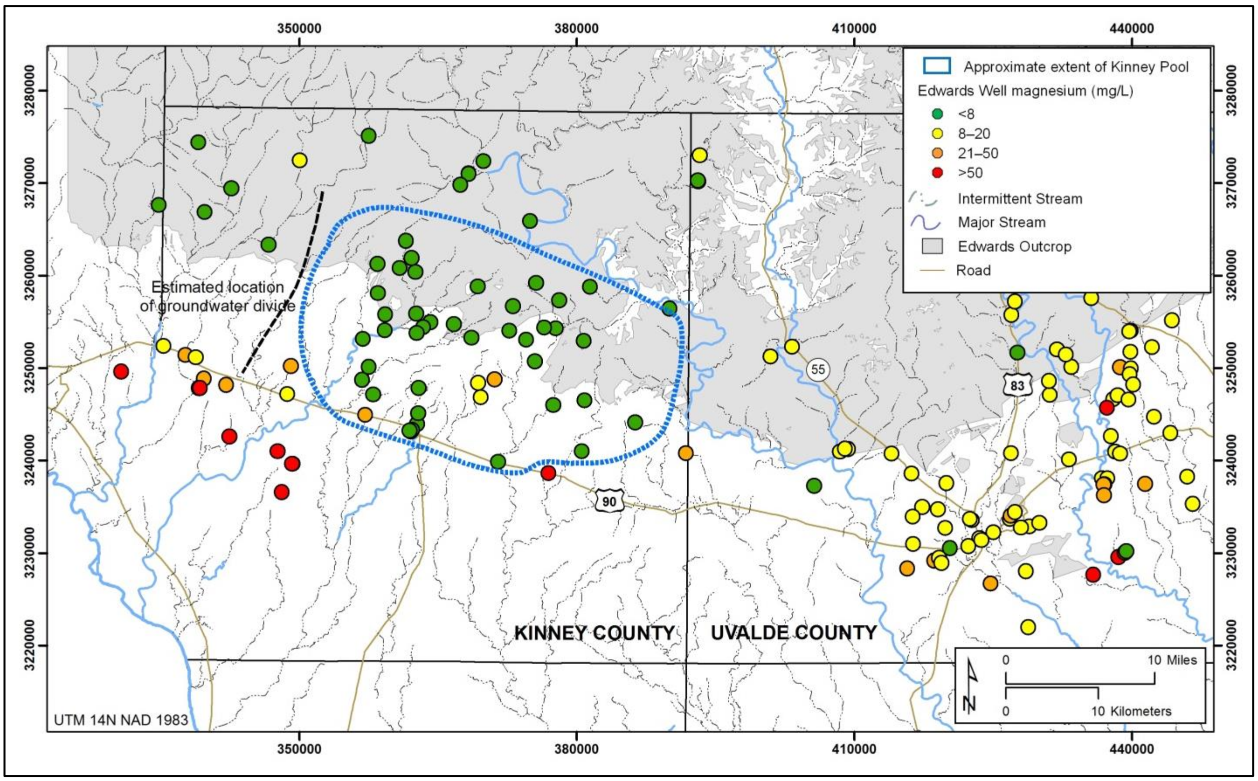


Figure 2.4.2.1-1. Map of the western portion of model area showing approximate location of the Kinney Pool. Measured concentrations of magnesium in Edwards Aquifer wells are also shown (mg/L).

The Edwards Aquifer in Kinney County is contained in the Maverick Basin facies, which comprises the Salmon Peak, McKnight, and West Nueces Formations (Figure 2.3.2-1). Of these formations, only the Salmon Peak typically has wells with capacity greater than 10 gallons per minute (gpm). Few wells are developed in either the McKnight or West Nueces Formations in Kinney County due to the limited transmissivity of these units. A map of the saturated thickness of the Salmon Peak Formation represents that portion of the Edwards Aquifer in Kinney County that functions as a water-bearing unit (Figure 2.4.2.1-3).

The Kinney Pool can be characterized as two northeast-southwest oriented embayments (Figure 2.4.2.1-2). The western embayment is coincident with Pinto Valley and is referred to as the Pinto Valley Embayment. The eastern embayment trends from Grass Valley in the northeast to Las Moras Creek in the southwest and is referred to as the Grass Valley Embayment. The eastern boundary of the Pinto Valley Embayment is punctuated by an upwelling in the base of the Edwards Aquifer, referred to here as the Kinney Salient. Insufficient structural evidence is available to describe the embayments as synclines or grabens. The interpretation that the embayments are synclines is consistent with the interpretation by Bennett and Sayre (1962). Conversely, faulting mapped in Kinney County suggests that the embayments are grabens. Regardless of their genesis, the greater depths in the base of the Salmon Peak Formation in the embayments explain, in part, the presence of high-capacity wells in Pinto and Grass valleys and wells with lesser capacity elsewhere in Kinney County (Green et al., 2006).

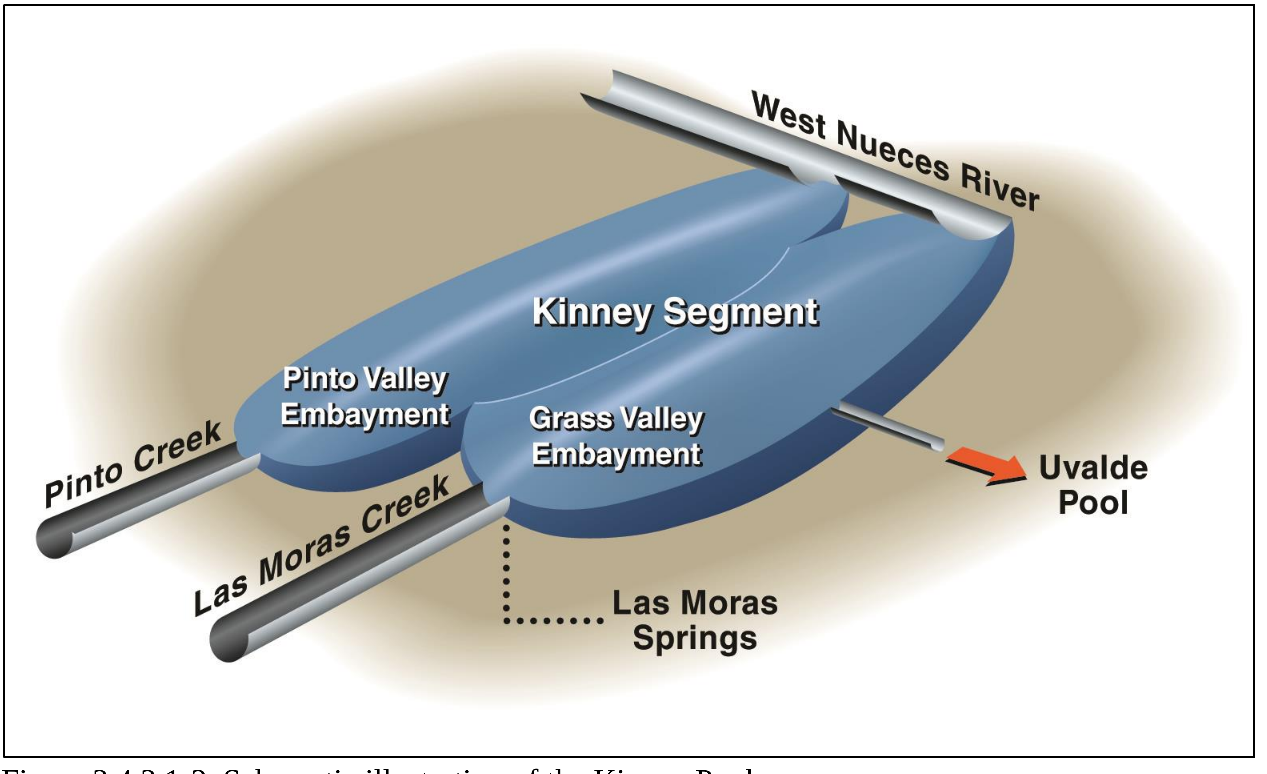


Figure 2.4.2.1-2. Schematic illustration of the Kinney Pool.

The geologic cross section in Figure 2.4.2.1-4 includes groundwater elevations from the 2006-synoptic survey relative to the structure of these units (Green et al., 2006). Of prime importance is that the superposition of the geologic structure and the groundwater elevations indicates a virtual dewatering of the 300-ft-thick permeable Salmon Peak Formation of the Edwards Aquifer slightly west of the Kinney and Uvalde County lines (Figure 2.4.2.1-4). The Kinney Salient is the principal reason the Salmon Peak Formation is unsaturated in eastern Kinney County. As a consequence of the geologic structure, there is limited opportunity for groundwater to flow from west-to-east from Kinney to Uvalde County, even though the groundwater elevation in Kinney County is greater than the groundwater elevation in Uvalde County. This dewatering of the Edwards Aquifer in eastern Kinney County forms a structural, hydraulic barrier that defines the eastern boundary of the Kinney Pool and the western boundary of the Uvalde Pool of the Edwards Aquifer (Figure 2.4.2.1-4).

Groundwater flow in the Edwards Aquifer from Kinney to Uvalde County is stage dependent. No flow would be expected during periods of low to moderate groundwater elevation, but limited flow from west to east is possible during periods when groundwater elevations are high. This limited hydraulic communication is interpreted as justification to designate this part of the Edwards Aquifer in Kinney County as a separate pool (Green et al., 2006).

The area that contributes to recharge of the Kinney Pool is not well defined. The contributing area has typically been equated to the West Nueces River watershed (Figure 2.1-3) (Bennett and Sayre, 1962; Mace and Anaya, 2004). This interpretation is predicated on the assumption that surface watershed divides coincide with groundwater basin divides.

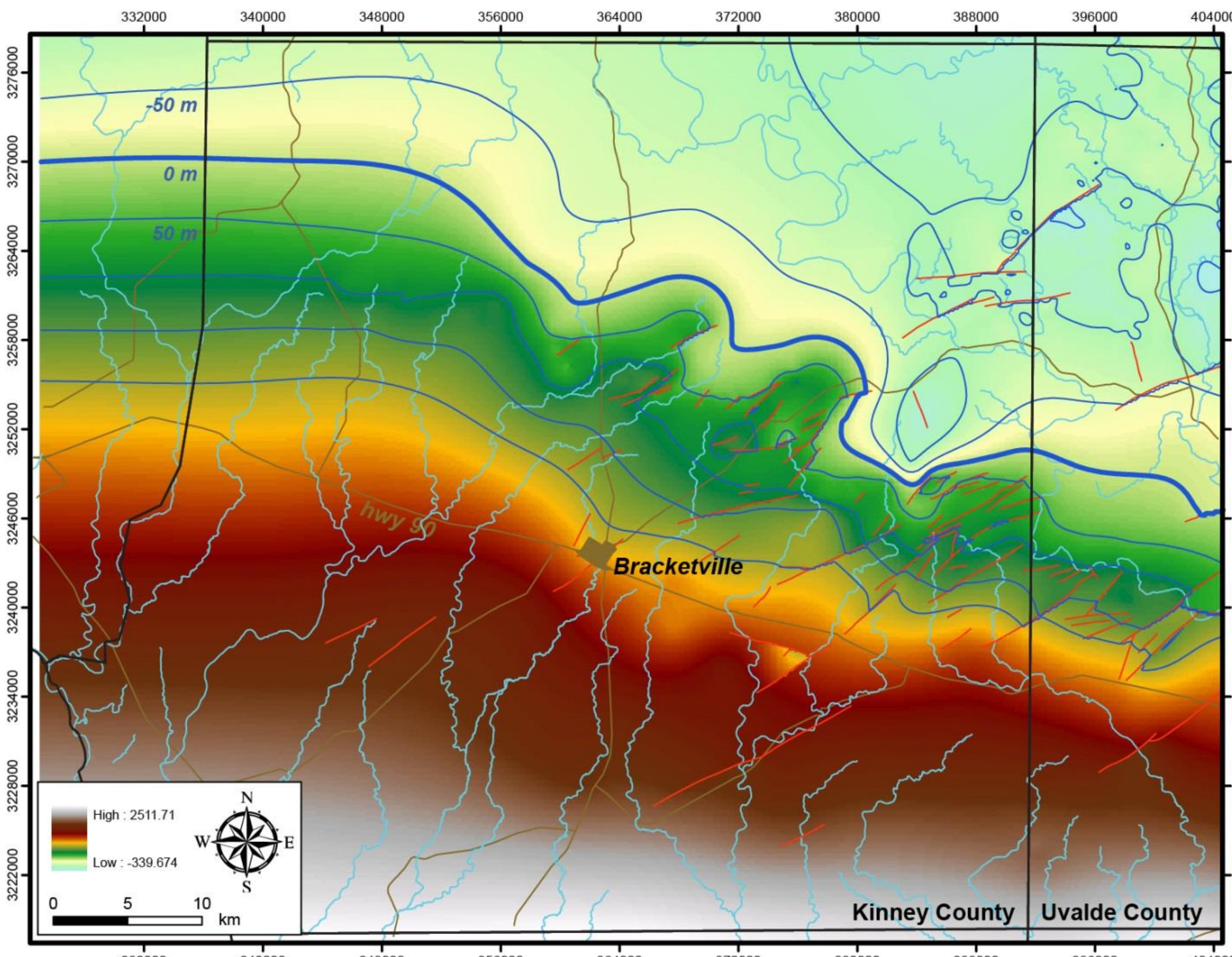


Figure 2.4.2.1-3. Map of the saturated thickness of the Salmon Peak Formation represents that portion of the Edwards Aquifer in Kinney County that functions as a water-bearing unit (m). Areas of the map showing negative saturated thickness in the Salmon Peak Formation indicates that the aquifer is dewatered.

The Sayre and Bennett (1942) and Bennett and Sayre (1962) conceptual models of groundwater flow assume that most recharge to the Edwards Aquifer in Kinney County originates in the Nueces-West Nueces River watersheds (Figure 2.1-3). Additional recharge that originates on the Edwards Plateau to the west of the Nueces-West Nueces River watersheds contribute to the Edwards-Trinity Aquifers in western Kinney and Val Verde Counties. Contours of the piezometric surface of the Edwards Aquifer in maps by Bennett and Sayre (1962) are parallel to the strike of the limestone (i.e., Balcones Fault Zone), suggesting that groundwater flow is downdip to the south in Kinney County. The only recognized points of discharge of the Edwards Aquifer in Kinney County are through springs and wells. Sayre and Bennett (1942) noted that there is no visible natural discharge south of the three largest springs in Kinney County (i.e., Pinto, Mud, and Las Moras). Sayre and Bennett (1942) also noted the Edwards Aquifer contains hydrogen sulfide to the south of the springs and that farther to the south groundwater is highly mineralized, suggesting that groundwater movement is minimal south of the springs.

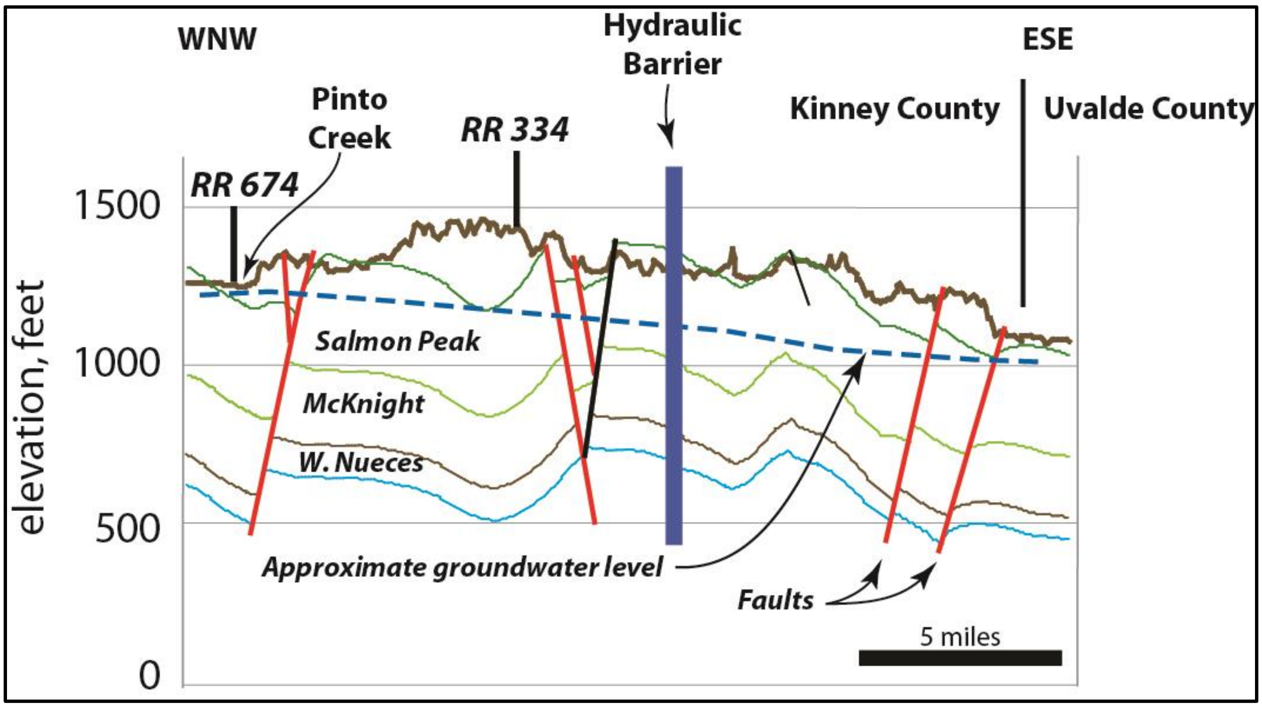


Figure 2.4.2.1-4. West-east geologic cross section illustrating the structural hydraulic barrier that defines the eastern boundary of the Kinney Pool. See Figure 2.4.2.1-3 for location of section line.

An observation by Bush et al. (1992) that groundwater flow in the Nueces-West Nueces River watersheds is to the southwest supports the conceptual model of a separate Edwards Aquifer Pool in Kinney County. This is a clear example of subterranean groundwater piracy, in which the flow of surface water is to the southeast in the West Nueces River and the flow of groundwater is to the southwest. Subterranean piracy in karst terrains is not uncommon, particularly in karst limestone aquifers, such as the Edwards Aquifer (Ford and Williams, 1989, White and White, 2001; White, 2006; Green and Bertetti, 2010a). Extending the observation by Bush et al. (1992), the conceptual model for a separate Kinney Pool indicates that recharge from the middle reaches of the West Nueces River goes to the Kinney Pool and recharge from the lower reaches of the

West Nueces River goes to the Uvalde Pool. This transition from the middle reach to the lower reach of the West Nueces River is interpreted to be at the eastern boundary of the Kinney Pool. If this interpretation is valid, the ultimate destination of groundwater discharged from the Kinney Pool of the Edwards Aquifer is the Rio Grande Basin, not the Nueces River Basin.

What is not well defined is the northern extent of the Kinney Pool groundwater basin. It is possible that portions of the upper reaches of the West Nueces River watershed also recharge the Uvalde Pool. Geochemical analyses of the Edwards-Trinity Aquifer systems corroborate the conceptualization that different reaches in the West Nueces River watershed provide recharge to both the Kinney and Uvalde Pools; however, the data are not conclusive (Nance, 2004). More conclusive are tracer tests conducted in the Edwards Aquifer in Kinney County to determine direction of groundwater flow. There have been two phases in the tracer testing, one performed in 2007 and the second performed in 2009 (Edwards Aquifer Authority, 2007, 2009). The dye injection locations and the inferred direct pathways from points of injection to points of detection are graphically illustrated in Figure 2.4.2.1-5. As shown, groundwater flow in the Kinney Pool remains in the Kinney Pool. There is no evidence of flow from the Kinney Pool to the Uvalde Pool. These dye tracer results substantiate the conceptualization that groundwater in the Kinney Pool flows toward Las Moras and Pinto Springs in south-central Kinney County and not from Kinney to Uvalde County

2.4.2.2 Kinney Pool Water Budget

Discharge at Las Moras Springs is variable with measured flow rates that have ranged from a maximum of 60 cubic feet per second (cfs) recorded on June 30, 1988 to periods of no flow. The average of 155 recorded measurements for Las Moras Springs provided in Bennett and Sayre (1962) during the period of 1895 to 1965 was 23.1 cfs, which equates to an annual discharge of 16,724 acre-ft. Using measurements from September 1939 to October 1940, Bennett and Sayre (1962) calculated the cumulative discharge from Las Moras, Pinto, and Mud Springs to be 23,000 acre-ft/yr of which discharge from Las Moras and Pinto Springs is 22,900 acre-ft/yr. Historic pumping records are limited for Kinney County. The total discharge from wells in Kinney County during 1955–1956, which occurred during the drought of record, was estimated to be the rate of about 4,000 acre-feet per year (Bennett and Sayre, 1962).

In the absence of continuously recorded pumping data, pumpage has been estimated for Kinney County using several techniques. Groundwater availability model runs by the Texas Water Development Board cite disparate estimates of pumping in Kinney County. There are three recent estimates for pumpage in Kinney County in these models. The range of these estimates is large. The first of these estimates of pumping were values assigned to simulations performed using Version 1.0 of the Edwards-Trinity Aquifer Groundwater Availability Model. Pumpage was estimated to vary from 2,102 to 9,057 acre-ft/yr and average 6,026 acre-ft/yr for the period 1980–1999 (Donnelly, 2007). Recharge for this case was distributed in the groundwater availability model based on a percent of annual precipitation and aquifer outcrop (surface geology).

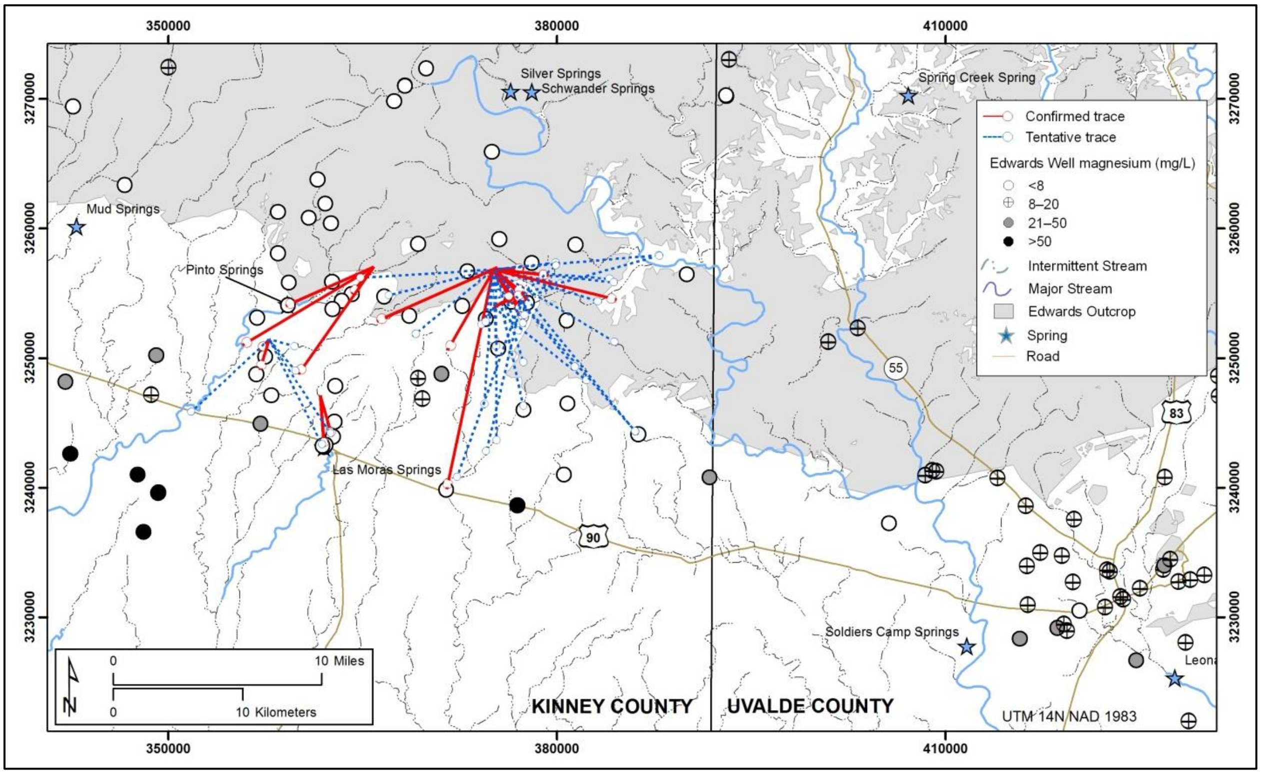


Figure 2.4.2.1-5. Map of tracer test results for traces conducted in Kinney County. Confirmed tracer detections (multiple detects in water samples) are shown as solid lines (red), while tentative traces (sporadic, single detections on charcoal) are shown as dashed lines (blue). Tracer detections are associated with locations of wells with low Mg concentration. ith the noted exception of detection patterns to the southeast, tracer detections follow established drainage features.

The Texas Water Development Board developed an alternative groundwater availability model that centered on Kinney County (Hutchison et al., 2011a). Pumpage values input into this model varied from a high of 59,126 acre-ft/yr in the early 1960s to a low of 16,613 acre-ft/yr in 2001. The database for pumpage values was provided to the Texas Water Development Board by the Kinney County Groundwater Conservation District. The period of record was 1960–2002.

The Texas Water Development Board also developed an alternative groundwater availability model of the Edwards-Trinity Aquifer that included all of the Edwards-Trinity Aquifer in Kinney County (Hutchison et al., 2011b). The calibration period of the alternative groundwater availability model was increased to 1930–2005. Pumpage for this period was revised upward from previous estimates during calibration, starting at 0 acre-ft/yr in 1930, increasing to 170,000 acre-ft/yr in the late 1960s before decreasing to 60,000 acre-ft/yr in 2005.

Annual pumpage also has been estimated for Kinney County by the Conservation Division of the Texas Water Development Board using different databases. Annual irrigation estimates for the years 1985–1988, 1990–1993, 1995–1999 were developed by using irrigated crop acreage from the Texas Agricultural Statistics Service and irrigation-use rates from the U.S. Department of Agriculture-Natural Resources Conservation Service. These data are presented in Table 2.4.2.2-

1. As shown in the table, water use for irrigation varied from a low of 894 acre-ft in 2009 to a high of 14,108 in 2000. The average water use for irrigation for this period was 5,897 acre-ft/yr. If domestic and livestock pumpage is estimated at 1,500 acre-ft/yr, total pumpage for this period was 7,400 acre-ft/yr.

The second estimate of irrigation pumping was for years 1958, 1964, 1969, 1974, 1979, 1984, 1989, 1994, and 2000. This estimate was developed by the U.S. Department of Agriculture-Natural Resources Conservation Service in cooperation with the Texas Water Development Board (Table 2.4.2.2-2). These data can be found in Texas Water Development Board numbered reports R127, R294, R329, and R347 at http://www.twdb.state.tx.us/publications/reports/ numbered_reports/. The average groundwater usage for irrigation was 9,200 acre-ft/yr for the period 1958–2000 using this estimation technique.

Table 2.4.2.2-1. Estimated irrigated acres and acre-ft of water for Kinney County. Water use is calculated using acreage of irrigated cropland and crop type. Data provided by the Texas Water Development Board (PublicInfo@twdb.state.tx.us) via email to SwRI on December 27, 2012.

Year	Estimated Irrigated Acres	Estimated Acre-Feet of Irrigation	Year	Estimated Irrigated Acres	Estimated Acre-Feet of Irrigation
1985	5,000	5,266	**1998**	4,861	6,323
1986	4,000	5,000	**1999**	4,061	4,357
1987	3,000	2,083	**2000**	7,355	14,108
1988	3,000	3,183	**2001**	4,485	5,961
1989	5,403	12,346	**2002**	4,468	5,857
1990	5,412	7,869	**2003**	5,181	9,868
1991	5,412	7,869	**2004**	4,013	4,513
1992	5,512	6,735	**2005**	3,075	3,980
1993	6,185	9,022	**2006**	2,867	4,775
1994	6,185	7,476	**2007**	2,169	1,638
1995	5,928	5,858	**2008**	1,930	2,040
1996	6,279	8,066	**2009**	665	894
1997	5,612	6,986	**2010**	1,195	1,258

Table 2.4.2.2-2. Estimated water usage in Kinney County. Information developed by U.S. Department of Agriculture-Natural Resources Conservation Service in cooperation with Texas Water Development Board. Data provided by the Texas Water Development Board (PublicInfo@twdb.state.tx.us) via email to SwRI on December 27, 2012.

YEAR	**Total Acres**	**Total Acre Feet**	**Surface Water Acres**	**Surface Water Acre Feet**	**Ground Water Acres**	**Ground Water Acre Feet**	**Combined Supply Acres**	**Combined Supply Acre Feet**	**Number Irrigation wells**	**Sprinkler System Acres**
1958	2,335	3,173	600	692	1,535	2,301	200	180	14	0
1964	5,900	11,147	600	1,000	5,300	10,147	0	0	36	0
1969	8,986	16,658	2,550	4,325	6,436	12,333	0	0	61	0
1974	8,550	14,317	2,500	3,497	6,050	10,820	0	0	50	0
1979	7,566	12,862	2,500	3,500	5,000	9,203	66	159	50	413
1984	4,706	10,335	671	1,212	4,035	9,123	0	0	28	1,555
1989	5,099	12,349	738	1,851	4,361	10,498	0	0	28	1,555
1994	4,735	7,479	0	0	4,735	7,479	0	0	25	1,510
2000	4,865	14,112	0	0	4,865	14,112	0	0	34	1,715

The third estimate is a summary of historical total surface water and groundwater usage in Kinney County provided by the Texas Water Development Board (Table 2.4.2.2-3). The average total groundwater usage for municipal, irrigation, and livestock purposes was 8,500 acre-ft per year. Municipal, irrigation, and livestock uses were 1,100, 7,000, and 400 acre-ft/yr, respectively.

Table 2.4.2.2-3. Historical water use summary by Groundwater (GW) and Surface Water (SW) measured in (acre-ft). Data provided by the Texas Water Development Board (PublicInfo@twdb.state.tx.us) via email to SwRI on December 27, 2012.

Year	**Source**	**Municipal**	**Irrigation**	**Livestock**	**Total**
1974	GW	622	10,820	706	12,148
1974	SW	0	3,497	74	3,571
	Total	**622**	**14,317**	**780**	**15,719**
1980	GW	1,031	9,308	495	10,834
1980	SW	0	1,782	123	1,905
	Total	**1,031**	**11,090**	**618**	**12,739**
1984	GW	1,074	9,123	386	10,583
1984	SW	0	1,515	96	1,611
	Total	**1,074**	**10,638**	**482**	**12,194**
1985	GW	1,057	4,634	375	6,066
1985	SW	0	695	93	788
	Total	**1,057**	**5,329**	**468**	**6,854**
1986	GW	1,082	5,000	454	6,536
1986	SW	0	0	113	113

Year	Source	Municipal	Irrigation	Livestock	Total
	Total	**1,082**	**5,000**	**567**	**6,649**
1987	GW	1,058	2,083	506	3,647
1987	SW	0	0	126	126
	Total	**1,058**	**2,083**	**632**	**3,773**
1988	GW	1,198	2,705	544	4,447
1988	SW	0	477	136	613
	Total	**1,198**	**3,182**	**680**	**5,060**
1989	GW	1,379	10,498	496	12,403
1989	SW	0	1,851	124	1,975
	Total	**1,379**	**12,349**	**620**	**14,378**
1990	GW	1,205	6,689	500	8,394
1990	SW	0	1,180	124	1,304
	Total	**1,205**	**7,869**	**624**	**9,698**
1991	GW	1,036	6,689	519	8,244
1991	SW	0	1,180	129	1,309
	Total	**1,036**	**7,869**	**648**	**9,553**
1992	GW	987	5,388	540	6,915
1992	SW	0	1,347	135	1,482
	Total	**987**	**6,735**	**675**	**8,397**
1993	GW	1,126	9,025	473	10,624
1993	SW	0	0	119	119
	Total	**1,126**	**9,025**	**592**	**10,743**
1994	GW	1,120	7,479	443	9,042
1994	SW	0	0	110	110
	Total	**1,120**	**7,479**	**553**	**9,152**
1995	GW	1,114	5,859	429	7,402
1995	SW	0	0	107	107
	Total	**1,114**	**5,859**	**536**	**7,509**
1996	GW	1,171	8,067	372	9,610
1996	SW	0	0	93	93
	Total	**1,171**	**8,067**	**465**	**9,703**
1997	GW	1,174	6,987	313	8,474
1997	SW	0	0	78	78
	Total	**1,174**	**6,987**	**391**	**8,552**
1998	GW	1,299	6,324	277	7,900
1998	SW	0	0	69	69
	Total	**1,299**	**6,324**	**346**	**7,969**
1999	GW	1,220	4,359	323	5,902
1999	SW	0	0	81	81
	Total	**1,220**	**4,359**	**404**	**5,983**
2000	GW	1,365	14,112	356	15,833
2000	SW	0	0	89	89
	Total	**1,365**	**14,112**	**445**	**15,922**

Year	Source	Municipal	Irrigation	Livestock	Total
2001	GW	838	5,965	172	6,975
2001	SW	0	0	247	247
	Total	**838**	**5,965**	**419**	**7,222**
2002	GW	844	5,860	159	6,863
2002	SW	0	0	228	228
	Total	**844**	**5,860**	**387**	**7,091**
2003	GW	1,162	9,868	117	11,147
2003	SW	0	0	168	168
	Total	**1,162**	**9,868**	**285**	**11,315**
2004	GW	1,001	4,513	127	5,641
2004	SW	0	0	182	182
	Total	**1,001**	**4,513**	**309**	**5,823**

Based on Texas Water Development Board estimates, the total acres in irrigation in Kinney County varied from 3,000–6,279 acre-ft/yr over the period 1985–1997 (Table 2.4.2.2-1) and from 2,335–8,986 acre-ft/yr over the period 1958–2000 (Table 2.4.2.2-2). Annual irrigation for crops grown in Kinney County (i.e., cotton, corn, wheat, etc.) do not typically require over 2 acre-ft/yr of irrigation water (McDaniels, 1962). In summary, the Conservation Division of the Texas Water Development Board estimates for pumpage in Kinney County using three different crop databases were similar and averaged between 7,400 to 9,200 acre-ft/yr for the period 1954–2010. The minimum pumpage for irrigation was about 900 acre-ft in 2009. The maximum estimated total pumpage was about 16,000 acre-ft in 2000.

Estimates of pumpage based on crop irrigation are consistent when compared with discharge at Las Moras Springs. Las Moras Springs discharge is correlated with land use (a surrogate of pumping for irrigation) in Figure 2.4.2.2-1. This figure indicates that irrigation pumping at about 5,000–8,000 acre-ft/year was insufficient to impact spring discharge to the point that the springs would quit flowing. Las Moras Springs quit flowing seven times during the period of the mid-1960s to the mid-1980s, when irrigation pumping was approximately 12,000–16,000 acre-ft/year. Las Moras Springs quit flowing only once since the mid-1980s, when irrigation pumping was reduced to approximately 6,000–16,000 acre-ft/year.

Historical pumpage is believed to be consistent with pumpage estimates using crop irrigation and with pumpage estimates documented by Donnelly (2007), which is significantly less than estimates by Hutchison et al. (2011a,b). Historical pumpage for Kinney County is therefore ascertained to usually be in the range of 7,400–9,200 acre-ft/yr; however, pumpage could vary from as low as 900 acre-ft/yr to as high as 16,000 acre-ft/yr.

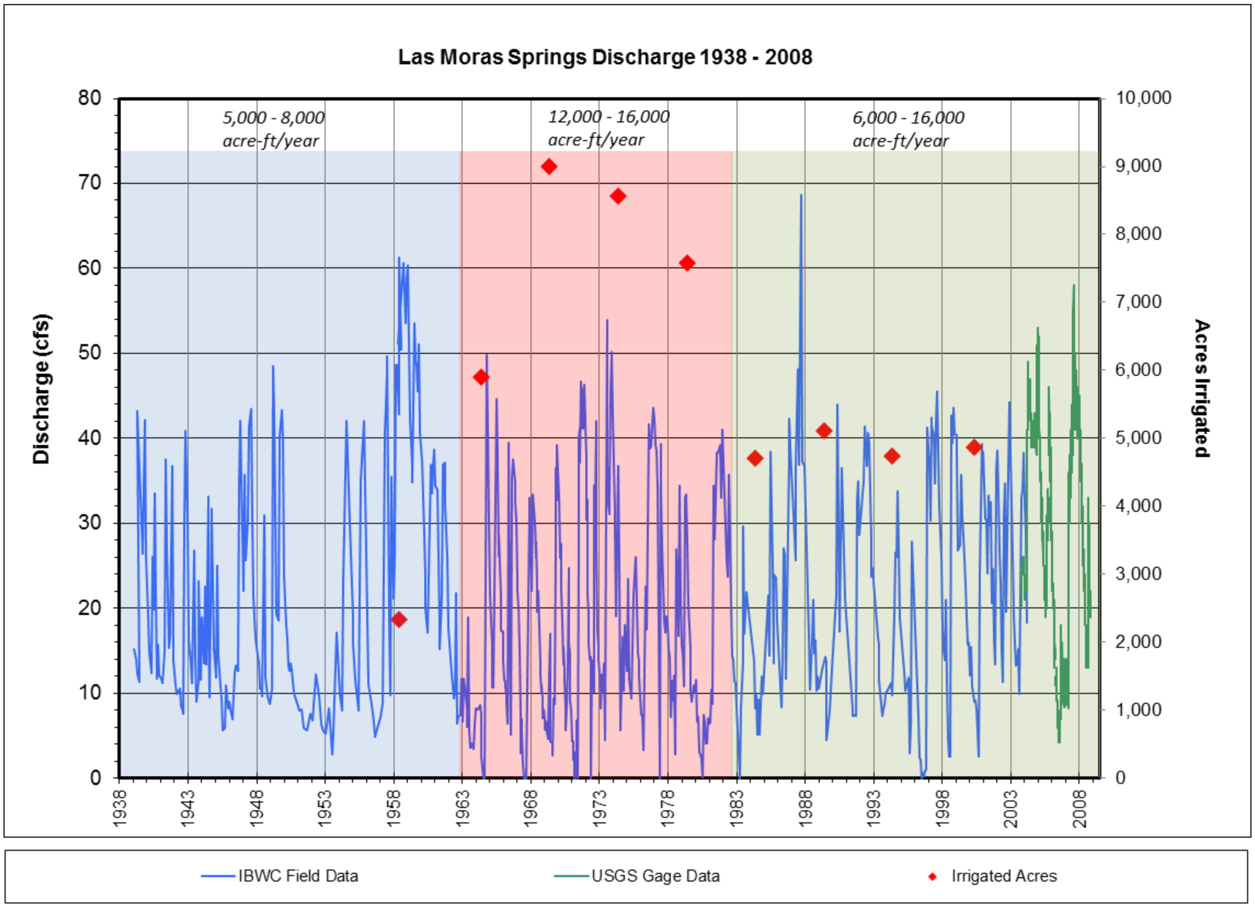


Figure 2.4.2.2-1. Las Moras Springs discharge 1938-2008 (LBG-Guyton Associates, 2010). Irrigated acres in Kinney County are designated for selected years with red diamonds. Pumping rates are calculated based on number of acres irrigated and crop type. [Land use information developed by USDA-NRCS in cooperation with TWDB. Data provided by the Texas Water Development Board (PublicInfo@twdb.state.tx.us) via email to SwRI on December 27, 2012.]

There have been several assessments of total recharge to the Edwards Aquifer in Kinney County. The first estimate of 70,000 acre-ft/yr was calculated by Bennett and Sayre (1962) based on data from 1939–1950 and did not include the period of the drought of record during the 1950s. The Bennett and Sayre (1962) analysis calculates the amount of recharge to the Edwards Aquifer that occurs in Kinney County. This estimate does not include underflow from outside Kinney County. Key assumptions in the Bennett and Sayre (1962) analysis were that: (i) the portion of the West Nueces River watershed in Kinney County is about half the total area of the Nueces-West Nueces River watersheds and (ii) the recharge area of the rest of the county is about equal to the portion of the West Nueces River watershed in Kinney County. Subsequent analyses of total recharge to the Edwards Aquifer in Kinney County by Muller and Price (1979), Kier (1998), and Khorzad (2002, 2003) were predicated on the approach of Bennett and Sayre (1962).

Muller and Price (1979) estimated recharge to the Edwards Plateau in the Nueces-West Nueces River watersheds at 107,500 acre-ft/yr, but the amount expected to recharge Kinney County was not specified. Kier (1998) estimated Kinney County recharge at 70,000 acre-ft/yr, factoring in contributions from Real and Edwards Counties and assuming an average recharge rate of 1.4 in/year. Kier (1998) estimated recharge would be 90,000 to 95,000 acre-ft/yr if the average distributed recharge rate is 2.0 in/year. Although Kier (1998) did not explicitly mention an underflow contribution from the Trinity Aquifer, a later report by Mace and Anaya (2004) interpreted that the Kier (1998) estimate included an underflow contribution from the Trinity to the Edwards Aquifer.

Khorzad (2002, 2003) asserted the U.S. Geological Survey stream gauging stations at Laguna, Brackettville, and Uvalde underestimated actual recharge because streamflow losses along ungauged tributaries, such as Live Oak and Sycamore Creeks, within the drainage basin are not included in the recharge estimates. Khorzad (2002, 2003) modified the basin size calculated by Bennett and Sayre (1962) to arrive at 71,382 acre-ft/yr recharge from the Nueces-West Nueces River watersheds. An assumption of 5 percent underflow recharge from the Trinity Aquifer was included in the estimate by Khorzad (2002, 2003).

Mace and Anaya (2004) evaluated the analyses by Bennett and Sayre (1962), Muller and Price (1979), and Khorzad (2002, 2003). The analysis of Mace and Anaya (2004) used the same general approach as Bennett and Sayre (1962). They detected errors in two assumptions in the original Bennett and Sayre (1962) analysis. First, the portion of the West Nueces River watershed in Kinney County is only 30 percent of the total area of the watershed, not the 50 percent as reported by Bennett and Sayre (1962). Second, Bennett and Sayre (1962) used the wrong streamflow value for the Nueces River for 1 year of the analysis. Mace and Anaya (2004) noted that analyses by Muller and Price (1979), Kier (1998), and Khorzad (2002, 2003) are in error because they relied on the inaccurate assumptions in the Bennett and Sayre (1962) analysis. They calculated recharge of the Edwards Aquifer Recharge Zone was for the area both inside (176,000 acre) and outside (138,240 acre) of the West Nueces River watershed in Kinney County. Mace and Anaya (2004) corrected the estimates of area and streamflow in the Bennett and Sayre (1962) analysis to arrive at an average recharge of the Edwards Aquifer in Kinney County of 69,800 acre-ft/yr for the period of analysis (1939–1950 and 1956–2001).The portion of the Edwards Aquifer Recharge Zone that is outside the West Nueces River watershed is interpreted here to be in a watershed that drains to the Rio Grande and is not within the model domain. There are, however, an additional 404,480 acres of Nueces-West Nueces River watersheds in Edwards County that do contribute to recharge of the Kinney Pool. The total area of the West Nueces River watershed upgradient from the river gauge in Brackettville is 580,480 acres.

The U.S. Geological Survey has been monitoring groundwater recharge to the Edwards Aquifer outcrop area in the Nueces-West Nueces River watersheds using precipitation and river leakage since 1934 (Tremallo et al., 2014). The U.S. Geological Survey estimated the groundwater recharge to the Edwards Recharge Zone (i.e. outcrop area) based on surface runoff in the catchment area of the Nueces-West Nueces River watersheds. For the period 1950–2005, the U.S. Geological Survey calculations for recharge averaged 132,038 acre-ft/yr. Hutchison et al. (2011b) provided refined values for recharge during calibration of the alternative groundwater availability model for Kinney County. Recharge to Edwards outcrop due to river leakage averaged 42,513 acre-ft/yr and recharge to the Edwards outcrop averaged

39,240 acre-ft/yr for a total of 81,752 acre-ft/yr for the same period as the U.S. Geological Survey calculation.

Over the 1934–2013 period of record, recharge of the Edwards Aquifer via the West Nueces-Nueces Rivers, which recharge both the Kinney and Uvalde Pools, , was calculated by the U.S. Geological Survey to vary from a low of 8,600 acre-ft in 1934 to a high of 481,900 acre-ft in 2004 with a mean value of 99,700 acre-ft/yr (Tremallo et al., 2014). Both recharge and discharge are regional estimates (i.e., for the combined Nueces-West Nueces River watersheds and the combined Frio-Dry Frio River watersheds).

The potential for significant recharge of the Edwards Aquifer from the West Nueces River has long been recognized (Sayre and Bennett, 1942; Bennett and Sayre, 1962); however, which portion of the Edwards Aquifer that is recharged by which reach of the river has not been clearly identified. Correlations between precipitation events near Rock Springs and Camp Wood in Edwards and Real Counties and discharge at Las Moras Springs (Keir, 1998) suggest the Edwards Aquifer in Kinney County is recharged by the West Nueces River.

Recharge of the Edwards Aquifer from Nueces-West Nueces River watersheds also can be estimated using an empirical relationship between annual average precipitation and recharge that was developed for the western Edwards Plateau region using recharge calculations based on stream baseflow separation analyses (Green and Bertetti, 2010a, Green et al., 2012a). This correlation can be presented

$$R = 0.15\ (P - 16.5) \quad \text{(Eq. 2.4.2.2-1)}$$

where *R* is recharge (inch/yr) and *P* is precipitation (inch/yr). If this correlation is appropriate for the West Nueces River component of the combined Nueces-West Nueces River watersheds, then the average annual precipitation of approximately 22 inch/yr of precipitation in Brackettville (Mace and Anaya, 2004) should provide about 0.82 inch/yr of recharge when averaged over the watersheds. Mace and Anaya (2004) reference recharge rates of 1.4 inch/yr (Muller and Price, 1979), 1.78 inch/yr (HDR Engineering, 2002), and their own estimate of 2.5 inch/yr. For a watershed of 580,480 acres, these recharge rates equate to 67,720, 86,100, 120,930 acre-ft/yr of recharge in the West Nueces River watershed, respectively.

Las Moras and Pinto Springs are the only identified points of discharge from the Kinney Pool with the possible exception of limited groundwater flow to the Uvalde Pool during periods of high stage. The combined average annual discharge for the period 1966–2009 from Las Moras Springs was 15,832 acre-ft/yr and for the period 1965–1995 from Pinto Springs was 2,254 acre-ft/yr (LBG-Guyton Associates, 2004) for a total of 18,086 acre-ft/yr. If the Kinney Pool conceptualization proposed here is valid, then either the recharge rate, the groundwater basins for the two springs, or both, are less than conceptualized by Mace and Anaya (2004).

Analyses by Bennett and Sayre (1962) and Mace and Anaya (2004) assumed that: (i) the surface watershed coincides with the groundwater basin of the West Nueces River watershed and (ii) cross-formational flow of water from the underlying rocks of the Trinity Group into the Edwards Aquifer is negligible. Neither assumption is believed valid based on water-budget analyses for the Kinney and Uvalde Pools. If these assumptions are accepted as valid, then too much water is recharged to the Kinney Pool and insufficient water is recharged to the Uvalde Pool. The conceptual model here is the groundwater basin(s) that feeds Las Moras and Pinto Springs is limited in extent and that much of the eastern or upper portion of the West Nueces River watershed drains to the Nueces River watershed.

2.4.2.3 Uvalde Pool

An assessment of available data on the hydrogeology of Uvalde County suggests the Edwards Aquifer in Uvalde County to the west of Knippa may act as a partially separate groundwater basin within the Edwards Aquifer (Green et al., 2006) (Figure 2.4.2.3-1). A schematic of Uvalde Pool is illustrated in Figure 2.4.2.3-2.

This groundwater basin is referred to as the Uvalde Pool. The hydraulic connection between the Uvalde and San Antonio Pools of the Edwards Aquifer to the east is variable and depends on groundwater elevation. In addition to the Edwards Aquifer, there are significant secondary aquifers in the Uvalde Pool, including the Austin Chalk, Buda Limestone, and the Leona Formation. The principal geological features that define the structural and hydraulic relationships among the aquifers in Uvalde County are the Balcones Fault Zone, the Uvalde Salient, a facies change in the Edwards Group, and the prevalence of igneous intrusions. The cumulative effect of these geologic factors is to impede the eastward flow of groundwater in the Edwards Aquifer in central Uvalde County. This impediment is referred to as the Knippa Gap (Maclay and Land, 1988). The highest and lowest groundwater elevations recorded at the Uvalde index well (J-27) located in the Uvalde Pool were 889 ft msl (June, 1987) and 811 ft msl (April, 1957) (www.edwardsaquifer.org accessed on March 6, 2009).

In the vicinity of the City of Uvalde, the Balcones Fault Zone is manifested by a large number of faults with relatively small down-to-the-southeast displacements, together with several faults antithetic to the main trend (i.e., down-to-the-northwest displacement) (Figure 2.4.2.3-3). To the northeast of the City of Uvalde, a smaller number of faults, one with a throw of 200 feet, accomplish the same amount of total displacement. The geological formations and the systematic displacements associated with the Balcones Fault Zone are disrupted in central Uvalde County along a structural uplift referred to as the Uvalde Salient (Welder and Reeves, 1962; Rives, 1967; Clark and Small, 1997; Clark, 2003). This structural high has the general shape of a ridge that is widest near Cook’s Fault to the north and thins and plunges to the south (Green et al., 2006, 2009a).

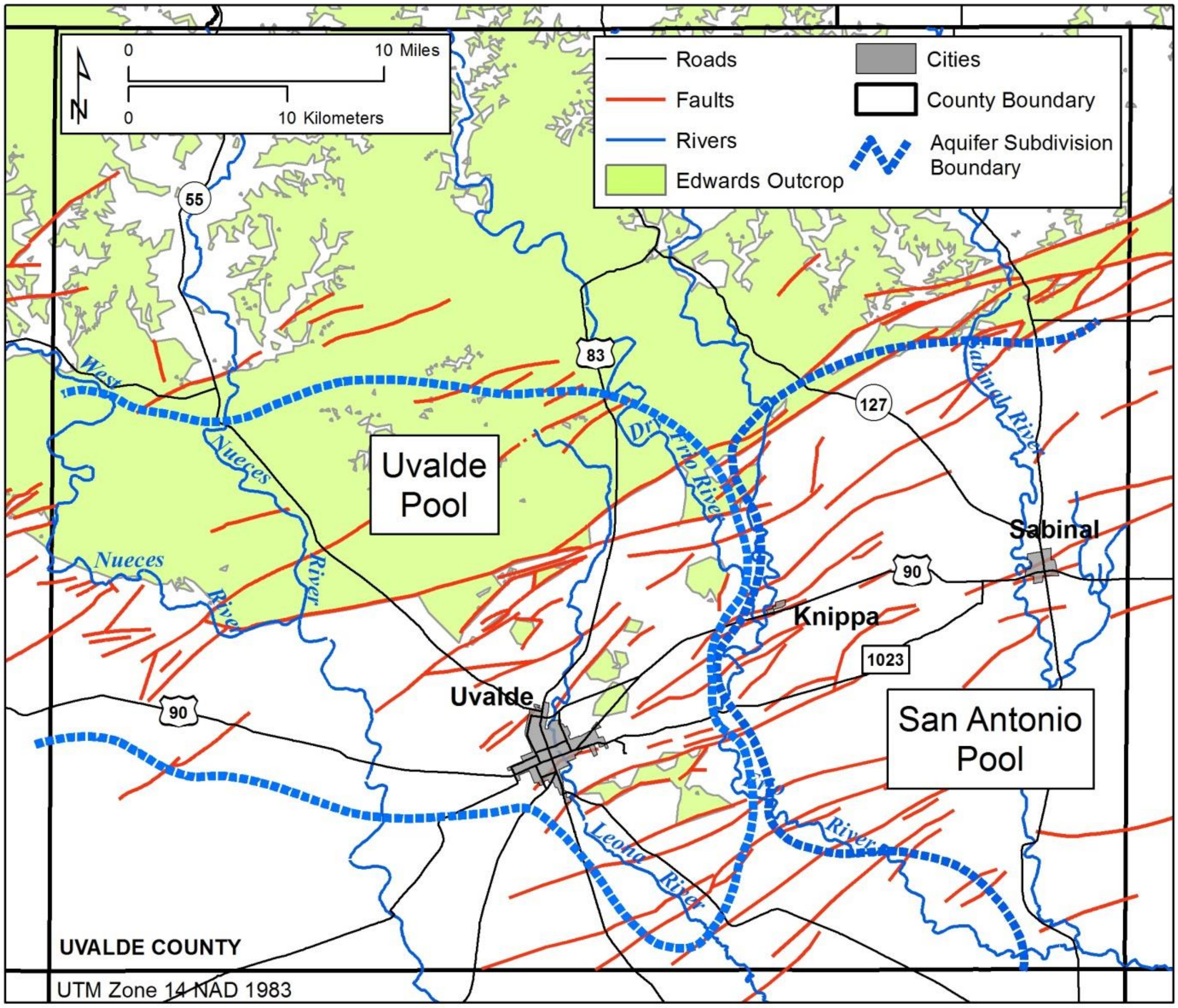


Figure 2.4.2.3-1. The Uvalde Pool is located in the western portion of Uvalde County and is bordered on the east by Knippa Gap, located at the City of Knippa (Green and Bertetti, 2010b).

Similarity of groundwater elevations to the west of the Uvalde Salient support the conceptualization that the Edwards, Buda Limestone, and Austin Chalk Aquifers are in hydraulic communication in the Uvalde Pool. The southern portion of the Uvalde Pool is classified as confined and is designated as the Confined Zone; however, since the Edwards Aquifer is in hydraulic communication with the Austin Chalk and Buda Aquifers, which are unconfined, the Uvalde Pool is in reality, unconfined. The maximum rate of decline in the groundwater level measured in the Uvalde Pool is approximately 0.5 ft per month, which supports the designation of the Uvalde Pool as an unconfined aquifer (Figure 2.4.2.3-4).

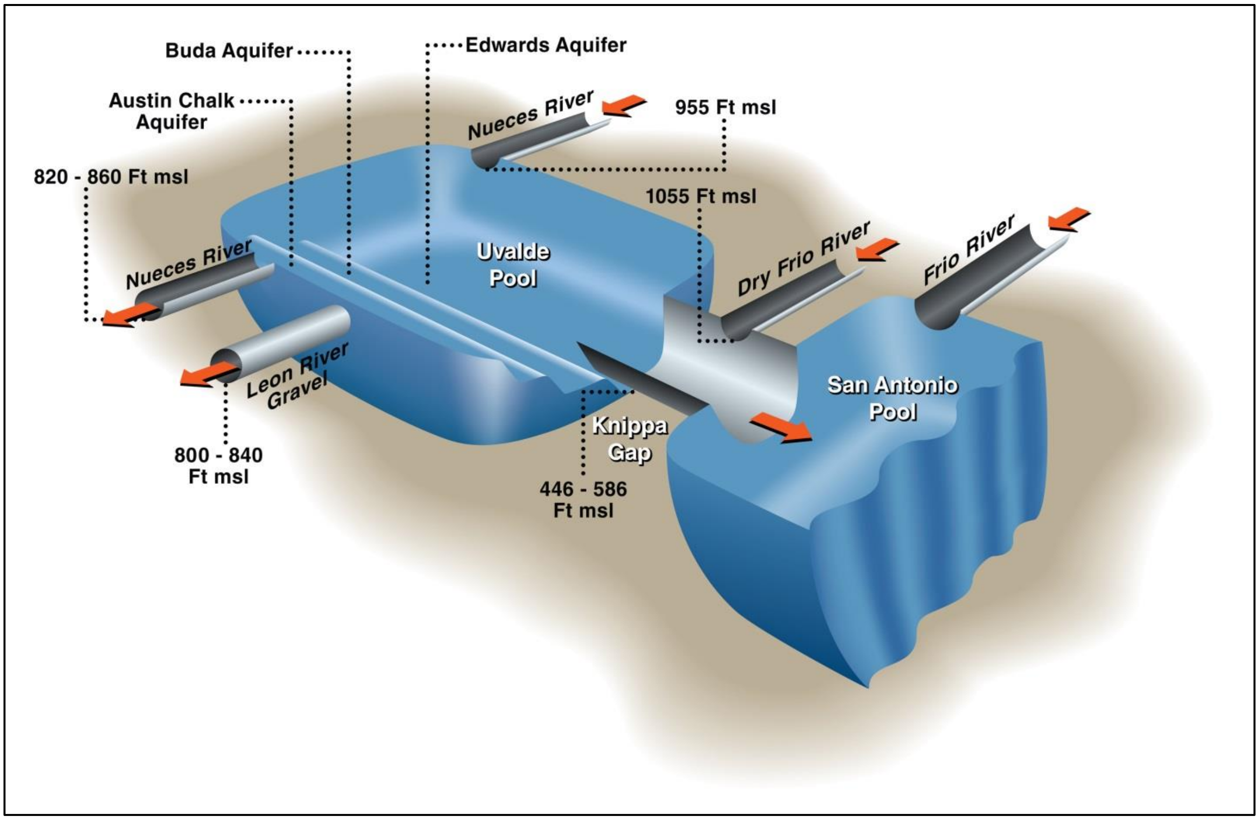


Figure 2.4.2.3-2. Schematic illustration of the Uvalde Pool.

Using a similar argument, the Leona Aquifer is apparently hydraulically connected with the Edwards, Buda Limestone, and Austin Chalk Aquifers at the headwaters of the Leona River from Highway 90 in the City of Uvalde south to Fort Inge (Green et al., 2008b, 2009a). To the south of Fort Inge, a difference in groundwater elevations between the Leona and Edwards Aquifers suggests the Leona Aquifer is not hydraulically connected with the Edwards Aquifer. Because of this hydraulic communication, the Austin Chalk and the Buda Limestone in the Uvalde Pool are included as part of the conceptual model of the Edwards Aquifer (Figure 2.4.2.3-5). Hydraulic communication among the aquifers does not appear to extend to the east of the Knippa Gap.

The principal source of recharge of the Uvalde Pool is the Nueces River, both as surface flow and as subsurface flow that occurs mostly as underflow in the bedrock associated with the Nueces River Channel. Groundwater flow pathways with enhanced permeability are believed to have developed in the Nueces River Channel (Woodruff and Abbott, 1979, 1986; Abbott and Woodruff, 1986; Green et al., 2014). There also is an opportunity for interformational flow from the Trinity to the Edwards Aquifer in interstream regions. The quantity of this interstream, interformational flow is not well defined, but not believed to be significant (Maclay and Land, 1988). The Dry Frio River is interpreted to recharge the Edwards Aquifer in proximity to the Knippa Gap. The Frio River clearly appears to recharge the San Antonio Pool of the Edwards Aquifer. Based on this conceptualization, neither the Dry Frio River nor the Frio River recharge the Uvalde Pool.

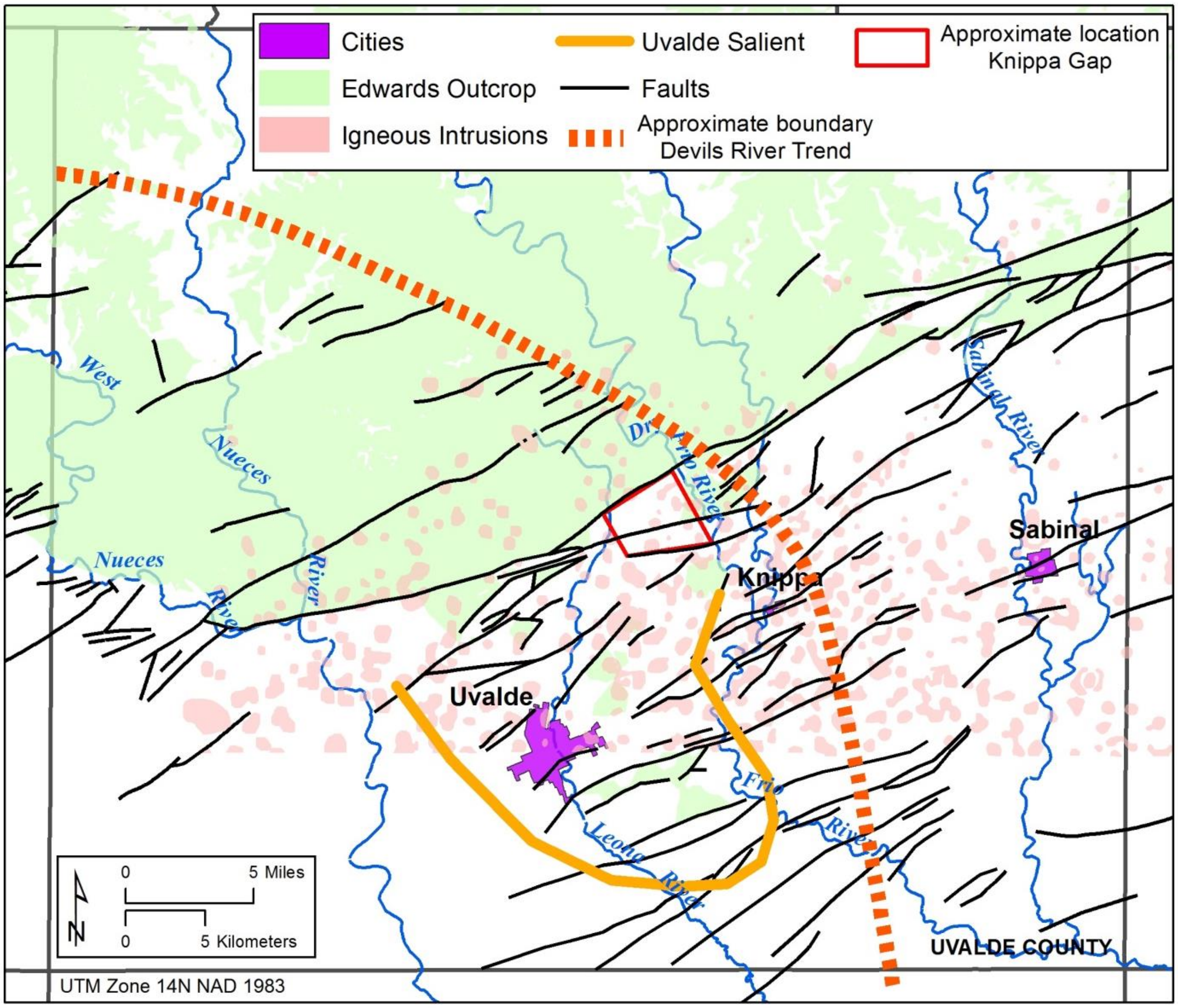


Figure 2.4.2.3-3. Geological features in Uvalde County. The dashed line denotes the approximate transition from Edwards Maverick Basin stratigraphy (Salmon Peak Limestone) to the west to Devils River Trend stratigraphy (Devils River Limestone) to the east (estimated from Clark, 2003). Outcrops of Edwards Limestone and underlying structure define the location of the Uvalde Salient (solid orange line) (Green, et al., 2009a). Inferred igneous intrusions based on aeromagnetic survey data are also shown (Smith, et al., 2008). The red box depicts the approximate location of the Knippa Gap (Green et al, 2009a).

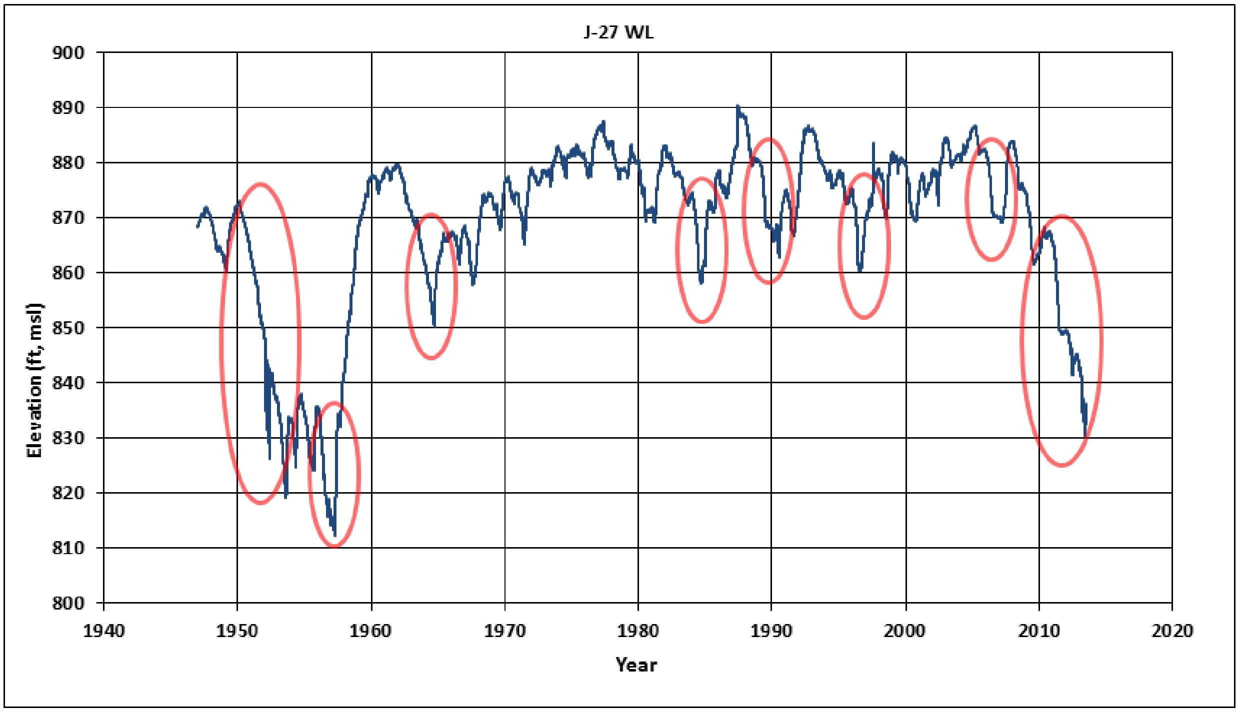


Figure 2.4.2.3-4. Water elevation at Uvalde index well J-27 measured in ft above mean sea level (ft, msl). Red ellipses indicate times when Uvalde Pool recharge is insufficient to maintain rates of discharge from the Uvalde Pool.

Water is naturally discharged from the Uvalde Pool via the Knippa Gap, Leona Formation gravels in the Leona River floodplain, and the Nueces River. Whether and how much water is discharged at these particular locations is a function of the groundwater elevation. It is important to note that rivers ,such as the Nueces that provide recharge in the upper reaches over the Edwards Aquifer Recharge Zone, also can act as discharge points where they exit the Recharge Zone. The highest point of discharge from the Uvalde Pool is the Nueces River via the Buda Limestone and Austin Chalk Aquifers because of the hydraulic communication among the Austin Chalk, Buda Limestone, and Edwards Aquifers in the Uvalde Pool. Soldiers Camp (or Rose) Springs, located where the Austin Chalk crops out at approximately 855 to 860 ft msl in the Nueces River channel south of the City of Uvalde, provide an opportunity for Edwards Aquifer water to discharge (indirectly via the Austin Chalk Aquifer) into the Nueces River (Brune, 1981). There also are unnamed springs in the Nueces River downstream from Soldiers Camp Springs. These unnamed springs, at 820 to 840 ft msl, appear to be the farthest downgradient opportunity for Edwards Aquifer to discharge into the Nueces River (Figure 2.4.2.3-6) (Green et al., 2009a).

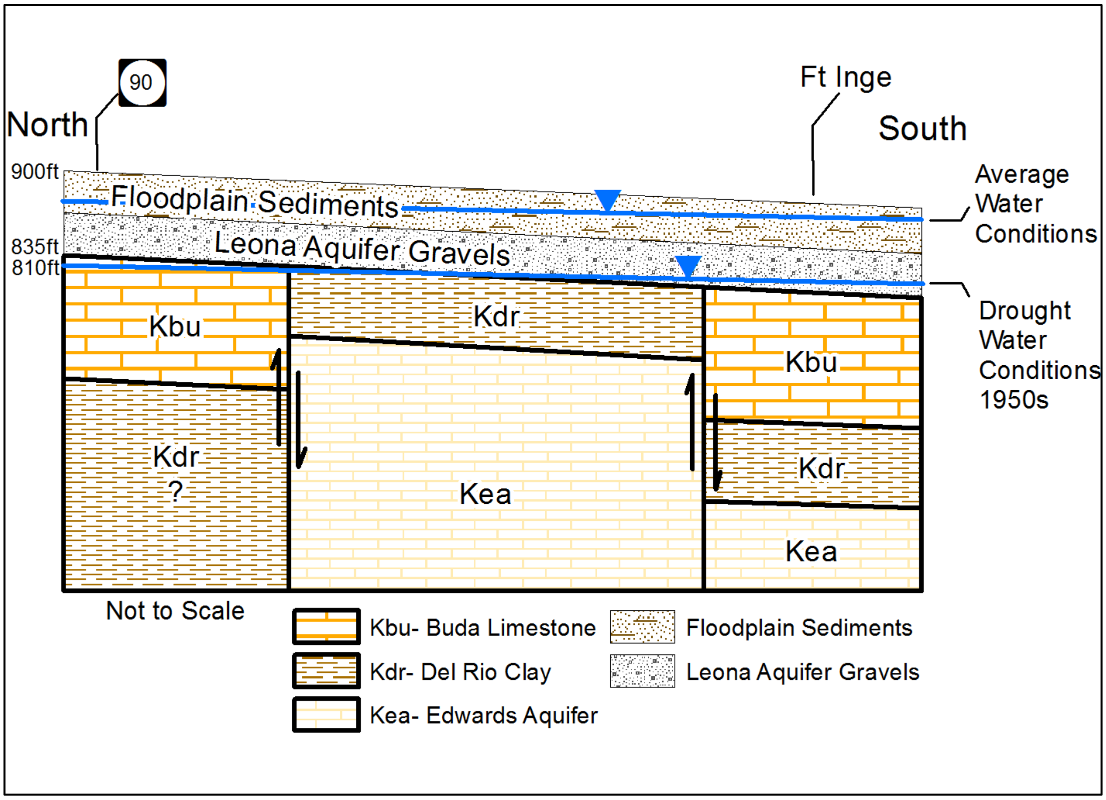


Figure 2.4.2.3-5. Conceptual cross section of the near-surface geology under the Leona River. The lower water level represents the drought of the 1950s. The upper water level represents average water conditions. Kea, Kdr, and Kbu represent the Buda and Edwards Aquifers and Del Rio Clay. Elevations are in ft msl. [not to scale]

Flow is observed in the Nueces River beginning at Solders Camp Springs under most conditions, even when no flow is observed upstream. U.S. Geological Survey gauging station 08192000 is located on the Nueces River approximately six miles downstream from the southern limit of the Austin Chalk Aquifer outcrop on the Nueces River. Mean monthly discharge has been recorded at this station since 1939 and has been zero only at times during the drought of the 1950s and during the drought that started in 2011. Comparison of Edwards Aquifer water level recorded at J-27 (Figure 2.4.2.3-7) with discharge measured at U.S. Geological Survey gauge 08192000 indicates that river flow ceased when the water level dropped below approximately 850 ft msl. Exceptions are times when river flow at gauging station 08192000 is due to excess surface runoff and not to discharge from the Edwards Aquifer. In the absence of monitoring the Nueces River flow upstream from Soldiers Camp Springs or separating baseflow from gauging station 08192000 flow measurements, the quantity of groundwater discharged from the Austin Chalk (and the Edwards Aquifer) to the Nueces River is not well known (Green et al., 2009a).

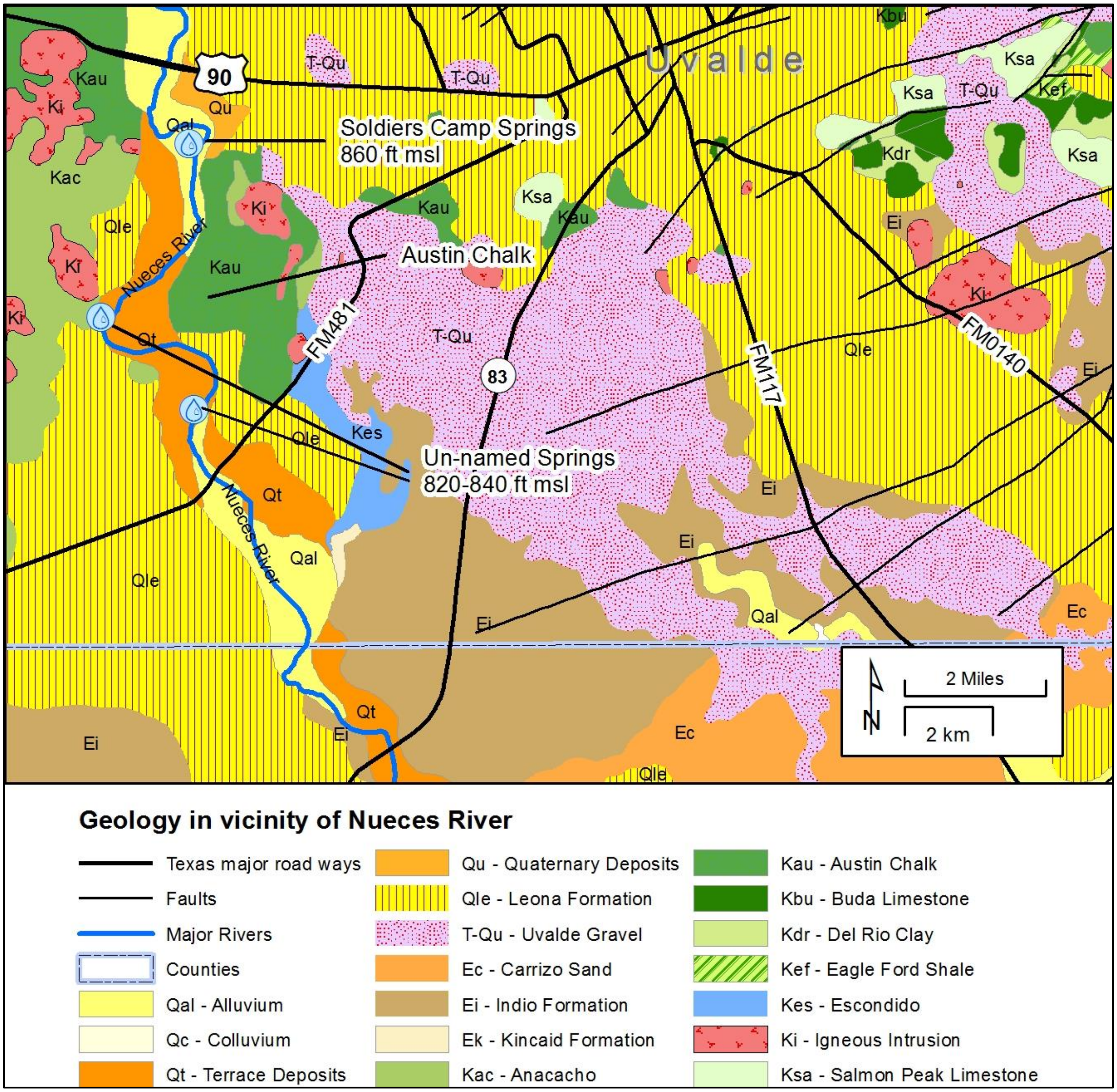


Figure 2.4.2.3-6. Geology of the Nueces River near Soldiers Camp Spring and other un-named springs (Fisher, 1983).

The Leona Formation gravels in a paleo-stream channel in the Leona River floodplain provide the next highest opportunity for discharge from the Uvalde Pool of the Edwards Aquifer. The basal elevation of the paleo-stream channel is variable with estimated elevations of 840 ft msl near Highway 90 decreasing to less than 800 ft msl at Fort Inge (Figure 2.4.2.3-5).

According to the structural conceptualization by Green et al. (2008b), the gravels are juxtaposed with the Edwards Aquifer near Highway 90 and with the Buda Limestone Aquifer near Fort Inge (Figure 2.4.2.3-5). In reality, the structural geology is more complex than suggested in Figure 2.4.2.3-5 and the Leona Formation gravels are probably juxtaposed with the Buda Limestone Aquifer near Highway 90 based on local well logs. However, since the Buda

Limestone and Edwards Aquifers are interpreted to be in hydraulic communication in this area based on similar groundwater elevations and water chemistry, water that discharges into Leona Formation gravels near Highway 90 actually originates in the Edwards Aquifer. It is possible that the Leona Formation gravels also are in hydraulic communication with the Austin Chalk. If so, this could allow for an opportunity for the Edwards Aquifer to discharge to the Leona Formation gravel at an elevation lower than 800 ft msl, possibly as low as 780 ft msl. There is no evidence, however, that the Leona Formation directly overlies the Austin Chalk Aquifer in the Leona River floodplain south of Fort Inge (Green et al., 2009a).

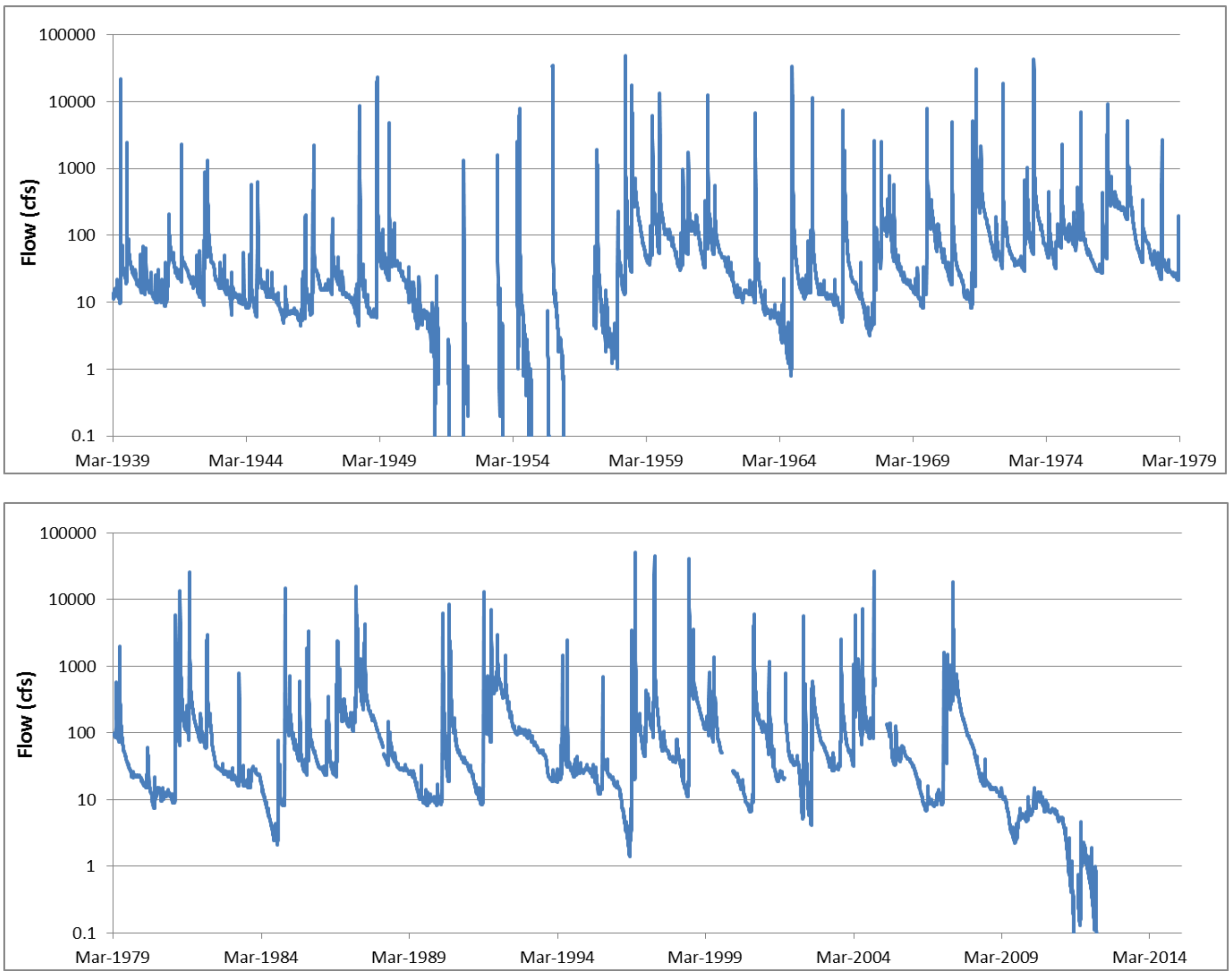


Figure 2.4.2.3-7. Graph of flow in cubic feet per second (cfs) recorded on the Nueces River at gauge 08192000 from 1939 through 2014. Minimum reported values were >0.1 cfs until June 2011 and >0.01 cfs after June 2011. The only flow values >0.01 cfs reported since June 2012 were during the period July 19–28, 2013, with a maximum flow of 0.06 cfs. These are not shown due to the graph minimum of 0.1 cfs.

Selected wells in the Leona River floodplain near the Zavala County line did not go dry during the 1950s drought of record (Vic Hildebran, personal communication). This provides evidence the gravels are recharged at a point lower than 811 ft msl, the historic low water level recorded on April 13, 1957 at the Uvalde index well (J-27). Because the base of the gravel is encountered at a depth of no greater than 65 ft below the Leona River floodplain ground surface (Cary Spurgeon, personal communication), the floodplain topographic elevation cannot be higher than approximately 865 to 875 ft msl to allow for recharge when groundwater at J-27 is at historic lows. This ground elevation occurs near Fort Inge, which suggests the lowest point of discharge to the Leona Formation gravel is near Fort Inge. An inspection of the geologic map of the area (Clark, 2003; Fisher, 1983) suggests that the Buda Limestone or possibly the Austin Chalk underlies the surficial sediments at this point (Green et al., 2009a).

The Knippa Gap is the lowest point of discharge from the Uvalde Pool (Figure 2.4.2.3-2). The extent of the Knippa Gap is defined by multiple geological factors, including the facies change from the Maverick Basin to the Devils River Trend, the Balcones Fault Zone, the Uvalde Salient, and volcanic intrusions. Maclay and Land (1988) correctly identified the Knippa Gap as a restriction to groundwater flow in the Edwards Aquifer. This restriction is bordered on the north by an extension of Cooks Fault located at the southern extent of the Edwards Aquifer Recharge Zone (Clark, 2003; Adkins, 2013, 2014) (Figure 2.4.2.3-8).

It is bordered on the south by an unnamed fault that is coincident with the east-west oriented section of Ranch Road 2690 where it intersects U.S. Highway 83. In general, the terrain south of this fault is dominated by either igneous intrusions or areas of the Uvalde Salient where the Salmon Peak is elevated so that much or most of the permeable portion of the Edwards Aquifer is above the water table. Two of the larger intrusions to the south of the Knippa Gap are Blue and Black Mountains (Figure 2.4.2.3-8). The hill between these two intrusive bodies summits at 1,241 ft msl and is composed of Cretaceous limestones with the Edwards Limestone exposed at the summit. The thickness of the Salmon Peak Formation averages 350 to 380 ft (Clark and Small, 1997; Blome et al., 2005a,b), therefore the base of the Salmon Peak Formation in this hill would be approximately 860 ft msl. Because water elevations rarely exceed 880 ft msl in this area, the Salmon Peak Formation of the Edwards Aquifer is mostly dewatered at this point (Green et al., 2009a).

Using the geologic constraints discussed above, the morphology of the Knippa Gap is defined. The narrowest width of the Knippa Gap is ascertained to be approximately 2.5 miles near the intersection of U.S. Highway 83 and Ranch Road 2690 (Figure 2.4.2.3-8). The top and bottom of the Salmon Peak Formation have been identified using driller logs and an assumed thickness of the formation. Key information from these well logs is summarized in Table 2.4.2.3-1. This location of the Knippa Gap is consistent with the location designated by Maclay and Land (1988). Clark et al. (2013) present a similar conceptualization of the geology in this area; however, they designate a location downgradient and to the southeast of the location noted here as the placement of the Knippa Gap.

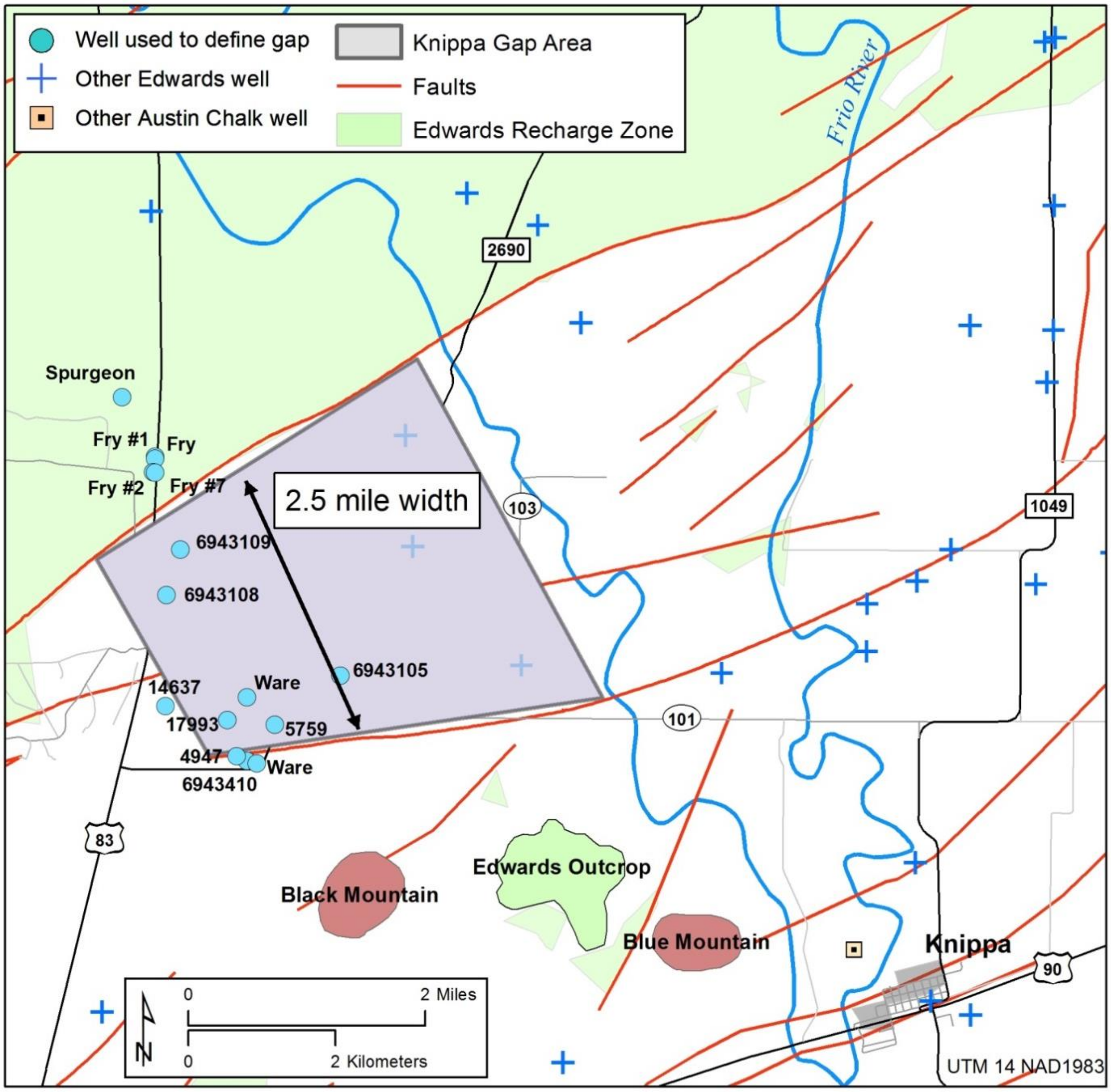


Figure 2.4.2.3-8 Location of the Knippa Gap.

Table 2.4.2.3-1. Wells used to establish the location and extent of the Knippa Gap. Elevations are in ft msl.

Well ID	Latitude	Longitude	Ground elevation	Top of Salmon Peak	Bottom of Salmon Peak	Groundwater Elevation
6943410	029 19 29	099 43 57	1055	777	-	889
6943109	029 21 02	099 44 31	1081	936	620*	936
Roberts	029 44 49	099 44 49	1054	979	616	
Ware	029 19 28	099 43 52	1052	782	-	862
Spurgeon	029 22 09	099 45 01	1120	1120	820	990
Ware	029 19 57	099 43 57	1057	857	507*	867

5759	029 19 45	099 43 43	1057	832	-	867
14637	029 19 53	099 44 38	1046	892	-	866
17993	029 19 47	099 44 07	1046	871	-	871
4947	029 19 31	099 44 02	1046	826	-	876
6943108	029 20 42	099 44 38	1061	1001	-	
6943105	029 20 07	099 43 10	1074	829	-	

*McKnight Formation was not detected, may not indicate full thickness of Salmon Peak Formation

Wells in the Knippa Gap tend to have high pumping capacity and did not have to be drilled through the entire section of the Salmon Peak to provide the required pumping capacity; thus, attesting to the high permeability of the formation. The ground elevation of the wells in this area varies from 1046 to 1081 ft msl. According to well logs, the top of the Salmon Peak is estimated at approximately 826 to 936 ft msl in the central portion of the Knippa Gap with higher elevations observed to the north and lower elevations observed to the south. If the thickness of the Salmon Peak is 350 to 380 ft, then the base of the Salmon Peak in the Knippa Gap would be 446 to 586 ft msl. Based on this conceptualization, the Salmon Peak is fully saturated in the Knippa Gap under normal hydrological conditions.

Elevations of groundwater measured at the Uvalde County (J-27), Medina County (Hondo), and Bexar County (J-17) index wells are presented in Figure 2.4.2.3-9. The graph illustrates two distinct differences between elevations measured at the Uvalde County index well and those elevations measured at the Medina and Bexar County wells. The first difference is the elevation at the Uvalde County index well relative to the Medina County index well is much greater than the difference between the Medina and Bexar County index wells, even though the distance between the Uvalde and Medina County wells is comparable to the distance between the Medina and Bexar County index wells. The higher groundwater elevations at the Uvalde County index well are attributed to the damming effect of the Knippa Gap on groundwater flow.

The second observation is the much lower amplitude change in the high-frequency changes in groundwater elevations observed at the Uvalde County well relative to either the Medina or Bexar County index wells. This modulating effect is attributed to increased capacity for discharge from the Uvalde Pool when the groundwater elevation in the Uvalde Pool is raised. This explains why only subtle changes in groundwater elevations are observed within the Uvalde Pool compared with much larger changes observed in the San Antonio Pool to the east of the Knippa Gap.

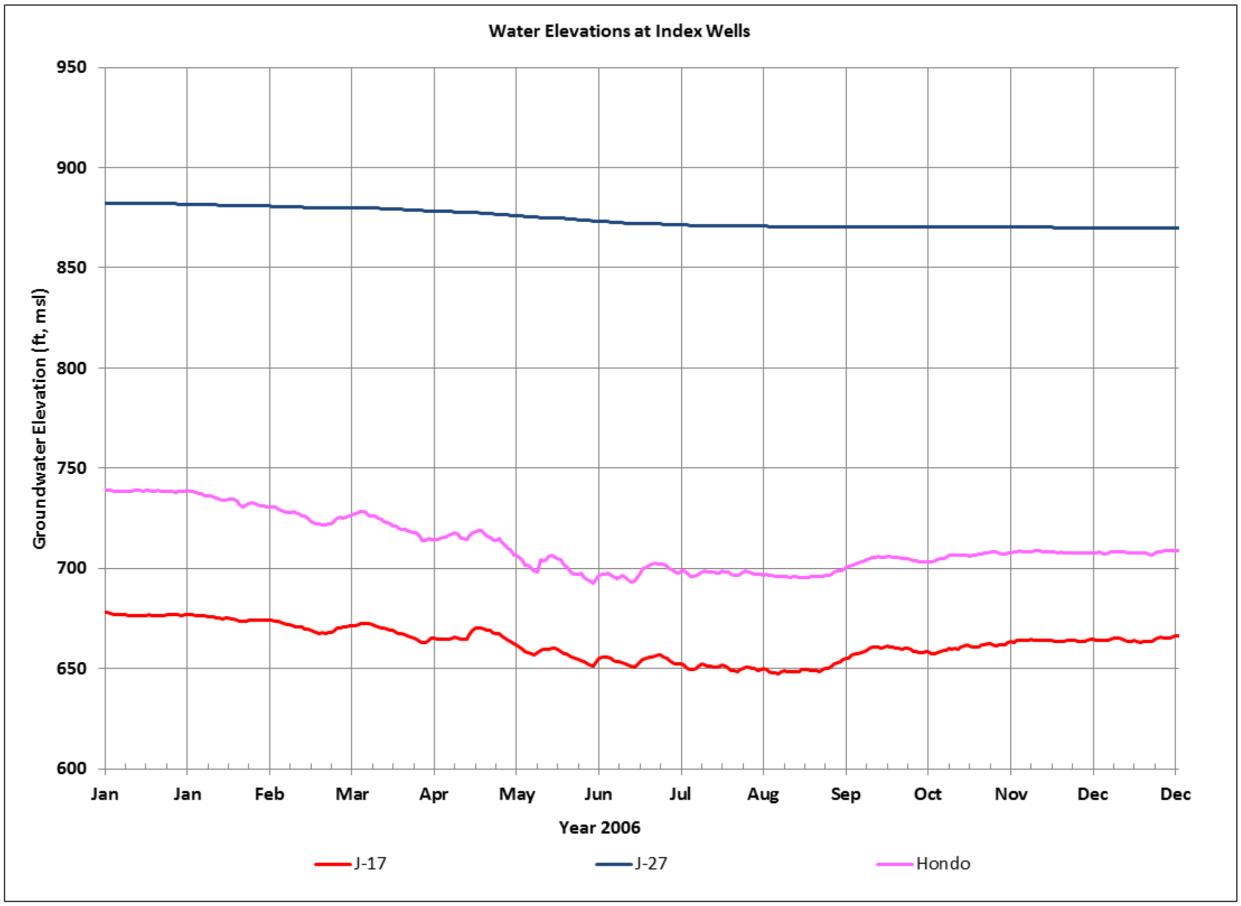


Figure 2.4.2.3-9. Water elevations measured at J-17 (red), Hondo (pink), and J-27 (blue) index wells (ft, msl).

Once water exits at either the Nueces River, Leona River channel gravels, or the Knippa Gap discharge points, the water is lost from the Uvalde Pool of the Edwards Aquifer. Surface flow from the Nueces, Frio, and Dry Frio Rivers and the Leona River and subsurface flow through the Leona Formation gravel in the Leona River floodplain is south of the Edwards Aquifer Recharge Zone and provides recharge to the Carrizo-Wilcox Aquifer and other aquifers to the south or continues as surface flow in rivers that eventually discharge into the Gulf of Mexico. Discharge via the Knippa Gap flows into the San Antonio Pool and continues to the east.

2.4.2.4 Uvalde Pool Water Budget

The Uvalde Pool has relatively limited areal extent over the area in which the Edwards Aquifer is fully saturated. The Uvalde Pool spans from approximately the Nueces River to the west, the Recharge Zone to the north, Knippa Gap to the east, and the Saline-Water Zone and Uvalde Salient to the south for a total area of approximately 100 mi^2 (64,000 acres). As discussed in the previous section, the Uvalde Pool, including the Knippa Gap, is characterized as unconfined. If a porosity of 10 percent is assigned to the Devils River Trend facies (Hovorka et al., 1995), then each foot of aquifer equates to approximately 6,400 acre-ft. The change in storage from the record high of 889 ft to the record low of 811 ft equates to approximately 500,000 acre-ft of storage. In summary, the Uvalde Pool is characterized as being highly permeable, mostly due to karst development of the Edwards Limestone Formation, but having relatively limited storage capacity.

Recorded water levels at J-27 substantiate this conceptualization (Figure 2.4.2.3-4). During most periods, groundwater elevation in the Uvalde Pool is relatively stable. Exceptions to this stability are isolated periods when the groundwater elevation in the Uvalde Pool drops precipitously (indicated with red ellipses in Figure 2.4.2.3-4). Periods when groundwater drops precipitously are interpreted, obviously, as times when recharge to the Uvalde Pool from the combined surface and subsurface recharge via the Nueces River channel is less than the combined discharge via natural and anthropogenic (i.e., pumping) mechanisms. It should be noted that natural discharge at high stage (i.e., J-27 > 850 ft, msl) is via the Leona and Nueces Rivers and the Knippa Gap, whereas naturally-occurring discharge during low stage is only by way of the Knippa Gap. Thus, during periods of insufficient recharge to the Uvalde Pool from the Nueces River, there is inadequate storage in the Uvalde Pool to maintain stable or even slowly decreasing water levels. As a result, water levels in the Uvalde Pool decline at a precipitous rate during these times of drought and insufficient recharge from the Nueces River.

Recharge (and discharge) of the Uvalde Pool is highly variable. Over the 1934–2013 period of record, recharge of the Edwards Aquifer via the West Nueces and Nueces Rivers was calculated by the U.S. Geological Survey to vary from a low of 8,600 acre-ft in 1934 to a high of 481,900 acre-ft in 2004 (Tremallo et al., 2014). Similar high levels of recharge occurred in 1990 and 2007. The median groundwater recharge to the Edwards Aquifer from the Nueces-West Nueces River watersheds calculated by the U.S. Geological Survey was 99,700 acre-ft/yr for the period 1934–2013 and 73,000 acre-ft/yr for the period 2003–2013. The median annual discharge by pumping and spring discharge for Uvalde County was calculated to be 76,400 acre-ft/yr for the period 1934–2013 and 78,300 acre-ft/yr for the period of 2003–2013. Discharge in Kinney County is included in the estimate for Uvalde County (Tremallo et al., 2014).

U.S. Geological Survey recharge estimates of the Uvalde Pool are predicated on several important assumptions. Both recharge and discharge are regional estimates (i.e., for the combined West Nueces-Nueces River watersheds and the combined Dry Frio- Frio River watersheds). An additional limitation inherent in the U.S. Geological Survey calculations is that recharge that occurs upstream from the river gauges used to calculate recharge is not captured in the calculations. Since river gauges are placed close to the Recharge Zone upstream boundary, recharge that does occur in the Contributing Zone is not included in either U.S. Geological Survey or the Hydrologic Simulation Program FORTRAN (HSPF) recharge calculations (Tremallo et al., 2014; Clear Creek Solutions, Inc., 2009, 2012, 2013).

Discharge from the Uvalde Pool has been quantified to the degree possible using results from recent investigations. Field-study results performed on the Leona River floodplain at a location four miles south of Uvalde, Texas, were evaluated to determine the quantity of water discharged from the Edwards Aquifer through the Leona River floodplain (Green, 2003; Green et al., 2008a). Principal components to the field studies were an electrical resistivity and a magnetic survey to determine the lateral and vertical extent of sand and gravel deposits and an aquifer test to determine the hydraulic properties of the Leona Aquifer. These studies were augmented by well logs to corroborate the geophysical survey interpretation.

Results from the geophysical surveys were used to delineate a paleo-stream channel embedded in the fluvial sediments of the Leona River floodplain (Figure 2.4.2.4-1). Flow through the Leona Formation gravels that compose the paleo-stream channel was calculated to be approximately 74,000 acre-ft/yr. When combined with the estimate of 7,300 acre-ft/yr of surface water flow in the Leona River, the total quantity of water discharged from the Edwards Aquifer through the Leona River floodplain may be as great as 81,300 acre-ft/yr (Green et al., 2008a). During periods of severe drought, discharge through the Leona River floodplain could be less than 18,700 acre-ft/yr with no surface flow and reduced underflow (Green et al., 2008a). Even this low-flow calculation exceeds the 11,200 acre-ft/yr target value for discharge from the Leona Springs specified by Lindgren et al. (2004) for steady-state calibration of their groundwater model of the Edwards Aquifer.

U.S. Geological Survey gauging station 08192000 is located on the Nueces River approximately six miles downstream from the southern limit of the Austin Chalk Aquifer outcrop that includes Soldiers Camp Springs and other un-named springs on the Nueces River. Measurements taken at this gauge allows calculation of how much the Nueces River has gained between Soldiers Camp Springs and the gauging station when there is no river flow in the reach upstream from Soldiers Camp Springs. Virtually all discharge to the Nueces River along this reach is believed to originate from the springs associated with the Austin Chalk Aquifer outcrop. Because of the hydraulic communication between the Austin Chalk and Edwards Aquifers, flow measurements at the gauging station are therefore a measure of discharge from the Edwards Aquifer to the Nueces River during times when there is no surface flow in the Nueces River upstream of the springs. River flow for the period 1940–2008 averaged 144 cfs (104,000 acre-ft/yr), with a maximum of 4,057 cfs during August 1998 (Green et al., 2009a). Without a measure of river flow above the springs or baseflow separation of flow at gauge 08192000, an estimate of discharge from the Edwards Aquifer to the Nueces River at this location is not known.

Pumping in Uvalde County has been highly variable over the past 80 years (Figure 2.4.2.4-2) (Green et al., 2009a).

Approximately 56 percent of pumping of Edwards Aquifer wells in Uvalde County occurs in the Uvalde Pool (i.e., 50,600 acre-ft/yr for the period of 1998 to 2007), with the remainder pumped from the San Antonio Pool (Ned Troshanov, personal communication). This estimate for pumping does not include amounts pumped by wells in the Buda Limestone and Austin Chalk Aquifers.

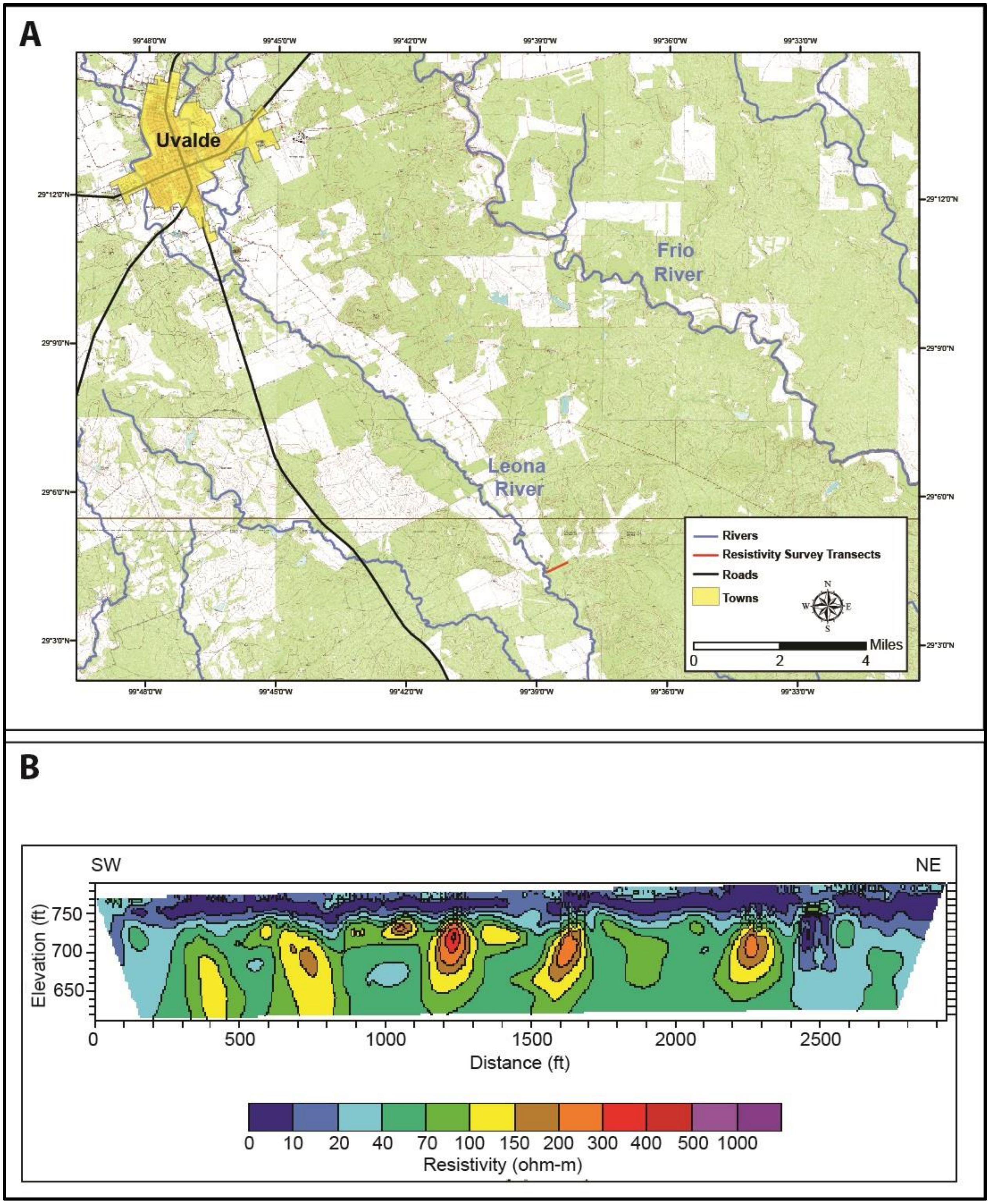


Figure 2.4.2.4-1. Vertical cross section illustrating the electrical resistivity of the Leona River floodplain on the east side of the river immediately south of the Uvalde/Zavala County line. The high resistivity zones indicate locations of paleo-stream channels in the Leona River floodplain (Green et al., 2008b).

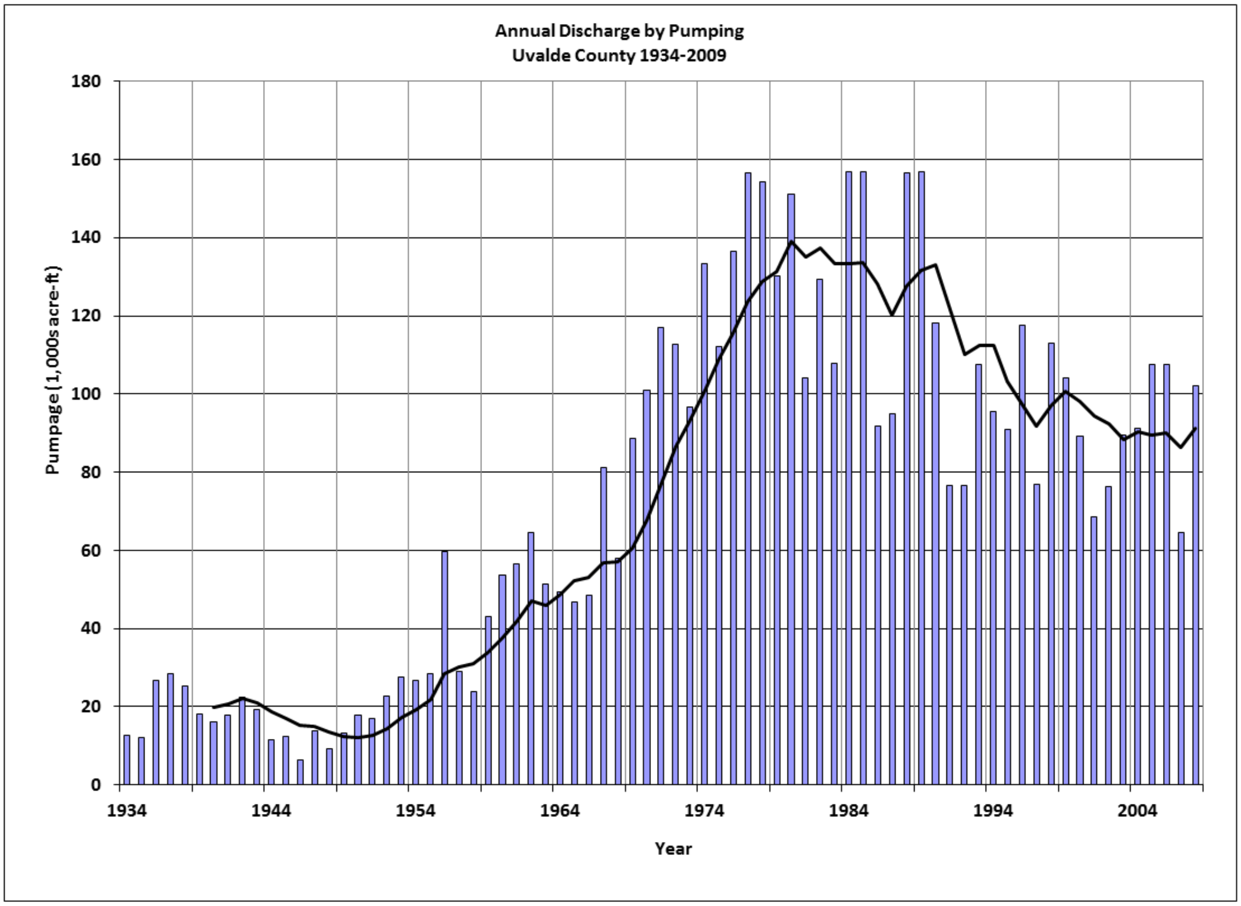


Figure 2.4.2.4-2. Annual discharge by pumping in Uvalde County for the period 1934–2009 (Edwards Aquifer Authority, 2009). The solid line denotes a 7-year running average.

Discharge via Knippa Gap can be estimated using the water budget of the Uvalde Pool. The Uvalde Pool water budget can be posed:

$$Q_{NR-GW}^{in} + Q_{NR-SW}^{in} + \Delta S = Q_{KG} + Q_{LR} + Q_{NR}^{out} + Q_{pumping} \qquad \text{(Eq. 2.4.2.4-1)}$$

where (all quantities are in terms of acre-ft/yr):

Q_{NR-GW}^{in} = recharge from Nueces River as groundwater
Q_{NR-SW}^{in} = recharge from Nueces River as surface water
Q_{KG} = discharge out via Knippa Gap
Q_{LR} = discharge out via Leona River
Q_{NR}^{out} = discharge out via Nueces River Springs
$Q_{pumping}$ = discharge out via pumping
ΔS = change in storage in the Uvalde Pool

The maximum rate that J-27 drops during times of drought provides an indication of the minimum flow rate via Knippa Gap. The minimum discharge is assumed to have occurred in the early 1950s. The water level at J-27 dropped by about 0.5 ft/month. This equates to about 38,400 acre-ft/yr. The water level at J-27 during the drought of the 1950s was below 845 ft, msl, thus there was minimal discharge via the Leona Formation gravel in the Leona River floodplain and no flow from the springs on the Nueces River. Discharge via the Leona Formation gravel, Q_{LR}, during periods of drought is estimated at 18,700 acre-ft/yr (Green et al., 2008a). Pumping in the early 1950s was about 15,000 acre-ft/yr for Uvalde County (Figure 2.4.2.4-2), of which 56 percent, or 8,400 acre-ft/yr is estimated to have been from the Uvalde Pool, $Q_{pumping}$. The U.S. Geological Survey measured recharge to the Uvalde Pool (Q_{NR-SW}^{in}) averaged 34,080 acre-ft/yr for the period 1950–1954. As previously discussed, recharge to the Uvalde Pool from the Nueces River as groundwater, Q_{NR-GW}^{in}, is not included in this measurement. Discharge during this period via the Knippa Gap is estimated at 45,380 acre-ft/yr plus recharge from Nueces River as groundwater, which is unknown.

The dimensions and hydraulic properties of the Knippa Gap can be calculated using Darcy's Law and this estimation of discharge. Use of Darcy's Law in a karst aquifer may be justified when strictly limited to a volumetric calculation. The use of Darcy's Law to determine flow velocity in a karst aquifer, such as the Edwards Aquifer particularly in the Knippa Gap where well-developed conduit flow is likely, is not appropriate. Darcy's Law for volumetric flow can be expressed

$$Q = AK\nabla h \qquad \text{(Eq. 2.4.2.4-2)}$$

where Q is volumetric flow, A is the cross sectional area, K is hydraulic conductivity, and ∇h is the hydraulic gradient.

A vertical cross section of Knippa Gap near the intersection of U.S. Highway 83 and Ranch Road 2960 is selected for analysis. The width of the cross section is estimated at 2.5 mi (Figure 2.4.2.3-8). The height is estimated relative to J-27, which is set at 830 ft, msl. If the base of the Knippa Gap is assumed to be 530 ft, msl, then the height of the saturated aquifer in Knippa Gap is 300 ft. Flow through the Knippa Gap is assumed to be 50,000 acre-ft/yr in the early 1950s. This estimate assumes groundwater flow of approximately 4,620 acre-ft/yr in addition to the surface-water recharge estimate given above. The hydraulic gradient is assumed to be 0.001 ft/ft. Using these assumptions, a hydraulic conductivity of 1,500 ft/day is calculated, which is consistent with published values (Hovorka et al., 1996, 1998; Mace and Hovorka, 2000; Painter et al., 2002).

Discharge via Knippa Gap can be estimated for high stage in the Uvalde Pool which is defined here to occur when J-27 is 880 ft, msl. The maximum recharge to the Uvalde Pool was measured by the U.S. Geological Survey at 481,900 acre-ft/yr in 2004. Again, this measurement did not include recharge as groundwater. In 2004, discharge from the Uvalde Pool via the springs on the Nueces River increased, however, because the U.S. Geological Survey gauge is located downstream from the springs, this discharge is accounted for in the U.S. Geological Survey Nueces River recharge calculations. Discharge via the Leona River channel is calculated to be as high as 81,300 acre-ft/yr (Green et al., 2008a). Pumping in 2004 was 91,300 acre-ft (Tremallo et al., 2014), of which 51,100 acre-ft was in the Uvalde Pool. This calculation indicates that 329,300 acre-ft (plus whatever amount was recharged via the Nueces River as groundwater), was discharged from the Uvalde Pool via the Knippa Gap in 2004.

This assessment is evaluated in terms of the hydraulic characterization of the Edwards Aquifer in the Knippa Gap as unconfined. Compared with a period of drought, the saturated thickness of the Edwards Aquifer is increased to 350 ft during periods of high stage in the Uvalde Pool. If the hydraulic conductivity and width of the Knippa Gap are assumed to remain constant and the hydraulic gradient is increased to 0.002 ft/ft, discharge from the Uvalde Pool via the Knippa Gap increases to 116,700 acre-ft/yr, which is approximately half of the estimated discharge in 1990. The assumption that the hydraulic conductivity in the Edwards Aquifer is constant may not be valid. The Upper Salmon Peak Formation may be more permeable with greater karst development than the lower portion of the Edwards Aquifer in the Knippa Gap (Maclay 1995; Clark and Small, 1997). If appropriate, then the 50-ft horizon of saturated aquifer that would be added during high stage could convey more water per unit thickness; however, this added capacity is unlikely to be able to account for the tremendous increase in recharge to the Uvalde Pool witnessed in 1990, 2004, and 2007. Thus, other avenues of discharge from the Uvalde Pool must be available to accommodate this increased quantity. The only recognized candidates are spring discharge on the Nueces River and discharge via the paleo-stream channel deposits in the Leona River channel.

Based on the conceptualization described in this document, actual recharge of the Uvalde Pool from the Nueces River is determined to be greater than either the U.S. Geological Survey or the HSPF calculations (Tremallo et al., 2014; Clear Creek Solutions, Inc., 2009, 2012, 2013). The increased recharge is due to Nueces River underflow and interformational flow from the Trinity Aquifer to the Edwards Aquifer. Neither of which are accommodated in the U.S. Geological Survey or HSPS recharge calculations. Lastly, the Knippa Gap appears to be incapable of accommodating the large quantities of recharge to the Uvalde Pool experienced during 1990, 2004, and 2007. This suggests that either the Nueces River Springs or Leona River channel underflow has greater capacity for discharge than previously thought.

2.4.3 Central Hydrogeology

2.4.3.1 Western San Antonio Pool

That portion of the Edwards Aquifer from the Knippa Gap on the west and to the east up to and including the Medina River watershed is referred to as the western San Antonio Pool. That portion of the western San Antonio Pool in Uvalde County was discussed, in part, in Sections 2.4.2.3 and 2.4.2.4 . The evaluation of secondary aquifers in Uvalde County concluded that the Austin Chalk and Buda Limestone are essentially unsaturated in eastern Uvalde County (Green et al., 2009a). Therefore, there is no opportunity for the Austin Chalk or Buda Limestone to recharge paleo-stream channels in eastern Uvalde County if there are any channels in this area. The presence or absence of paleo-stream channels in eastern Uvalde County is inconsequential to water budget analysis because significant quantities of water are not being transported or discharged from shallow or secondary aquifers in this area.

Early assessments of the geology, hydrology, and water resources of Medina County by the U.S. Geological Survey (i.e., Holt, 1959; Maclay and Small, 1984; Maclay and Land, 1988; Maclay, 1995) have been augmented with recent focused studies on geologic structure (Small and Clark, 2000; Blome et al., 2005a,b, 2007; Green et al., 2006; Clark et al., 2006; Pantea et al., 2008; Clark et al., 2009), groundwater flow paths (Clark and Journey, 2006; Green et al., 2006, 2009a,b, 2012b), and water balance (Lambert et al., 2000; Slattery and Miller, 2004; Ockerman, 2005; Pedraza and Ockerman, 2012; Green et al., 2012b) to develop a conceptual model of the hydrogeology of the western San Antonio Pool.

The first section of the western San Antonio Pool to be evaluated is that area that is recharged by the Dry Frio, Frio, and Sabinal River watersheds. As discussed in Section 2.3.3, the groundwater basin of the Frio River was ascertained to extend farther north than the surface watershed. And as discussed in Sections 2.4.2.3 and 2.4.2.4, the Dry Frio River recharges the Edwards Aquifer in close proximity with the Knippa Gap. There is no evidence that recharge from the Dry Frio River watershed enters the Uvalde Pool. Mapped concentrations of specific conductance provides a strong case that the low specific conductance water from groundwater sampling in the Dry Frio River watershed recharges the Edwards Aquifer downgradient from the Uvalde Pool (Green et al., 2006) (Figure 2.4.3.1-1). Low specific conductance values are interpreted to indicate that most of the recharge from both the Dry Frio and Frio Rivers occurs well upgradient in the Recharge Zone and likely in the Contributing Zone. These two rivers seldom flow in the lower reaches of the Recharge Zone, a consequence of the fact that long reaches of both the Dry Frio and Frio Rivers pass over the Recharge Zone. This results in all baseflow infiltrating well before these two rivers exit the Recharge Zone.

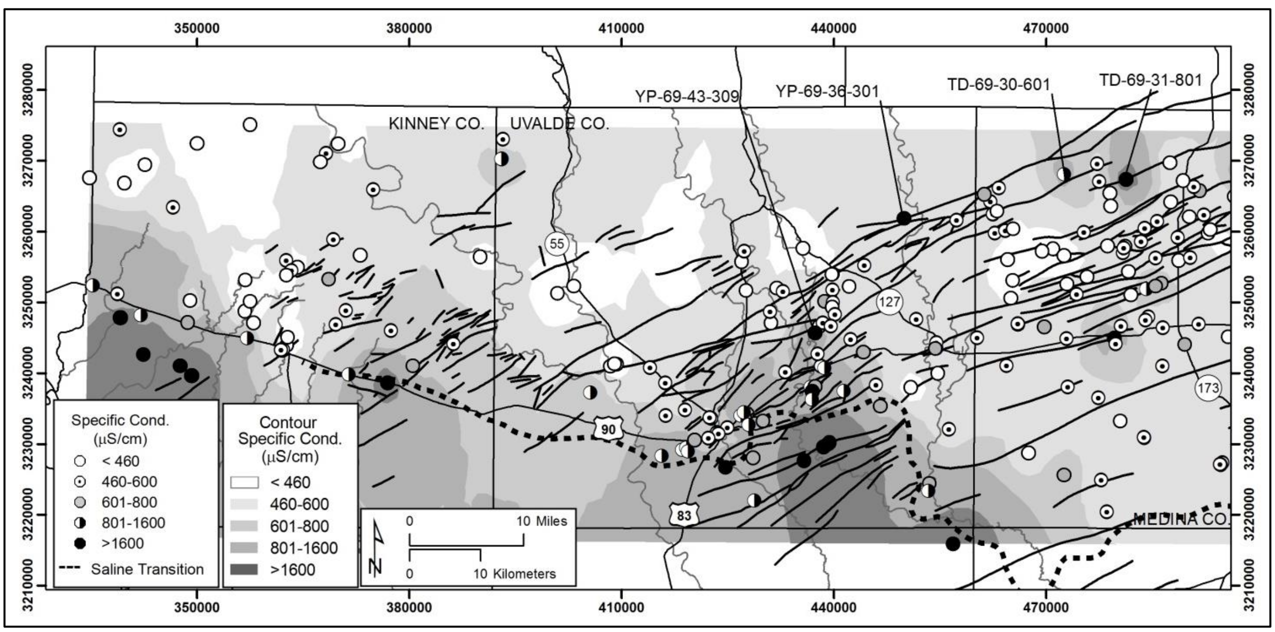


Figure 2.4.3.1-1. Specific conductance of the Edwards Aquifer in eastern Kinney, Uvalde, and western Medina counties (μS/cm). Wells YP-69-36-301, TD-69-30-601, and TD-69-31-801 are listed as Edwards Aquifer wells but, based on hydrochemical data, likely draw water from the Glen Rose Aquifer.

As indicated by the river basin map, Figure 2.1-3, the Sabinal River watershed is not extensive and the reach of the river that crosses the Recharge Zone is relatively short compared to those of the Dry Frio and Frio Rivers. In addition, the large river flow measurements on the Medina River at Bandera (i.e., 4.54 inch/yr, Green and Bertetti, 2010a), suggest that the Medina River groundwater basin extends beyond the limits of the surface watershed. This would further reduce the recharge in the Sabinal River Basin if the Medina River groundwater basin did in fact encroach into the Sabinal River groundwater basin. There is insufficient data to determine if this is the case.

The only opportunity for discharge in this region is a series of Balcones Fault Zone-type springs on the Frio River in southern Uvalde County (Green et al., 2009b). The springs appear as waterholes, not flowing springs. Accordingly, they are identified as Black Waterhole North, Black Waterhole South, Cypress Waterhole, and Toadstool Waterhole (Figure 2.4.3.1-2). The chemistry of water from Black Waterhole North is consistent with the Austin Chalk Aquifer, while the chemistry of water from the southern three waterholes is consistent with the Edwards Aquifer. Discharge to these waterholes is sufficiently low that these springs do not affect the San Antonio Pool water budget. Inspection of electrical resistivity vertical cross sections on the Frio River illustrates the absence of alluvial sediments in the Frio River channel (Figure 2.4.3.1-3) (Green et al., 2009b) confirming the interpretation that the waterholes are expressions of Balcones Fault Zone-type springs and not river underflow.

Holt (1956, 1959) first characterized faults in northern Medina County as barriers to groundwater flow and characterized the ensuing structures in northern Medina County as flow-path controlling features. Holt stated that groundwater flows in solution channels along fractures generally parallel to the fault pattern. Faults with sufficiently large displacements to offset the aquifer from itself sufficiently to form barriers, diverting groundwater. Water entering the Edwards limestone from the Medina Lake area flows downdip to the south where movement is diverted by the Haby Crossing Fault (Figure 2.3.4-1). Most of this groundwater flows to the southwest, along the fault, to the area north of Quihi where the throw is less than the thickness of the Edwards Aquifer. From there, groundwater passes across the fault into the downthrown block to the south.

Holt (1959) noted that the throw of the faults is not sufficient to completely offset the Edwards limestone in the vicinity of Hondo and Verde Creeks and divert groundwater. According to Holt's (1959) characterization, the Medina Lake Fault and the fault to its north locally divert the groundwater moving in the outcrop area of the limestone. Faulting between the Medina Lake Fault and Hondo does not appreciably affect the southward movement of the ground water.

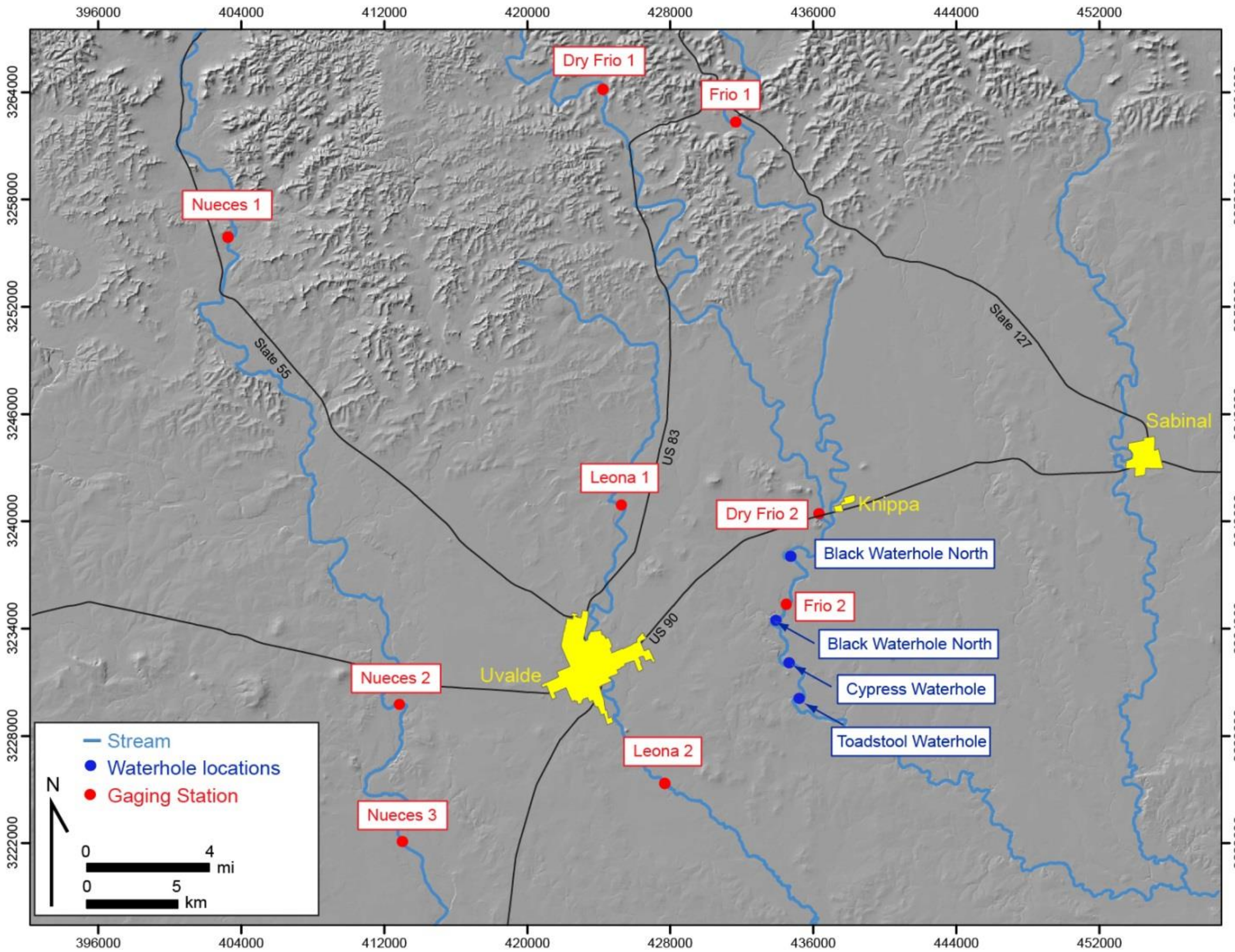


Figure 2.4.3.1-2. Balcones Fault Zone-type springs on the Frio River. From north to south, Black Waterhole North, Black Waterhole South, Cypress Waterhole, and Toadstool Waterhole.

In the area near Woodard Cave where the Edwards limestone crops out, the faulting is sufficient to affect the movement of the water but does not completely prevent movement across the major fault. The displacement along the fault south of this area is too small to appreciably affect the movement of the groundwater. The Pearson Fault and several of the faults southwest of Dunlay may serve as effective barriers to the downdip movement of the Edwards water.

Maclay and Small (1984), Maclay and Land (1988), and Maclay (1995) retained the concept that Balcones Fault Zone Faults in northern Medina County act as barriers to flow and that these barriers divert groundwater flow from northeast to southwest Medina County. In this conceptualization, a fault was considered a barrier if offset equated to 50 percent or greater of the aquifer thickness. Clark and Journey (2006) evaluated geological structural data, hydraulic correlations, and water chemistry to support their conceptualization of faults acting as barriers to flow in Medina County, although the hydraulic and water chemistry data were mostly from the eastern half of the county.

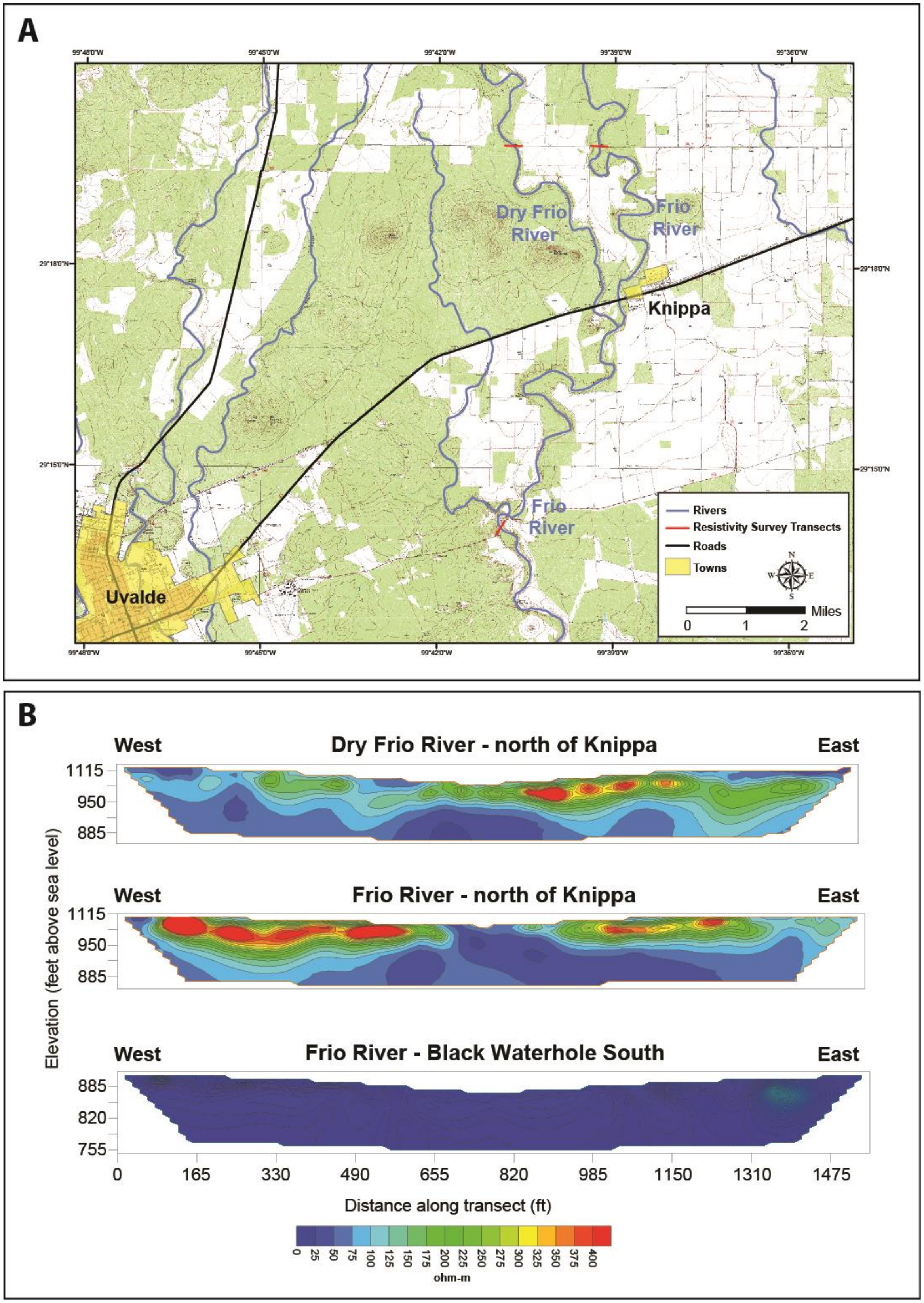


Figure 2.4.3.1-3. Vertical cross section of electrical resistivity at three transects on the Frio River (Green et al., 2009b).

The next portion of the western San Antonio Pool to be discussed is the region between the Sabinal River floodplain to the west and the Seco and ParkerCcreeks floodplain to the east and downgradient from where the Cretaceous-age rocks crop out (Figures 2.4.3.1-4 and 2.4.3.1-5). There is a major fault aligned with Seco Creek on the east and the Uvalde Salient on the west of this region (Figure 2.3.4-1). The combined effect of these two structural features has elevated the base of the Leona Formation where it abuts the southern extent of the Austin Chalk Recharge Zone. The elevation of the downdip boundary of the Austin Chalk Recharge Zzone is approximately 1,050 ft msl at the Uvalde-Medina County line. The base of the Leona Formation with a maximum thickness of 65 ft (Cary Spurgeon, personal communication) is approximately 985 ft msl where it abuts the Austin Chalk. The Edwards Aquifer groundwater elevation in this area is less than 850 ft msl (Green et al., 2006), thus the elevation of Edwards Aquifer groundwater in eastern Uvalde County and western Medina County (i.e., west of Seco Creek) is too low discharge to the Leona Formation. This assessment is substantiated by the limited number of Leona Formation wells in this region (Green et al., 2012b).

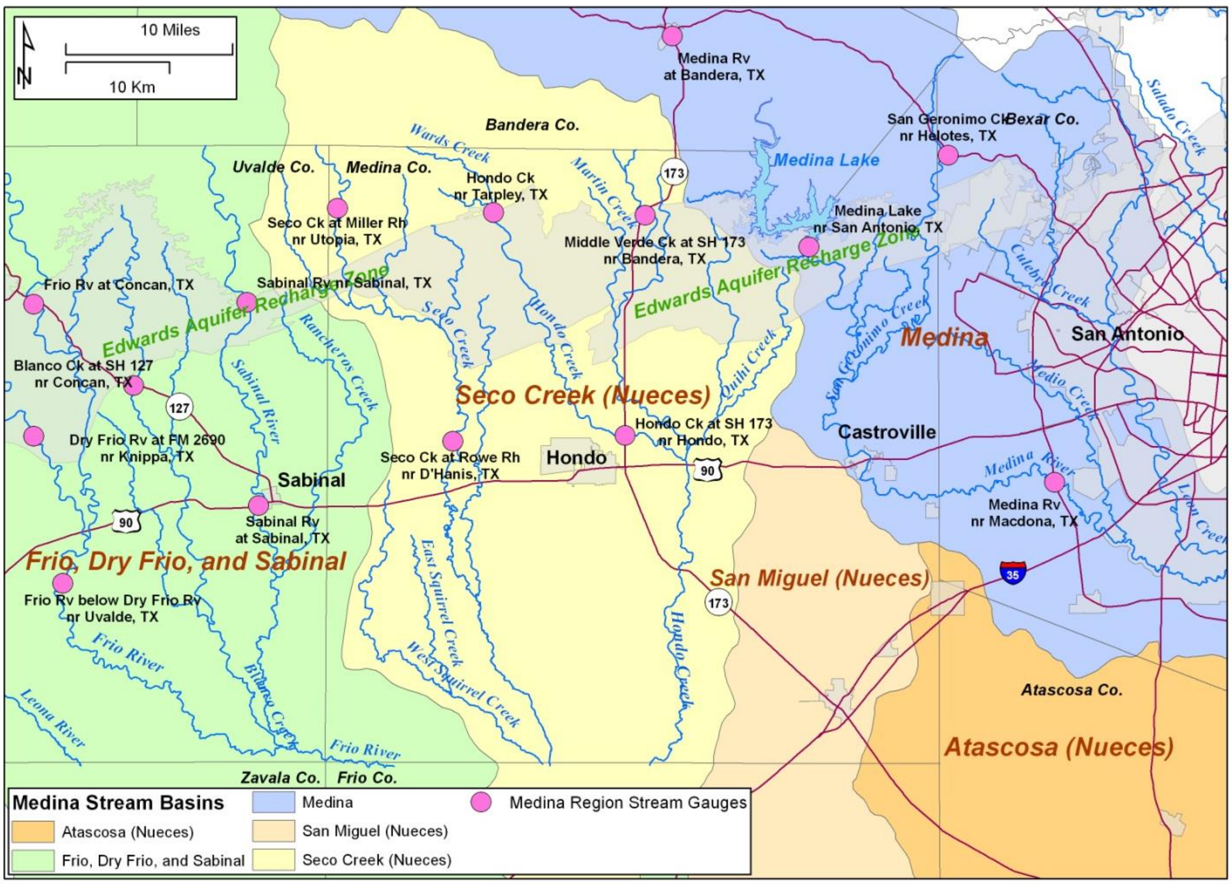


Figure 2.4.3.1-4. River watershed basins and surface water gauging stations operated by the U.S. Geological Survey in Medina County, Texas.

The next two portions in the western San Antonio Pool are subdivided according to surface watersheds. Surface-water flow in Medina County occurs in two principal watersheds: (i) the watershed located between the Sabinal and Medina River watersheds and (ii) the Medina River watershed (Figure 2.1-3). Within the watershed located between the Sabinal and Medina River watersheds, floodplains of Seco, Parker, Live Oak, Hondo, Verde, Elm, and Quihi Creeks coalesce to form a contiguous expanse of Leona Formation sediments in an outwash plain (Figures 2.4.3.1-5 and 2.4.3.1-6). The potential area for paleo-stream channels in the Leona Formation in the central Medina County was evaluated using an electrical resistivity survey (Green et al., 2012b). Survey results indicated the paleo-stream channels in these floodplains are marginal in size when compared with the paleo-stream channel in the Leona River floodplain.

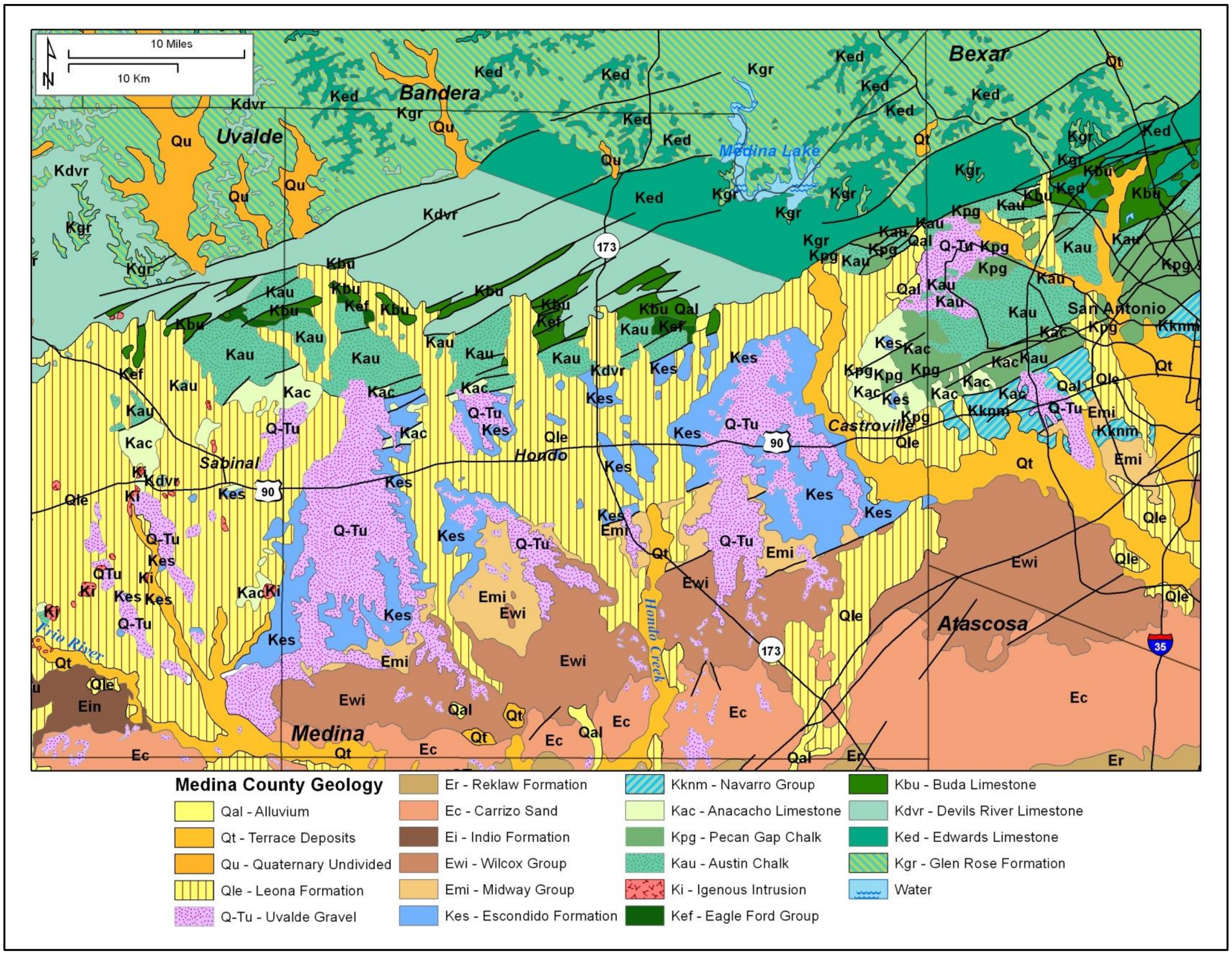


Figure 2.4.3.1-5. Geological map of Medina County (map data adapted from Blome et al., 2004).

Ancestral headwater locations of the paleo-stream channels in Medina County are interpreted to be located at the southern extent of the Austin Chalk surface exposure. This interpretation is based on the coincident alignment of the downdip boundary of the Austin Chalk and the most updip occurrence of wells located in the paleo-stream channel (Figure 2.4.3.1-7). If this interpretation is valid, the paleo-stream channels are recharged directly from the Austin Chalk. Aerial exposure of the ancestral springs likely ceased in the late Pleistocene, after which subsequent alluviation buried the springs and paleo-stream channels with 40-50 ft of sediments resulting in the current state of the floodplain (Doyle, 2003).

Elevations of the ancestral springs that discharge to the paleo-stream channels in Seco, Parker, Live Oak, Hondo, Verde, Elm, and Quihi Creeks were calculated by subtracting 65 ft (the maximum depth of the base of the Leona Formation, Cary Spurgeon, personal communication) from the surface elevation of the creek beds at the estimated southern extent of the Austin Chalk Recharge Zone (Table 2.4.3.1-1). These estimates are approximate and could be refined with controlled borehole information, but elevations of the seven ancestral springs are consistent with values varying from 835 to 890 ft msl. The estimates are believed to be conservatively low and could be higher if the depth of the Leona Formation is less than 65 ft (Green et al., 2012b).

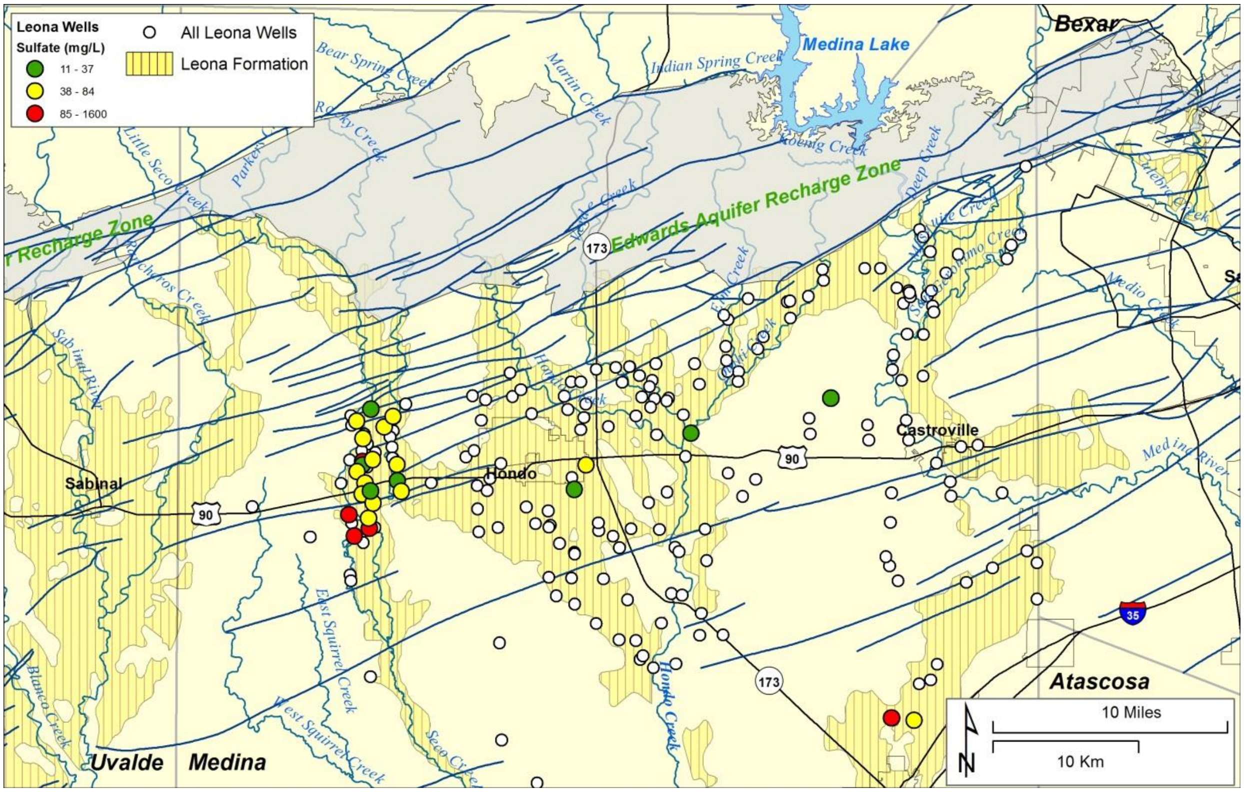


Figure 2.4.3.1-6. Map of fluvial Leona Formation deposits in Medina County. Leona Formation wells are illustrated with circles that are color-filled based on water chemistry where data are available, and otherwise filled white. Data are from the Texas Water Development Board (2011) database. Blue lines represent major faults.

The groundwater elevation in the Austin Chalk at the locations of the ancestral springs has to be at least as high as the base elevation of the Leona Formation at the locations of the ancestral springs if the paleo-stream channels are to be recharged. Edwards Aquifer groundwater elevations near the ancestral springs were estimated using results from the EAA 1999-groundwater-elevation synoptic survey (Hamilton et al., 2006). As presented in Table 2.4.3.1-1, the elevation of groundwater in the Edwards Aquifer is significantly and consistently lower than the elevation of the ancestral springs. This difference in elevations confirms that the ancestral springs and the paleo-stream channels are not in direct hydraulic communication with the Edwards Aquifer. Similarly, by extension, the Austin Chalk is not in direct hydraulic communication with the Edwards Aquifer in central Medina County. The offset of faulting between the Edwards Aquifer and the Austin Chalk is apparently sufficiently large to preclude direct hydraulic communication between the two units.

Table 2.4.3.1-1. Comparison of base elevation of ancestral springs and groundwater elevations of nearby Edwards Aquifer wells using the July 1999 synoptic survey measurements (Tremallo et al., 2014). The ancestral spring is set at the base elevation of the Leona Formation (Green et al., 2012b).

Creek	Ground Elevation (ft, msl)	Base Elevation of Leona Formation (ft, msl)	Closest EAA Monitoring Well	Edwards Aquifer Groundwater Elevation (ft, msl)
Seco	920	855	69-38-902	778.30
Parker	935	870	69-38-906	783.18
Live Oak	955	890	69-39-801	767.97
Hondo	945	880	69-39-901	700.93
Verde	900	835	69-40-403	793.85
Elm	900	835	69-40-901	723.91
Quihi	945	880	68-33-102	845.83

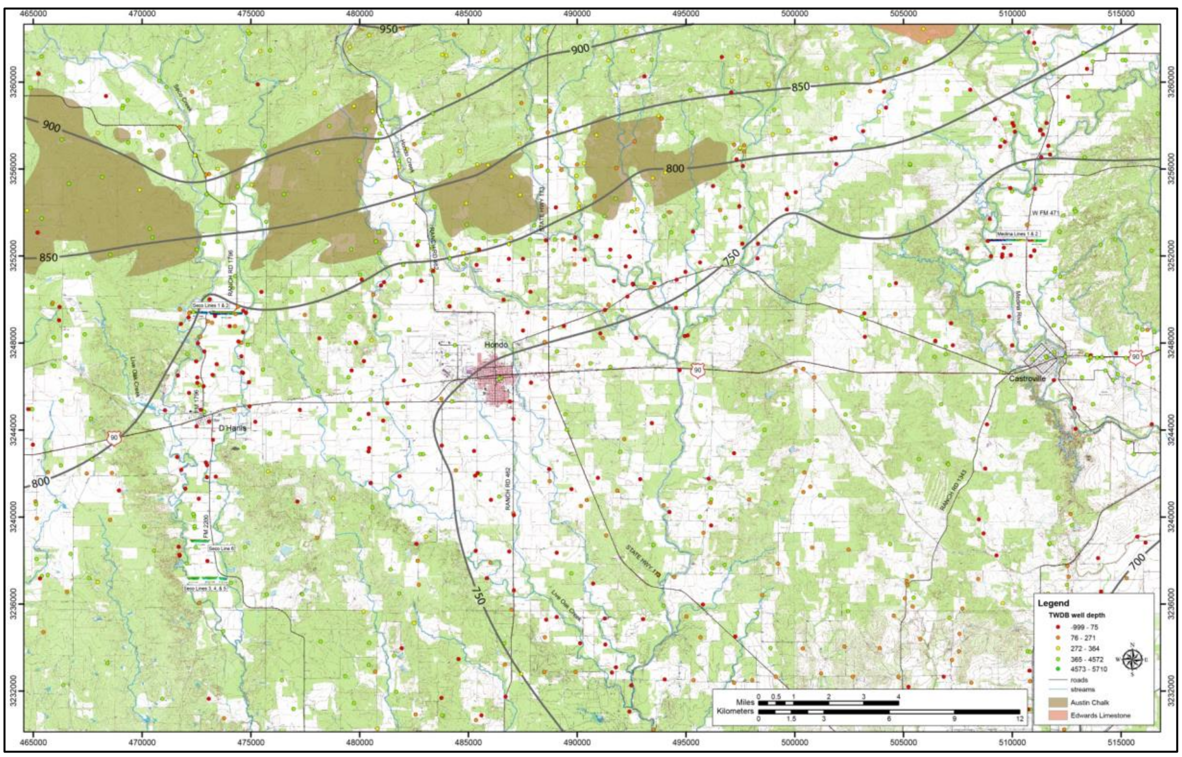


Figure 2.4.3.1-7. Potentiometric contours for the Edwards Aquifer and outcrop of the Austin Chalk in Medina County, Texas.

A limited number of Leona Formation irrigation wells in the floodplain south of Hondo indicates that paleo-stream channels in that region are sufficiently recharged to sustain pumping needed for irrigation. Groundwater that flows downstream from the outwash plain via the central Medina County paleo-stream channels eventually arrives at the recharge area for the Carrizo-Wilcox Aquifer. The northern boundary of the Wilcox Formation is slightly north of the confluence of Live Oak and Hondo Creeks or about eight miles south of Highway 90. Because of the absence of the high-capacity shallow wells from this point south, groundwater flow in the paleo-stream channels in the north is believed to have either discharged into the creeks as surface flow or recharged the Carrizo-Wilcox Aquifer (Green et al., 2012b).

Inspection of the geologic map of Medina County indicates the absence of Leona Formation sediments to the east of Quihi Creek and west of the Medina River Basin. The Chacon Creek Basin is a minor exception. Its floodplain is limited in size, both in width and lengthwise. It appears to be a sub-basin that originates south of the Medina River floodplain. There are only about five known Leona Formation wells in the sub-basin and the well capacities are not known. The small size of the Chacon Creek floodplain and the limited number of Leona Formation wells suggest that paleo-stream channels, if present in the floodplain, would not have significant capacity for underflow. There are no other Leona Formation deposits mapped between the floodplains of Chacon Creek and Medina River. In the absence of Leona Formation sediments, there is no prospect for paleo-stream channels to have formed in this region. Given the higher elevation of streams located between the Sabinal and Medina Rivers, the streams in this portion of the model domain do not provide an avenue for discharge from the Edwards Aquifer (Green et al., 2012b).

2.4.3.2 Western San Antonio Pool Water Budget

Inspection of the river-basin map (Figure 2.1-3) confirms what is discussed in this section, that the western portion of the San Antonio Pool is recharged by flow from the Uvalde Pool via the Knippa Gap and from recharge from the Dry Frio-Frio River watershed. This watershed, as defined here, includes the Sabinal River, however, recharge from the Sabinal River watershed appears to be minimal. Due to a groundwater flow barrier associated with the Haby Crossing Fault, the western San Antonio Pool also is recharged by discharge out of Medina River watershed (discussed separately in Section 2.4.3.3). In addition, there may be limited recharge from streams that flow in the upper reaches of the watershed in Medina County located between the Sabinal River watershed on the west and the Medina River watershed on the east (Figure 2.1-3).

Water that is conveyed south as either surface water or groundwater out of the region from east of the Sabinal River watershed on the west to Quihi Creek watershed on the east is discharged from the Austin Chalk and other shallow formations that are not in hydraulic connection with the Edwards Aquifer. Based on this conceptualization, the only recharge to the Edwards Aquifer that occurs in this region would have to be in the headwaters of the watershed. Water that flows south is soon hydraulically perched above the Edwards Aquifer when it enters the Austin Chalk Aquifer and related hydraulic formations.

There are no known points of discharge from the western San Antonio Pool, with the exception of three virtually nonflowing waterholes on the Frio River. Thus, all water in the western San Antonio Pool flows downgradient in the Edwards Aquifer. Downgradient flow is restricted to the southern portion of the Edwards Aquifer in Medina County, since groundwater flow in the northern portion of Medina County is diverted to the southwest due to Haby Crossing Fault and possibly other faults in mid-Medina County. The first opportunity for natural discharge of this water from the Edwards Aquifer is San Antonio and San Pedro Springs in Bexar County.

The water budget of the western San Antonio Pool, prior to the addition of water diverted from northeast Medina County can be expressed

$$Q_{DIS} = Q_{KG} + Q_{DFR} + Q_{FR} + Q_{SR} + \Delta S - Q_{pumping} \qquad \text{(Eq. 2.4.3.2-1)}$$

where (all quantities are in terms of acre-ft/yr):

Q_{DIS} = discharge to Lower Edwards Aquifer
Q_{KG} = recharge from the Knippa Gap
Q_{DFR} = recharge from Dry Frio River Basin
Q_{FR} = recharge from Frio River Basin
Q_{SR} = recharge from Sabinal River Basin
ΔS = change in storage
$Q_{pumping}$= discharge by pumping

For this evaluation, steady-state conditions are assumed; thus, there will be no change in storage, ΔS. The only remaining sources of recharge are those from the Dry Frio, Frio, and Sabinal River Basins.

The combined area of recharge of the Dry Frio, Frio, and Sabinal River watersheds above the Confined Zone is 594,176 acres (LBG-Guyton Associates and Aqua Terra Consultants, 2005). The recharge rate calculated for the Frio River Basin using baseflow separation suggests the groundwater basin of the Frio River could be greater than this area, however how much greater is not clear.

The U.S. Geological Survey calculated median and mean recharge for the period 2001–2011 to be 143,900 acre-ft/yr and 203,100 acre-ft/yr, respectively. A mean recharge of 143,900 acre-ft over 594,176 acres equates to 2.91 inch/yr. This value is somewhat less than the 3.34 inch/yr recharge estimate for the Frio River Basin derived using baseflow separation. Given that the U.S. Geological Survey calculation does not account for recharge that occurs in the Contributing Zone upstream of the river gauges, values of recharge for the Dry Frio, Frio, and Sabinal River watersheds in excess of the U.S. Geological Survey calculations appear to be justified.

The EAA documents annual recharge assessments made by the U.S. Geological Survey for the major watersheds in the Edwards Aquifer Recharge Zone (Tremallo et al., 2014). The Edwards Aquifer in Medina County benefits from recharge by two principal watersheds: (i) the watershed located between the Sabinal and Medina River watersheds and (ii) the Medina River watershed (Figure 2.1-3) (LBG-Guyton Associates and Aqua Terra Consultants, 2005).

Total average annual recharge to the San Antonio segment of the Edwards Aquifer for the period 1934–2006 is estimated to be 711,600 acre-ft of which 174,600 acre-ft, or 25 percent, is attributed to the two principal watersheds in Medina County (Tremallo et al., 2014). Recharge of the Edwards Aquifer via the two watersheds is estimated using gain-loss river flow measurements, Tremallo et al. (2014). Recharge estimates published in Tremallo et al. (2014) assume that river-gauge measurements accurately reflect the amount of water that enters and exits the Edwards Aquifer along reaches of the creeks and rivers that cross the Recharge Zone. The accuracy of this recharge calculation also is predicated on the assumption that little or no subsurface flow occurs in the floodplains where the creeks and rivers enter and exit the Recharge Zone. Assessment of subsurface flow in the Leona River floodplain in Uvalde County indicates the subsurface flow component could be significant (Green et al., 2006, 2008a,b). Conversely, similar assessments of the Nueces and Frio Rivers indicated no significant subsurface flow component (Green et al., 2008b, 2009b).

2.4.3.3 Medina River Watershed

Field studies by Green et al. (2012b) provided new information that prompted development of an alternative conceptual model of the hydrologic relationship between the Medina Lake/Diversion Lake System and the Edwards Aquifer (Figure 2.4.3.3-1). A significant paleo-stream channel comprised of the Leona Formation gravel (Fisher, 1983) was detected in the Medina River floodplain during an electrical resistivity survey conducted in 2012 (Figure 2.4.3.3-2) (Green et al., 2012b). Because of the pervasive extent of the high electrical resistivity zone in the Medina River transect, the Leona Formation gravel paleo-stream channel is interpreted as a high-energy fluvial deposit composed mostly of sands and gravels.

The Pleistocene-age Leona Formation gravel was overlain in the Medina River channel by younger fluvial terrace deposits. Given the absence of alluvial deposits upstream from Haby Crossing Fault, the Leona Formation gravel paleo-stream channel appears to originate at Haby Crossing Fault. It is hypothesized that a spring was once present at the origin of the gravel deposits at Haby Crossing Fault. The spring and the paleo-stream channel deposits were later overlain by the fluvial terrace deposits; however, the significant transmissive capacity of the paleo-stream channel deposits remained. The current Medina River is incised into the fluvial terrace deposits.

It is this Leona Formation gravel paleo-stream channel that forms the basis for the alternative conceptual model. The new conceptual model hypothesizes that groundwater flows out of Medina and Diversion Lakes and discharges into the Leona Formation gravel paleo-stream channel and does not recharge into the Edwards Aquifer. This interpretation is substantiated by examining the hydrostratigraphy where Medina River crosses the Haby Crossing Fault. A vertical cross section of the generalized geology where the Medina River crosses the Haby Crossing Fault is illustrated in Figure 2.4.3.3-3.

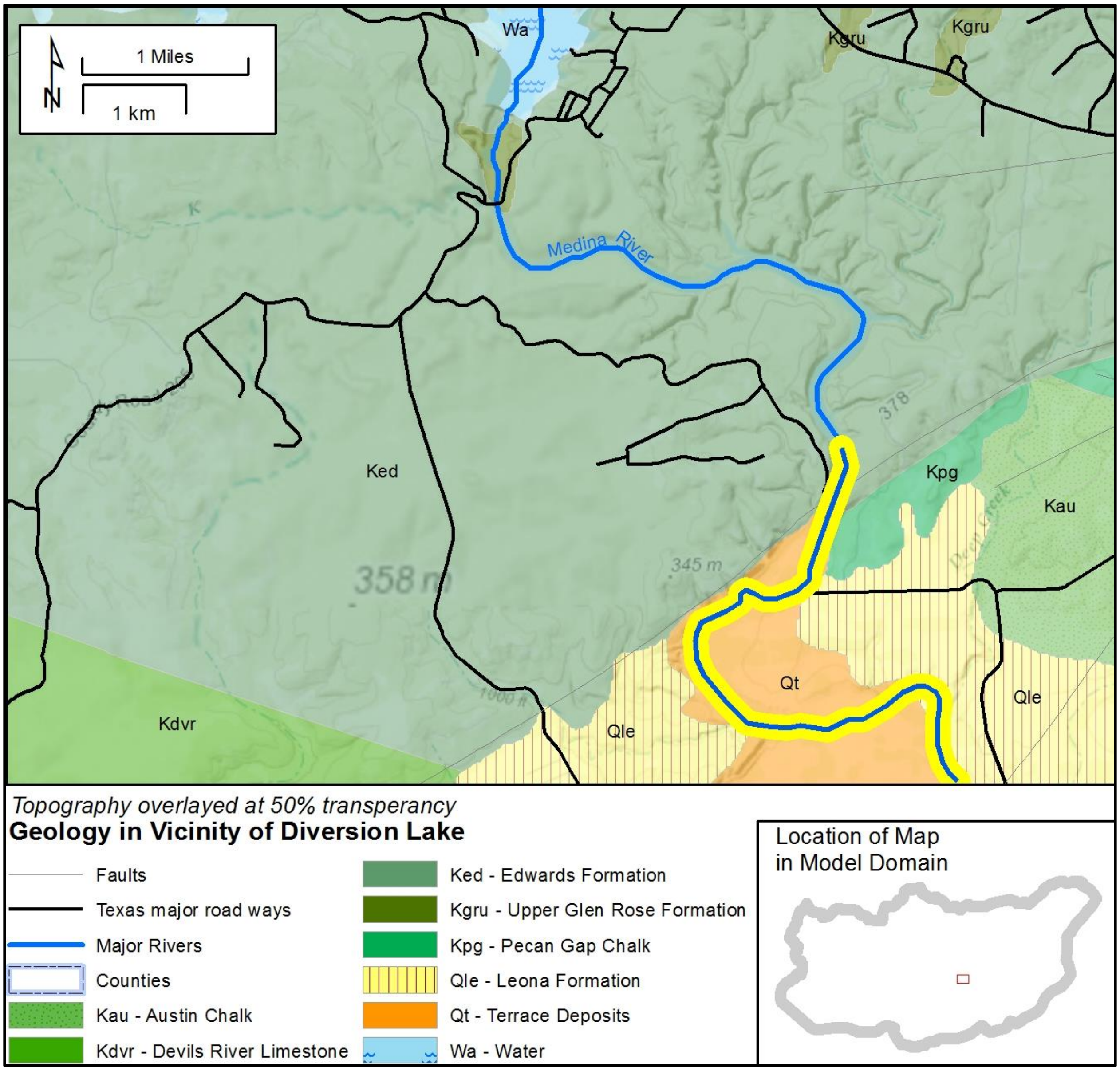
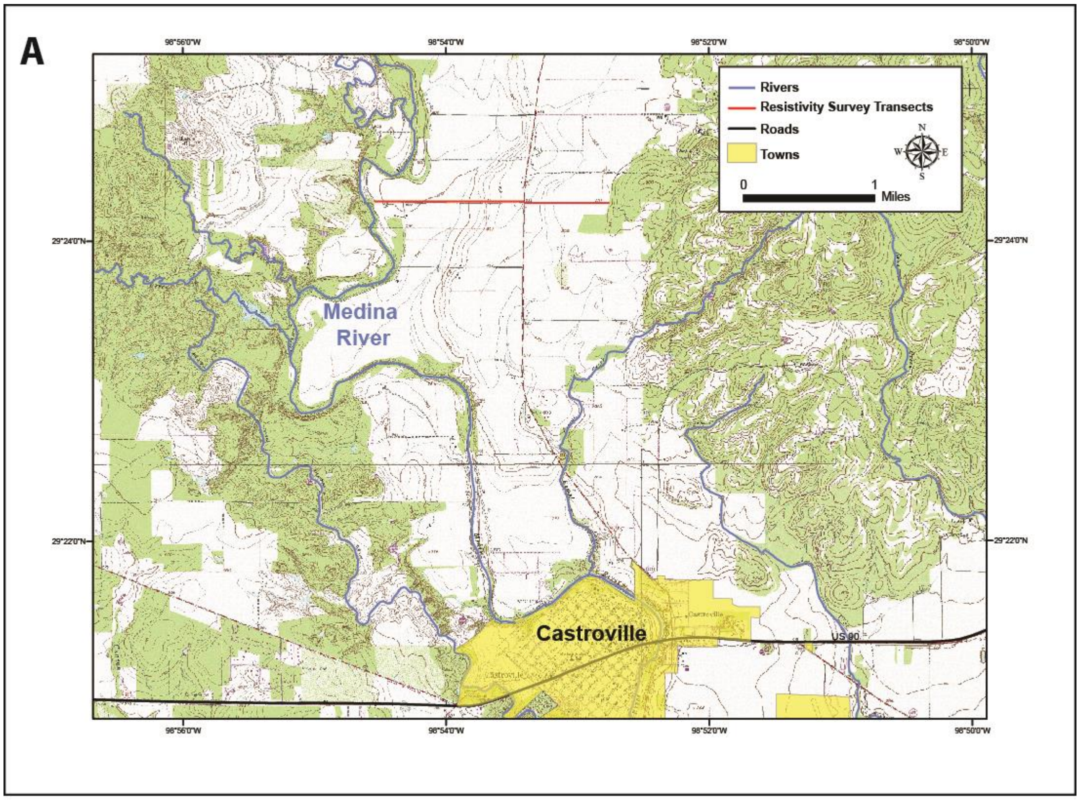


Figure 2.4.3.3-1. Geologic map of the Diversion Lake area, NE Medina County. Medina River downstream of Diversion Lake is highlighted with a yellow line. Taken from Lambert et al (2000).



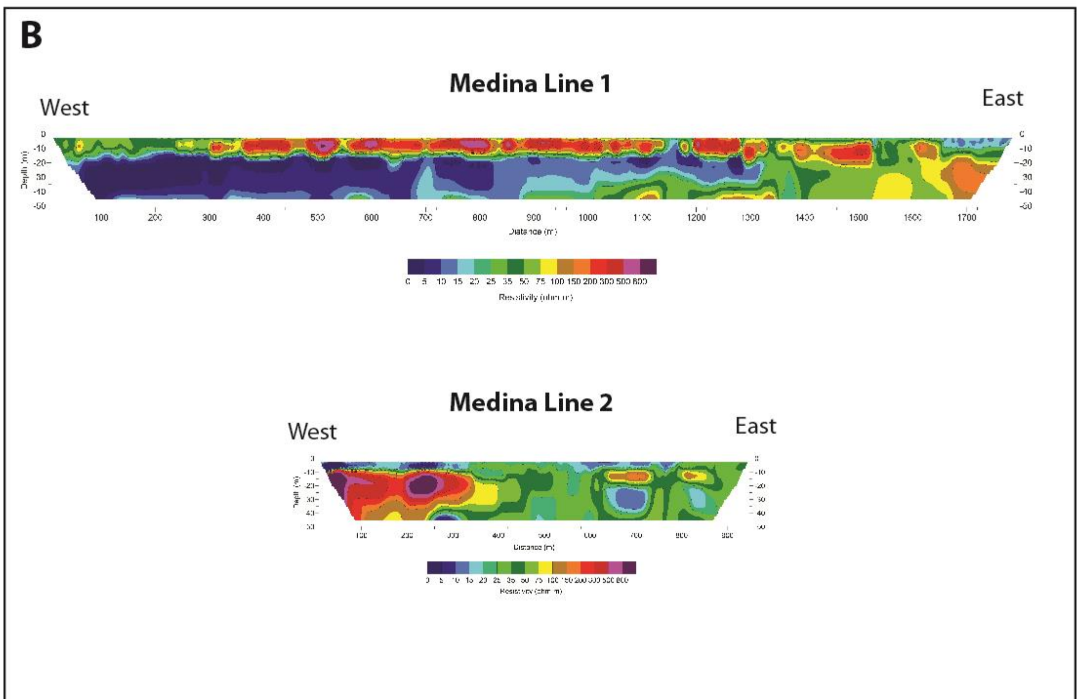


Figure 2.4.3.3-2. A) Location of resistivity B) Electrical resistivity survey cross sections of the Medina River floodplain. Warm colors indicate the locations of the Leona Formation gravels and the morphology of a paleo-stream channel.

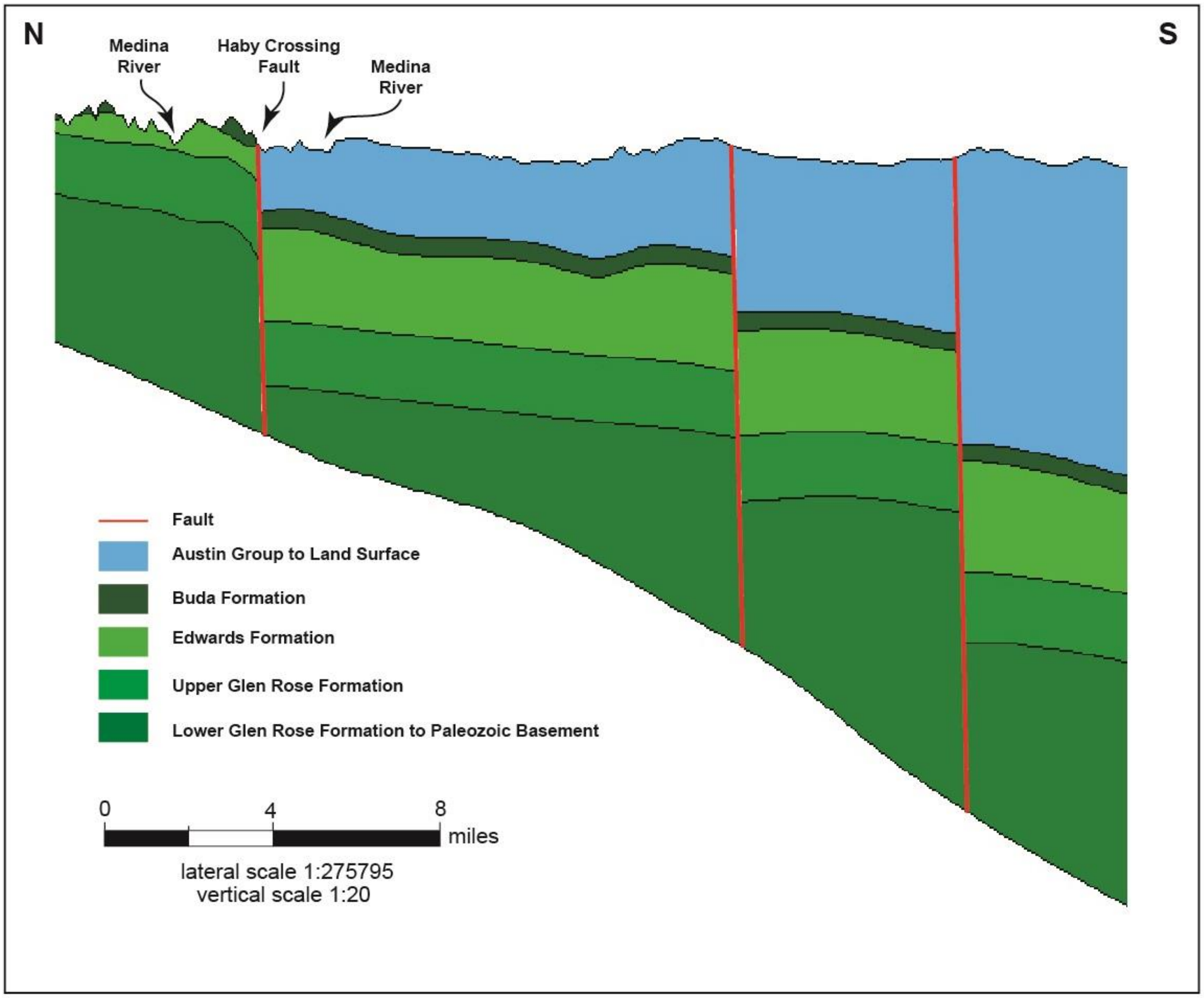


Figure 2.4.3.3-3. North-trending vertical cross section of the generalized geology where the Medina River crosses the Haby Crossing Fault.

The Leona Formation gravel is only present on the downdip side of Haby Crossing Fault. The Edwards Aquifer is overlain by approximately 1,000 ft of younger formations on the downdip side of Haby Crossing Fault. Hydraulic communication between the Leona Formation gravel and the Edwards Aquifer in the Medina River floodplain is unlikely. The elevation of the base of the Medina River floodplain where it exits the Recharge Zone at Haby Crossing Fault is approximately 870 ft msl. The maximum depth of the base of the Leona Formation gravel in the Leona River channel occurs at a depth of 65 ft (Cary Spurgeon, personal communication). If the same depth estimate is valid for the Medina River channel, the base of the Leona Formation gravel in the Medina River channel, where the channel exits the Recharge Zone, is approximately 805 ft msl. Given this geometry, the potentiometric surface of the Edwards Aquifer at this location is approximately 850 ft msl, thus, the paleo-stream channel deposits can be conceivably recharged by Edwards Aquifer water provided a flowpath exists from the Edwards Aquifer to the paleo-stream channel gravel deposits.

2.4.3.4 Medina River Watershed Water Budget

Data from the Medina River gauge at Bandera (U.S. Geological Survey gauging station 08178880) provide an opportunity to evaluate recharge in the upper Medina River watershed. The average annual discharge in Medina River at Bandera is assumed representative for Medina River flow upgradient from the hydrologic effect of the dam at Medina River. Baseflow was separated from flow measurements taken at U.S. Geological Survey gauging station 08178880 on the Medina River at Bandera (Green and Bertetti, 2010a). The long-term average flow at this station equates to 6.77 in/yr when averaged over the upstream watershed. The baseflow fraction of 0.68 indicates that 4.60 inch/year of the 6.77 inch/yr of average flow is attributed to recharge. 453,696 acres of the Medina River watershed are in the Contributing and Recharge Zones of the Edwards Aquifer (LBG-Guyton Associates and Aqua Terra Consultants. 2005). This suggests that 173,900 acre-ft/yr is recharged to the Medina River watershed. This estimate for recharge, which is considered high when compared with recharge estimates for adjoining basins, suggests the groundwater basin for Medina River may extend beyond the boundary of the surface watershed. Insufficient information is available to surmise which groundwater basin boundary extends beyond the surface watershed boundary. Alternatively, it is possible that a recharge rate of 4.60 inch/yr is representative of actual recharge given the localized high in precipitation (i.e., 37 inch/yr) due to an orographic effect associated with local highlands at the headwaters of the Medina River watershed (Figure 2.1-3).

Medina and Diversion Lakes (which is the Medina River dammed downstream from Medina Lake dam) have been evaluated to determine what role they play in the water budget of the Edwards Aquifer and how much water they recharge to the Edwards Aquifer (Green et al., 2012b). Lambert et al. (2000) evaluated the hydrogeology of the Medina Lake and Medina Lake Diversion and used the following water-budget from Lee and Swancar (1997) and prior work by Espey, Huston & Associates, Inc. (1989) to calculate the outflow from Medina and Diversion Lakes:

$$\Delta S \pm e_s = P \pm e_P - E \pm e_E + SW_{in} \pm e_{SWi} - SW_{out} \pm e_{SWo} + GW_{in} \pm e_{GW} - GW_{out} \pm e_{GWo} \quad \text{(Eq. 2.4.3.4-1)}$$

where:

ΔS = change in lake storage
P = precipitation on the lake
E = evaporation from the lake surface
SW_{in} = surface-water inflow to the lake
SW_{out} = surface-water outflow from the lake
GW_{in} = subsurface inflow into the watershed
GW_{out} = subsurface outflow from the lake (losses from lakes/recharge to the ground-water system)
e_{i} = uncertainty or error in each term

The water-budget expression was rearranged in terms of discharge as groundwater:

$$GW_{out} \pm e_{GWo} = P \pm e_P - E \pm e_E + SW_{in} \pm e_{SWi} - SW_{out} \pm e_{SWo} + GW_{in} \pm e_{GW} - \Delta S \pm e_s \quad \text{(Eq. 2.4.3.4-2)}$$

The bed of the southern half of Medina and Diversion Lake bottoms is mapped as the basal nodular unit of the Edwards Aquifer (Figure 2.4.3.3-1). Lambert et al. (2000) interpreted this to imply that water is recharged in the base of Medina Lake, thereby the GW_{out} term was interpreted as recharge to the Edwards Aquifer. Lambert et al. (2000) used Equation Eq. 2.4.3.4-2 to calculate recharge for three separate domains: (i) from Medina Lake, (ii) from Diversion Lake, and (iii) from the combination of Medina and Diversion Lakes all for the period 10/1/1995–9/30/1996. During this period, Medina Lake stage decreased from 1,045 ft msl to 1,019 ft msl. Average rates of water lost from Medina Lake varied from 62.00 to 443.60 acre-ft/day. Similarly, Diversion Lake varied from an increase of 20.62 acre-ft/day to a loss of 25.82 acre-ft/day over this same period. When calculated together, the average loss of water from the combined Medina and Diversion Lake system varied from 63.33 to 547.85 acre-ft/day (Lambert et al., 2000). The uncertainty in these calculations is significant. Lambert et al. (2000) recognized this uncertainty and expressed it as average errors in the recharge values for Medina, Diversion, and combined Medina-Diversion Lakes. Average errors for the three sets of calculations are 19.69–60.13, 44.40–45.69, and 23.14–71.27 acre-ft/day, respectively.

The Lambert et al. (2000) conceptual model was used as the basis for the follow-on study by Slattery and Miller (2004) and in HSPF calculations by Clear Creek Solutions (2009). Calculations by Slattery and Miller (2004) and Clear Creek Solutions (2009) were predicated on the conceptual model developed by Lambert et al. (2000). Slattery and Miller (2004) refined the recharge calculations by extending the stage of Medina Lake for which recharge was calculated. The period of data for the Slattery and Miller (2004) was expanded to include 1955–1964 and 2001–2002, periods when Medina Lake stage varied from as low as 963 ft msl and as high as 1,040 ft msl. Using a linear equation developed based on data from these periods, Slattery and Miller (2004) estimated that during the period 1934–2003, recharge to the Edwards Aquifer from the Medina River varied from a low of 6,500 acre-ft/yr in 1956 to a high of 104,000 acre-ft/yr in 1960 with an average recharge of 62,700 acre-ft/yr during this period.

Clear Creek Solutions (2009) refined the HSPF model of the Medina River watershed to provide better estimates of recharge of the Edwards Aquifer. The refined HSPF model was predicated on the Slattery and Miller (2004) conceptualization and was used to predict recharge of the Edwards Aquifer from the Medina watershed for the period 1950–2006. Estimates of recharge to the Edwards Aquifer varied from a low of 24,089 acre-ft/yr in 1950 to a high of 120,091 acre-ft/yr in 1987. In summary, estimates of recharge to the Edwards Aquifer from the Medina Lake/ Diversion Lake system by Lambert et al. (2000), Slattery and Miller (2004), and Clear Creek Solutions (2009) are relatively similar.

Detection of the extensive paleo-stream channel in the Medina River channel provided the basis for an alternative conceptualization of the water budget of the Medina River watershed. The paleo-stream channel in the Medina River floodplain is estimated to be 6,000-ft wide and 7-ft thick for a cross sectional area of 42,000 ft^2. The gradient of the paleo-stream channel is assumed to be consistent with the gradient of the current Medina River or 0.0025 ft/ft. This gradient also is consistent with the measured hydraulic gradient of the Leona River floodplain paleo-stream channel (Green et al., 2008a, 2009b). The hydraulic properties of the Leona Formation in the Medina River floodplain have not been measured with an aquifer test and are estimated using documented values for a coarse gravel (i.e., 20,000–200,000 ft/day, Bear, 1972; Freeze and Cherry, 1979). This equates to approximately 24–240 cfs or 17,500–175,000 acre-ft/yr of flow through the Medina River floodplain paleo-stream channel deposits. If an average hydraulic conductivity of 100,000 ft/day is assumed for the Leona Formation deposits, underflow would be 120 cfs or 88,000 acre-ft/yr in the Medina River floodplain. This large value for hydraulic is consistent with the presence of irrigation wells in the gravel with a capacity estimated to be as great as 10,000 gpm.

Average annual Medina River surface discharge downstream from Haby Crossing Fault is 202 cfs or 146,000 acre-ft/yr for the period 1981–2011 (U.S. Geological Survey website measured at station 08180700 near Macdona, Texas). Based on this assessment, discharge as underflow could be comparable to surface flow in the Medina River floodplain. If average values are assumed, total flow via the Medina River floodplain is approximately 322 cfs (~234,000 acre-ft/yr). Underflow in the paleo-stream channel in the Medina River floodplain accounts for approximately 38 percent of the total average discharge via the Medina River floodplain.

Note that the annual Medina River discharge varied from a low of 38.1 cfs in 2009 to as high as 953.7 cfs in 1992, a factor of 25 greater. It is likely that the paleo-stream channel underflow also varies with time; however, insufficient data are available to ascertain this variance. The paleo-stream channel rate of 120 cfs (88,000 acre-ft/year) is believed representative of average conditions, and year-to-year variances could be considerable. This underflow rate is consistent with the calculations for GW_{out} by Lambert et al. (2000), Slattery and Miller (2004), and Clear Creek (2009), however they attributed GW_{out} to recharge to the Edwards Aquifer. In contrast, this loss of groundwater is assumed in this characterization to be discharged to the paleo-stream channel in the Medina River channel.

The Lambert et al. (2000) conceptual model does not account for the large flow of water in the paleo-stream channel in the Medina River floodplain. For the Lambert et al. (2000) and Lee and Swancar (1997) water budget to be appropriate, the groundwater outflow term needs to be recasts as:

$$GW_{out} = GW_{Edwards} + GW_{Leona} \quad \text{(Eq. 2.4.3.4-3)}$$

where groundwater outflow has two components, outflow to the Edwards Aquifer and outflow to the Leona Formation gravel in the Medina River floodplain. The GW_{Leona} component is underflow in the Medina River floodplain. If the conceptualization of significant outflow through the Medina River paleo-stream channel deposits is correct, then recharge from the Medina-Diversion Lake System to the Edwards Aquifer is negligible or possibly nonexisitant.

In summary, the average annual discharge in Medina River at Bandera is representative for Medina River flow upgradient from the hydrologic effect of the dam at Medina River. The baseflow fraction of flow indicates that 4.60 inch/year is attributed to recharge (Green and Bertetti, 2010a). 453,696 acres of the Medina River watershed are in the Contributing and Recharge Zones of the Edwards Aquifer. This suggests that the Medina River watershed could provide significant recharge, i.e., 173,900 acre-ft/yr, to the Edwards Aquifer, even when accounting for discharge via the paleo-stream channel in the Medina River channel.

2.4.4 Eastern Hydrogeology

2.4.4.1 Interbasin Area Between Medina River and Cibolo Creek Basins

The interbasin area between the Medina River and Cibolo Creek Basins includes San Geronimo, Helotes, Leon, and San Pedro Creeks and the San Antonio River. The interbasin area extends into Contributing Zone, but does not extend to the northern boundary of the model domain.

Recharge in the San Geronimo and Helotes Creek watersheds were evaluated by assessing their water budgets using river-flow measurements. U.S. Geological Survey river gauges Helotes Creek at Helotes (08181400), and Laurel Canyon Creek (Government Canyon State Natural Area) near Helotes (08180942) were used in the evaluation. The average annual discharge in Laurel Canyon Creek (located in the San Geronimo Creek watershed) for the period 2003–2009 was 0.068 cfs which equates to 1.54 inch/yr over the 384-acre watershed. The average annual discharge in Helotes Creek for the period 1969–2013 was 0.55 cfs. This equates to 0.50 inch/yr over the 9,600-acre watershed. As mentioned, baseflow was not separated out of the Laurel Canyon and Helotes Creek flow measurements.

Recharge values for both these creeks are unrealistically low. This discrepancy is explained by the fact that most flow in Helotes Creek recharges the Upper Glen Rose upstream from the river gauge, which is located at the boundary of the Edwards Aquifer Recharge Zone. Similarly, flow in San Geronimo Creek only reaches the Edwards Aquifer Recharge Zone during periods of significant surface runoff and flow. Farther east, Leon Creek is believed to exhibit similar characteristics. This observation is consistent with the interpretation that the Upper Glen Rose Formation has sufficiently high permeability to accept the baseflow in Helotes San Geronimo, and Leon Creeks.

The watershed source areas for San Pedro Creek and San Antonio River are in the Pecan Gap Formation, a formation significantly higher in the stratigraphic column–overlying the Austin Chalk–and hydraulically distinct from the Edwards Aquifer (Figure 2.3.2-1). River flow measured on San Pedro Creek (U.S. Geological Survey river gauge 08178504 at Probandt St) and the San Antonio River (U.S. Geological Survey river gauge 08178050 at Mitchell St) in south San Antonio represent water discharged from the Edwards Aquifer via San Pedro and San Antonio Springs (Figure 2.4.4.1-1). However, additional flow in San Pedro Creek and San Antonio River where they exit the model domain is due to distributed recharge that is accumulated downstream of the Recharge Zone and should not be included in the Edwards Aquifer water budget.

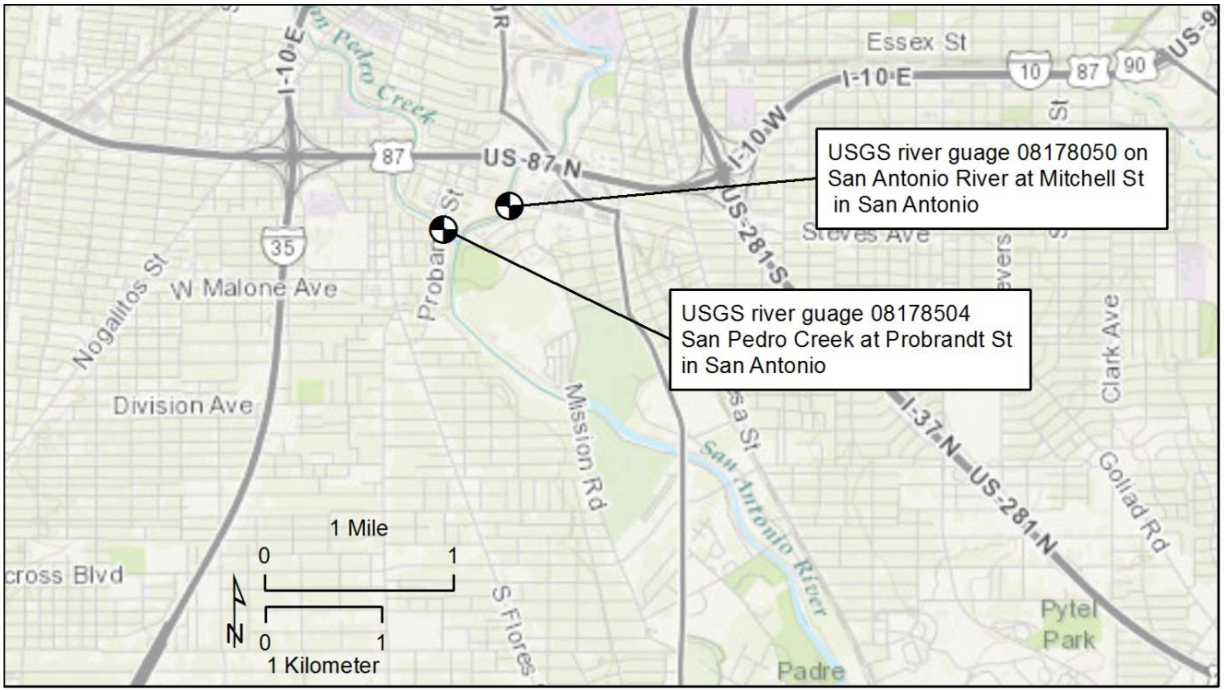


Figure 2.4.4.1-1. Map illustrating river gauge locations on San Pedro Creek and San Antonio River in south San Antonio.

2.4.4.2 Cibolo Creek Watershed

Cibolo Creek exhibits perennial flow only in its upper reaches and is ephemeral elsewhere (Slade et al., 2002). The absence of flow in Cibolo Creek, except after large precipitation events, is evidence of the large capacity of the bedrock along Cibolo Creek to accept recharge. Water loss in Cibolo Creek is recognized as Edwards Aquifer recharge by the designation of the Upper Glen Rose exposed in the creek bed as part of the Edwards Aquifer Recharge Zone. Texas Water Quality Board Order No. 74-0326-4, effective March 27, 1974, identified the Edwards Aquifer Recharge Zone to include that area within the 100-year flood plain of Cibolo Creek from where it begins at Herff Falls in Kendall County and continues downstream to the Edwards and associated limestones outcrop (Texas Commission on Environmental Quality Edwards Aquifer Recharge Zone–Chapter 213 Rules) (Figure 2.4.4.2-1).

River-flow data for three gauging stations on Cibolo Creek are analyzed. Two gauges are located near its headwaters where the creek has mostly perennial flow. The third gauge is located near where Cibolo Creek enters the Edwards Aquifer Recharge Zone and flow is ephemeral. U.S. Geological Survey gauge 08183900 near Boerne and U.S. Geological Survey gauge 08183890 at Cibolo Nature Center near Boerne are located where flow is mostly perennial. The average annual flow at gauge 08183890 for the period 2007–2011 was 26.4 cfs (19,145 acre-ft/yr). The watershed above this gauging station is 36,032 acres which equates to 5.38 inches of recharge and runoff per year. The average annual flow at gauge 08183900 for the period 1963–1995 was 29.2 cfs (21,130 acre-ft/yr). The watershed above this gauging station is 43,776 acres which equates to 5.79 inches of recharge and runoff per year.

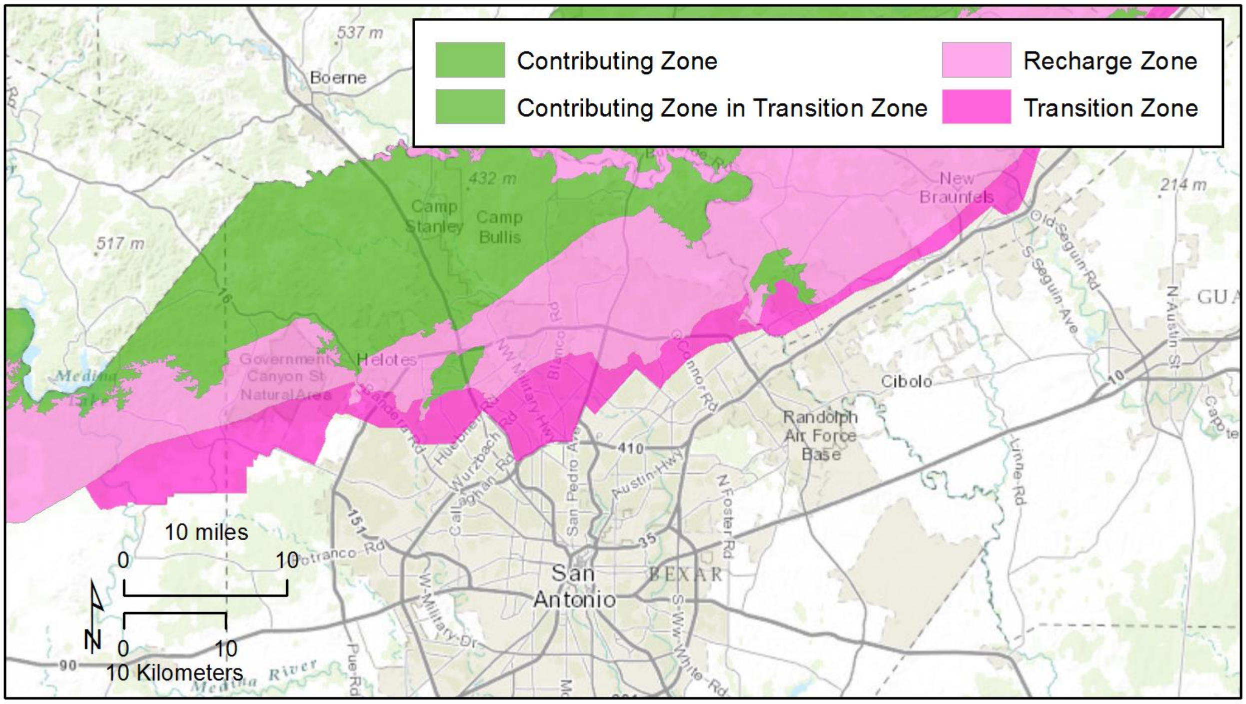


Figure 2.4.4.2-1. Map illustrating the designation of the Cibolo Creek 100-yr flood plain as part of the Edwards Aquifer Recharge Zone (Texas Commission on Environmental Quality map database). Contributing (green), Recharge (light pink), and Transition (dark pink) Zones, as designated by the Texas Commission on Environmental Quality are illustrated.

The gauge upstream of Selma on Cibolo Creek (U.S. Geological Survey gauge 08185000) is in a reach where flow is ephemeral and the creek is dry 90 percent of the time. The average annual flow at gauge 08185000 for the period 1978–2011 was 27.6 cfs (19,982 acre-ft/yr). The watershed above gauge 08185000 spans 175,360 acres. Thus the reach between gauge 08183900 at the Cibolo Nature Center in Boerne and gauge 08185000 at Selma is losing. This observation is consistent with a compendium of gain-loss studies by the U.S. Geological Survey (Slade et al., 2002) (Figure 2.4.4.2-2). Water recharged along this reach is characterized as recharge to the Edwards Aquifer via an unidentified subsurface flow path.

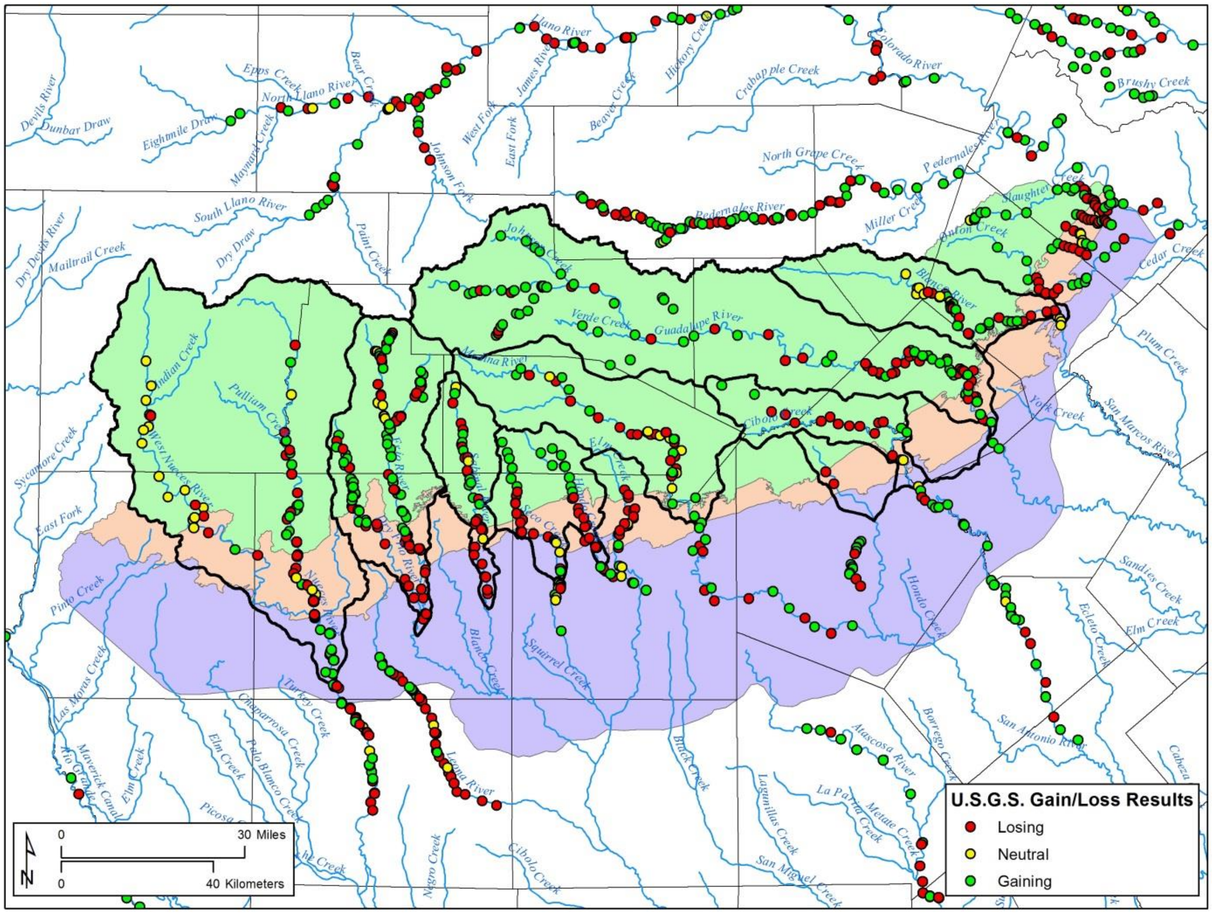


Figure 2.4.4.2-2. Map of model domain illustrating river reaches that are gaining (green dots), losing (red dots), or neither (yellow dots). Stream data are from Slade et al. (2002).

Johnson and Schindel (2008) provide insight on the relationship of recharge between Cibolo Creek and discharge to the major springs (Figure 2.4.4.2-3). The Selma gauge on Cibolo Creek is located in the Artesian Fault block. There is a positive correlation between flow on Cibolo Creek and discharge at Hueco Springs. This correlation varies with Cibolo Creek flow rate. There is one correlation when Cibolo Creek flow at Boerne is between 30 cfs and 70 cfs and a different correlation at high flow rates. When there is no flow in the Cibolo River at Selma, Hueco Springs discharge averages 54 cfs. When Cibolo Creek is flowing at Selma, Hueco Springs discharge averages 100 cfs. This suggests flow in Cibolo Creek recharges the Hueco Springs Fault block only during high river-flow periods.

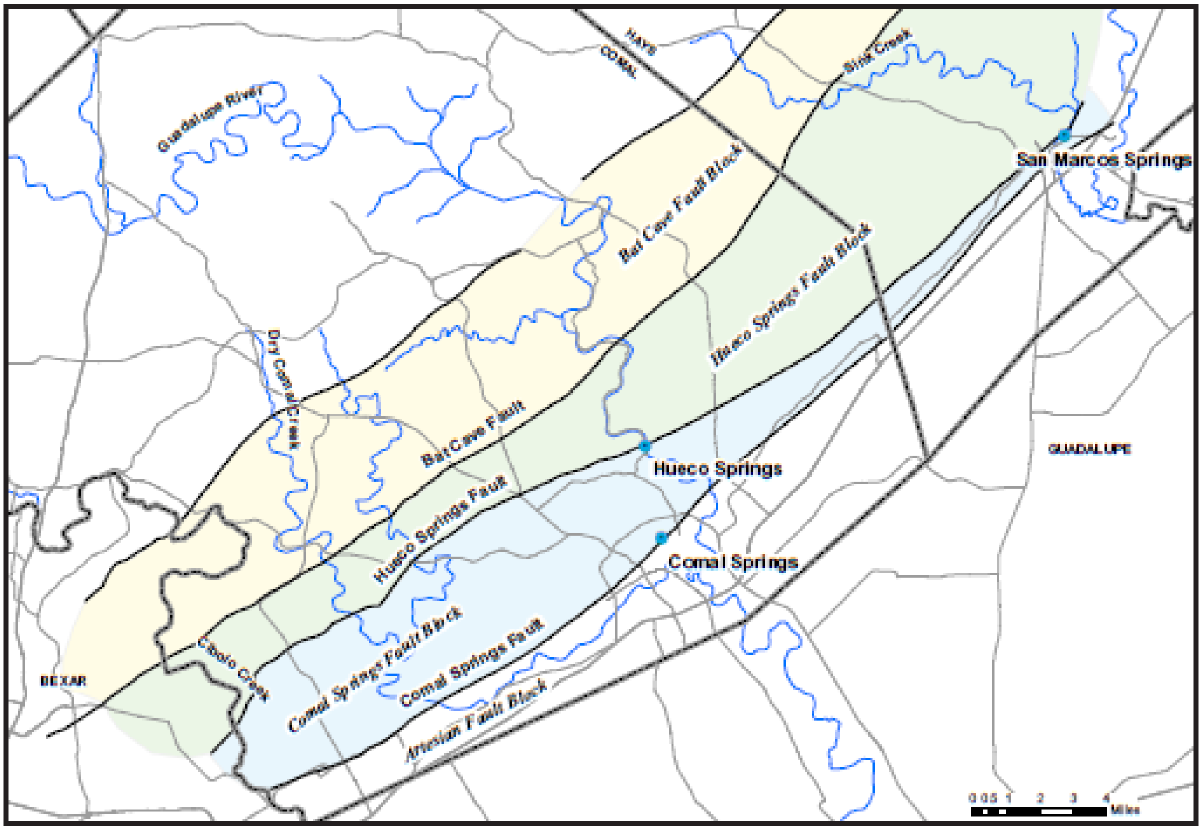


Figure 2.4.4.2-3. Fault block designations near Comal, Hueco, and San Marcos springs (from Johnson and Schindel, 2008).

Cibolo Creek gains in the Bat Cave Fault block and loses in the Hueco Springs Fault block. There is no correlation between Cibolo Creek flow at Boerne and groundwater elevation in wells in the Bat Cave Fault block. There is no correlation between Cibolo Creek flow at Boerne and groundwater elevation in wells in the Artesian Fault block. Although Johnson and Schindel (2008) do not examine the correlation between Cibolo Creek flow at Boerne and discharge at Comal Springs, it is expected that this correlation would be minimal because Comal Springs is recharged by the Artesian Fault block.

Johnson and Schindel (2008) note that there is little evidence to suggest that Cibolo Creek is a major contributor to the San Marcos spring system. Based on limited data, Cibolo Creek contributes a relatively small fraction of San Marcos Springs discharge below 150 cfs and a slightly larger fraction above 150 cfs. They note that George et al. (1952) held the same conceptualization and that they estimate that Cibolo Creek contributes one-quarter to one-third of the flow at Comal Springs.

2.4.4.3 Cibolo Creek Watershed Water Budget

The Cibolo Creek watershed obviously provides significant recharge to the Edwards Aquifer. Examination of the geologic structure near Cibolo Creek indicates that fault offset in the Balcones Fault Zone south of the Cibolo Creek is less significant than north of the Cibolo Creek.

This local reduction in fault offset is consistent with the increased width of the Edwards Aquifer Recharge Zone to the south of Cibolo Creek.

Recharge of the Edwards Aquifer from Cibolo Creek watershed can be estimated using upstream river-gauge measurements and an empirical relationship between annual average precipitation and recharge. A correlation between precipitation and recharge was developed for the western Edwards Plateau region using recharge calculations based on stream baseflow separation analyses (Eq. 2.4.2.2-1) (Green and Bertetti, 2010a and Green et al., 2012a). If this correlation is appropriate for the Cibolo Creek watershed, then the average annual precipitation of 33.74 inch/yr of precipitation in Boerne should provide about 2.6 inch/yr of recharge when averaged over the watershed. For the 175,360-acre watershed upstream from Selma, recharge from Cibolo Creek watershed should average approximately 37,800 acre-ft/yr if this evaluation is valid.

2.4.4.4 Guadalupe River Watershed

The Guadalupe River is the only river in the Edwards Aquifer Contributing Zone that is perennial from its headwaters to the Recharge Zone. Other rivers in the Contributing Zone may be perennial near their headwaters but are ephemeral at downstream locations, particularly at reaches close to the Recharge Zone where the Upper Glen Rose Formation is exposed in river beds. In comparison, the Guadalupe River retains perennial flow even where it overlies the Upper Glen Rose Formation. The Guadalupe River crosses Comal and San Marcos Springs and Bat Cave fault blocks at locations where the faults that separate the major fault blocks are believed to act as barriers to flow. Johnson and Schindel (2008) note that although the Guadalupe River carries large volumes of water, discharge measurements above and below the Recharge Zone indicate it is a minor contributor to the Edwards Aquifer.

There are six U.S. Geological Survey gauges on the Guadalupe River upstream of New Braunfels that provide significant flow data for analysis: 08165300 North Fork near Hunt, 08165500 at Hunt, 08166200 at Kerrville, 08167000 at Comfort, 08167500 near Spring Branch, and 08168500 above Comal River. Long-term average flow for each gauge is included in Table 2.4.4.4-1. The monotonically increasing flow measurements are consistent with gain-loss measurements summarized by Slade et al. (2002) (Figure 2.4.4.2-2) that suggest that the Guadalupe River is essentially a gaining river with limited flow lost to recharge. The exception to this generalization is a reach of the Guadalupe River immediately upstream from the Edwards Aquifer Recharge Zone.

Flow data and analyses on the Guadalupe River watershed provide some insight into the hydraulic relationship of the river with the subsurface. Data include flow measurements and baseflow separation analyses (Table 2.4.4.4-2). The baseflow fractions at the four river gauges have been calculated. The four values of .8165, 0.695, 0.865, and 0.635 are relatively similar with an average value of 0.76. If this baseflow fraction is representative of the Guadalupe River, then recharge for the Guadalupe River watershed would be 3.96 inch/yr when using average annual flow measured at the Guadalupe River above Comal River. Annual average precipitation is variable over the Guadalupe River watershed from 31 inch/yr in Kerr County to the west to 35.8 inch/yr in the east for an average precipitation of about 33.5 inch/yr. The 3.96 inch/yr calculation for recharge is somewhat greater than a recharge value of 2.8 inch/yr calculated using

Equation 2.4.2.2-1, however, it should be noted the Equation 2.4.2.2-1 was developed for drier environments and may not be valid for average annual precipitation as large as 30 inch/yr.

Table 2.4.4.4-1. Average flow recorded at six U.S. Geological Survey gauging stations on the Guadalupe River.

Gauge	Gauge Location	Watershed Area (acres)	Average Flow (acre-ft/yr)	Flow per Acre (in/yr)
8165300	North Fork near Hunt	108,160	25,218	2.76
8165500	Hunt	184,320	54,145	3.48
8166200	Kerrville	326,400	101,154	3.72
8167000	Comfort	536,960	164,645	3.72
8167500	Spring Branch	841,600	269,750	3.84
8168500	above Comal River	971,520	417,852	5.16

Table 2.4.4.4-2. Flow measurements and baseflow separation analyses from the Guadalupe River watershed.

Gauge	Gauge Location	Weighted Baseflow Fraction	Average Annual Discharge (acre-ft/yr)	Total Flow (inch/yr)	Recharge Rate (inch/yr)
8165300	North Fork near Hunt	0.39	25,218	2.79	1.09
8166200	Kerrville	0.695	101,154	3.72	2.58
8166250	Center Point	0.865	-	3.48	3.01
8167000	Comfort	0.635	164,645	3.72	2.36

2.4.4.5 Guadalupe River Watershed Water Budget

Average annual flow at Comal River (219,424 acre-ft/yr) when added with the Guadalupe River above the confluence with the Comal River (417,852 acre-ft/yr) sums to 637,276 acre-ft/yr, however the average flow at downstream gauge 08169500 is only 555,467 acre-ft/yr, a difference of 81,809 acre-ft/yr (Figure 2.4.4.5-1). Average annual flow in the Guadalupe River at the Seguin gauge 08169792, which is farther downstream, is 589,283 acre-ft/yr, still a difference of almost 48,000 acre-ft/yr from the sum of the Comal River and the upstream Guadalupe River flows. All river gauges illustrated in Figure 2.4.4.5-1 are within the Edwards Aquifer Confined Zone. None are within the Recharge Zone. Thus, loss of flow between the confluence of Comal and Guadalupe Rivers cannot be directly attributed to be recharge of the Edwards Aquifer, although this prospect cannot be completely dismissed.

George et al. (1952) posited that the Guadalupe River contributes very little water to Comal Springs. LBG-Guyton Associates (2004) concluded that San Marcos Springs receive water from local and regional sources and that the Guadalupe River watershed may contribute to Comal Springs as a local source. Woodruff and Abbott (1986) reported that the Guadalupe River contributes little or no water to the San Marcos hydrologic system. Johnson and Schindel (2008) used well data near the Guadalupe River to estimate that he maximum recharge from the

Guadalupe River to the Edwards Aquifer is estimated at 10 percent of flow below 500 cfs, for a maximum recharge rate of 50 cfs, although they acknowledge that this estimate may be high. Musgrove and Crow (2012) examined the chemistry of water discharged from San Marcos Springs and found little evidence for dilution by local recharge. These analyses suggest the Guadalupe provides a maximum of 36,000 acre-ft/yr of recharge to the Edwards Aquifer, less than 9 percent of the annual average flow of 417,852 acre-ft/yr measured at gauge 08168500 located above the confluence with Comal River.

The consensus of these evaluations is that most recharge from the Guadalupe River watershed is conveyed out of the Contributing Zone, past the Recharge Zone, and beyond the Contributing Zone without recharging the Edwards Aquifer. This attribute sets the Guadalupe River watershed apart from the other major watersheds in the Edwards Aquifer Contributing Zone. Nonetheless, it appears that a minor component of recharge from the Guadalupe River does recharge the Edwards Aquifer.

2.4.4.6 Blanco River Watershed

Blanco River flow at Wimberley ranged from 3.9 to 600 cfs, with an average of approximately 15 cfs (Johnson and Schindel, 2008). A comparison of flow at U.S. Geological Survey gauges at Wimberley (08171000; upstream) and at Kyle (08171300; downstream) suggests that the channel is losing where it crosses the Bat Cave Fault block and the Hueco Springs Fault block (Figure 2.4.4.6-1). When there is no flow at the Kyle gauge, all flow that flows past the Wimberley gauge recharges the Edwards Aquifer and is available for discharge at San Marcos Springs.

2.4.4.7 Blanco River Watershed Water Budget

Of importance is how much the Blanco River contributes to discharge at San Marcos Springs under different hydrological conditions. The northern orifices of San Marcos Springs–Cabomba, Hotel, Johnny (aka Weissmuller), and Divergent (aka Diversion)–are recharged by the Blanco River, Sink Creek, and areas downgradient to the north. These recharge areas are south of the groundwater divide near Onion Creek that separates the San Marcos recharge basin from the Barton Springs recharge basin (Johnson and Schindel, 2008). The Blanco River also carries large volumes of water through the area believed to be within the San Marcos springshed. Discharge of both the Blanco River at Wimberley and San Marcos Springs are flashy, responding quickly to storm events. Statistically, however, correlation of Blanco River flow and discharge at San Marcos Springs is relatively low (approximately 60 percent) (Johnson and Schindel, 2008). Guyton (1979) contended that regional groundwater comprises 55 to 60 percent of San Marcos springflow. Consistent with this assessment, McKinney and Sharp (1995) found that local sources such as Purgatory and York Creeks and the Blanco River contribute up to 35 percent of San Marcos Springs discharge. LBG-Guyton Associates (2004) concurred that San Marcos Springs receive water from local and regional sources. They identified Blanco River and other parts of the Blanco River watershed and possibly the Guadalupe River watershed as local sources.

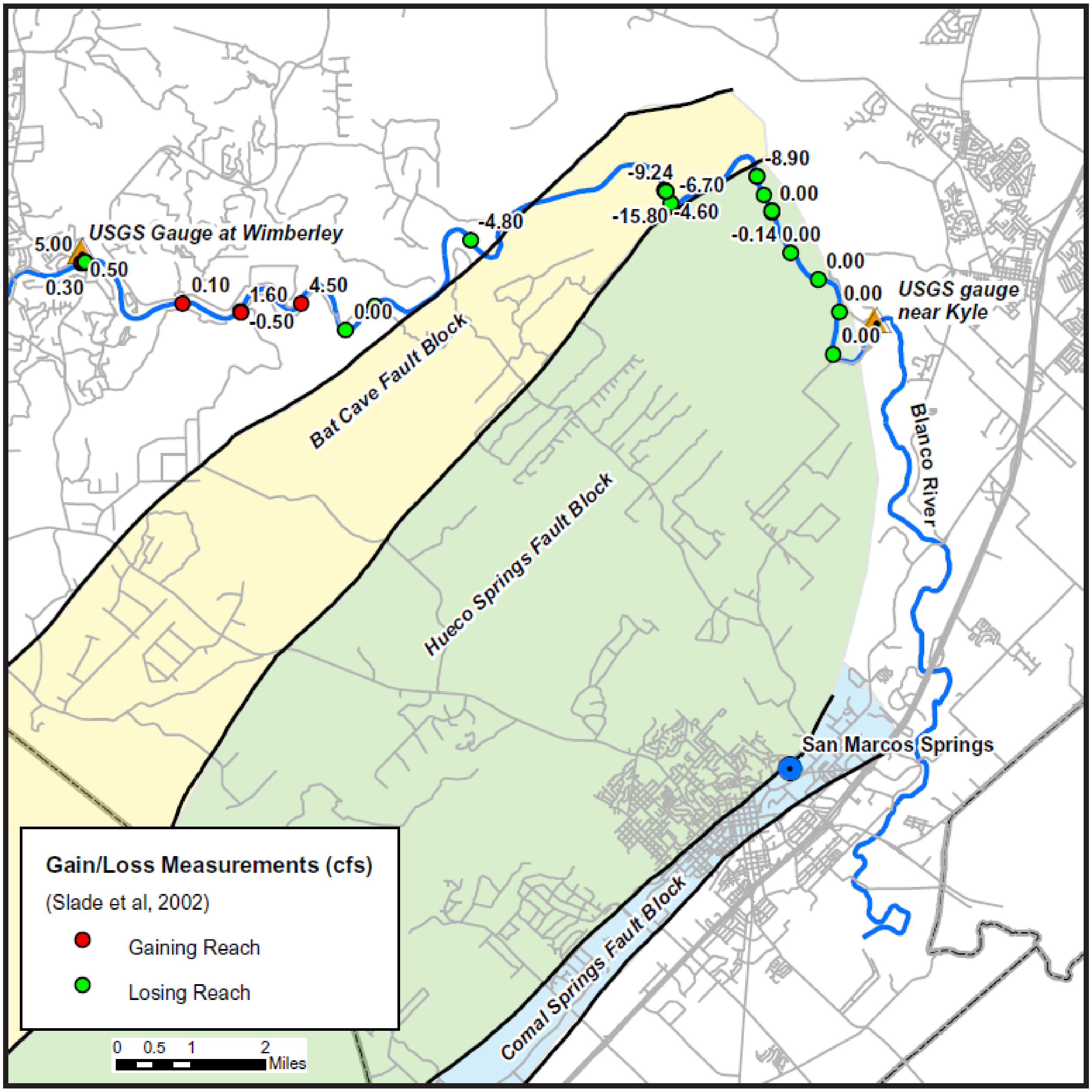


Figure 2.4.4.6-1. Gain-loss measurements on the Blanco River (data from Slade et al., 2002; figure from Johnson and Schindel, 2008).

Previous estimates of the amount of recharge that the Blanco River provides to San Marcos Springs are mixed. Klemt and others (1979) attributed 47 percent of the Blanco River flow directly to San Marcos Springs discharge. In contrast, Texas Board of Water Engineers (1960), Watson (1985), and Slade and others (2002) measured channel losses in the Blanco River over the recharge zone at less than 20 cfs, meaning there is limited infiltration in the Blanco River available for discharge at San Marcos Springs. Streamflow measurements by the U.S. Geological Survey and Texas Department of Water Resources indicated 15 cfs as the maximum loss rate for the Blanco River. However, Watson (1985) concluded that rate was appropriate at river stages up to two feet. He increased his estimate to 30 cfs because additional water would flow into Tarbuttons Showerbath Cave at higher river stages. When San Marcos Springs discharge is less than 100 cfs, the Blanco River contributes only a small percentage of water to San Marcos Springs discharge. If all flow from the Blanco River recharged San Marcos Springs during periods of no flow at Kyle, its contribution would range from approximately 8 to 25 percent of springflow (Johnson and Schindel, 2008). Recharge of the Edwards Aquifer from the Blanco River basin remains uncertain, however, the consensus of these assessments suggests that the Blanco River does provide limited, but meaningful recharge to the Edwards Aquifer and that this recharge is of the order of 15 cfs or 10,900 acre-ft/yr, although this amount could vary significantly.

3. Model Assignments

The Contributing and Recharge Zones of the model domain are incorporated as three layers in the numerical model. Layers 1, 2, and 3 represent the Edwards Aquifer, Upper Glen Rose Formation, and the Lower Glen Rose Formation, respectively. The lateral extents of the three layers in the Contributing Zone are the same. The Confined Zone is incorporated as a single layer, the Edwards Aquifer (Figure 3-1).

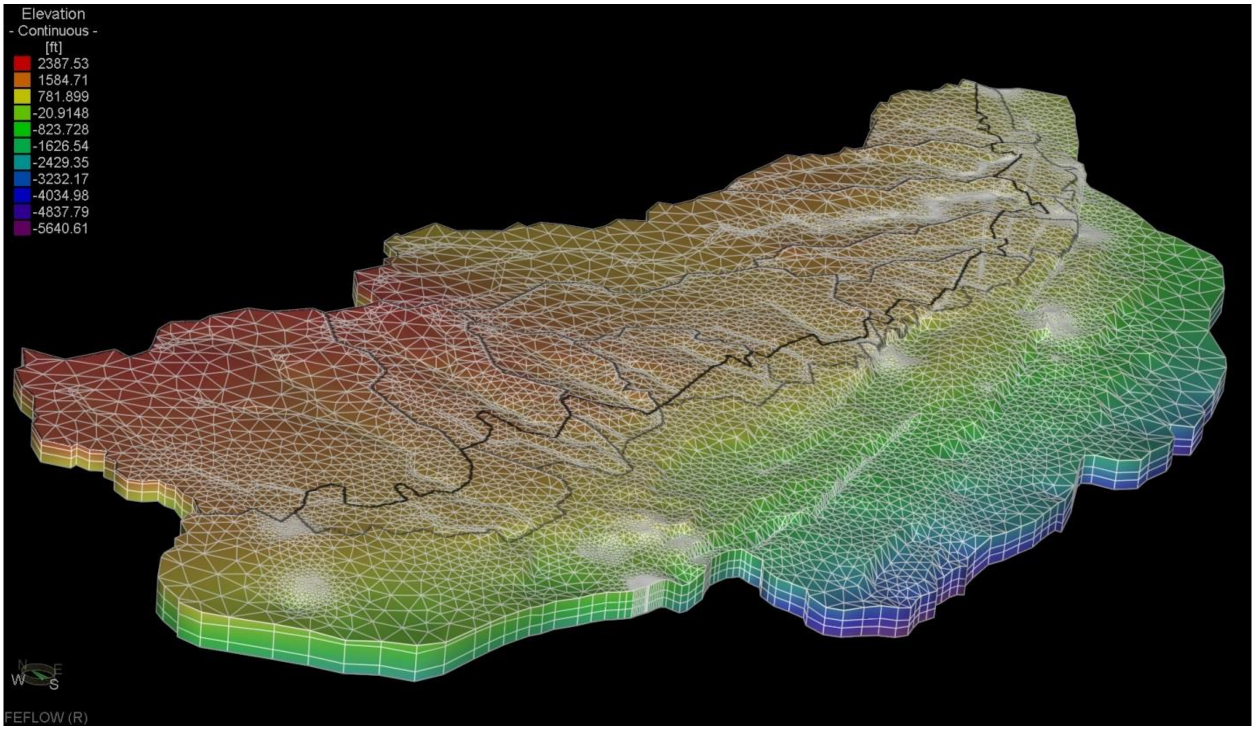


Figure 3-1. Illustration of numerical model.

The Edwards Aquifer layer includes the Georgetown or its equivalent and the full extent of the Edwards Aquifer, with the exception of the Kinney Pool. The Edwards Aquifer in the Kinney Pool does not include the McKnight and West Nueces Formations because these two lower formations have sufficiently low permeability to be considered an aquiclude, if not an aquitard (Green et al., 2006). For this reason, only the Salmon Peak Formation is included in the Edwards Aquifer in the Kinney Pool. The base of the Edwards Aquifer, as it is represented in the Kinney Pool, was adjusted to be coincident with the base of the Salmon Peak Formation.

The model domain is discretized into finite elements for development of the numerical model. There are 9,610 nodes and 18,913 elements in each of the three layers of the model for a total of 38,440 nodes and 56,739 elements in the model (Figure 3-2).

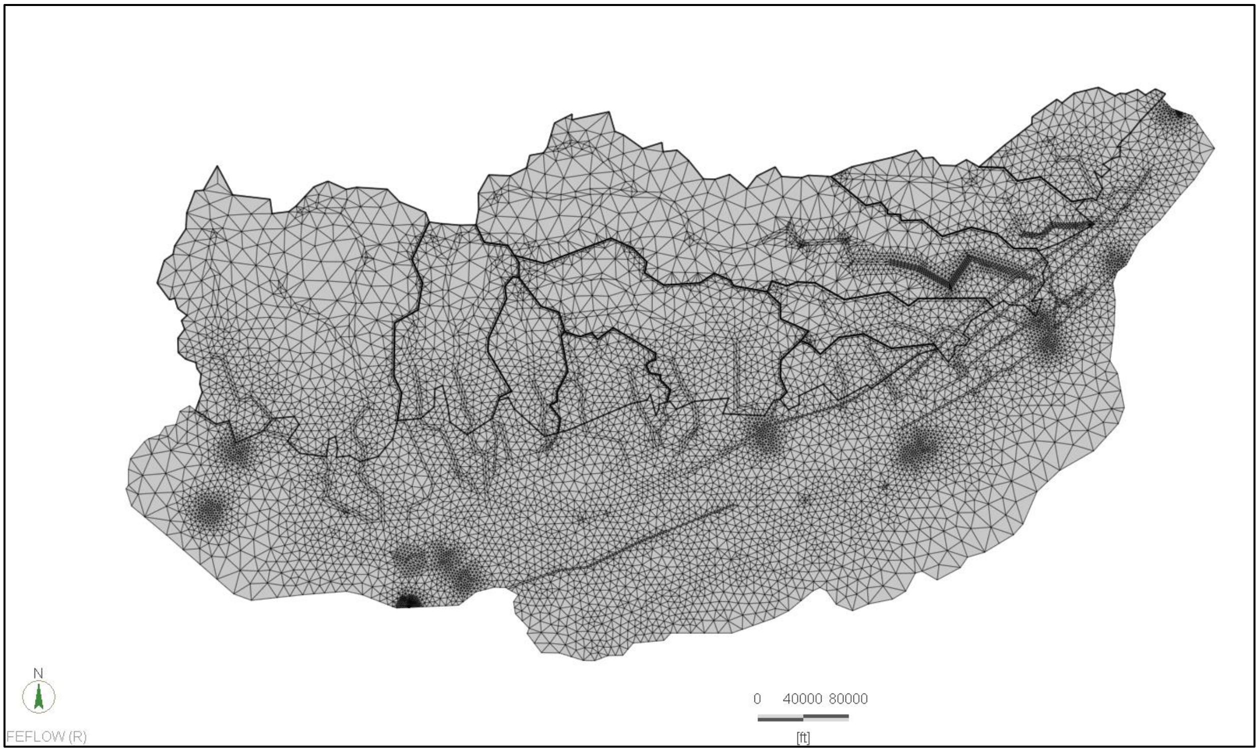
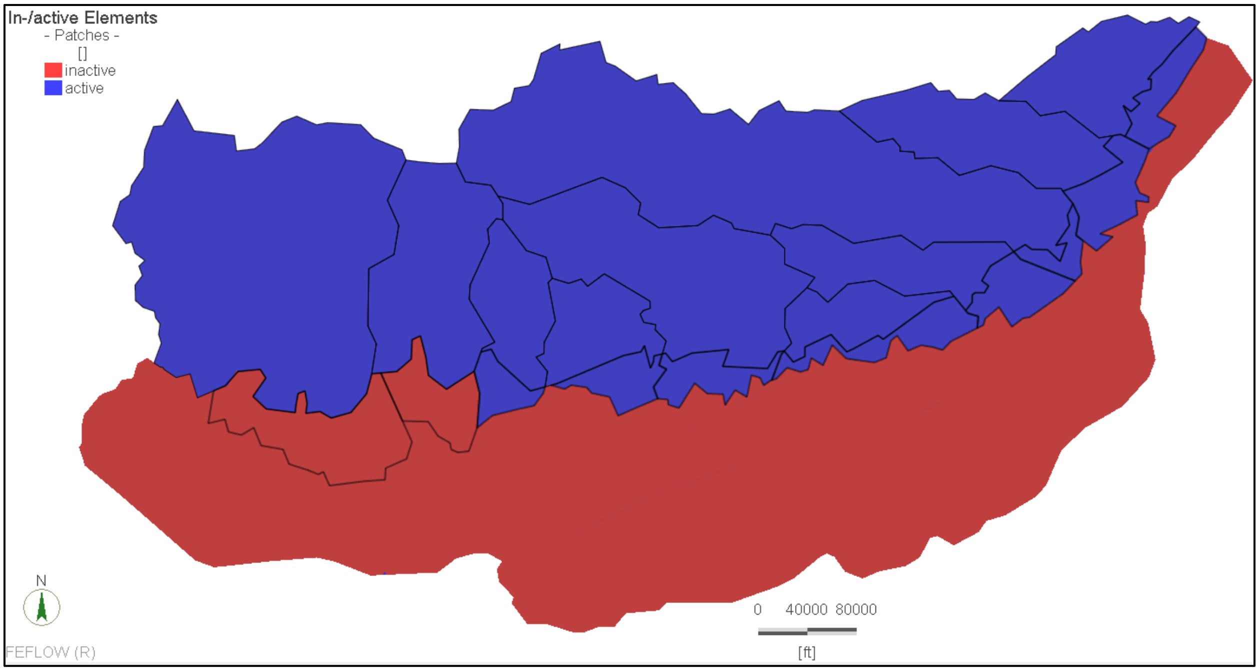


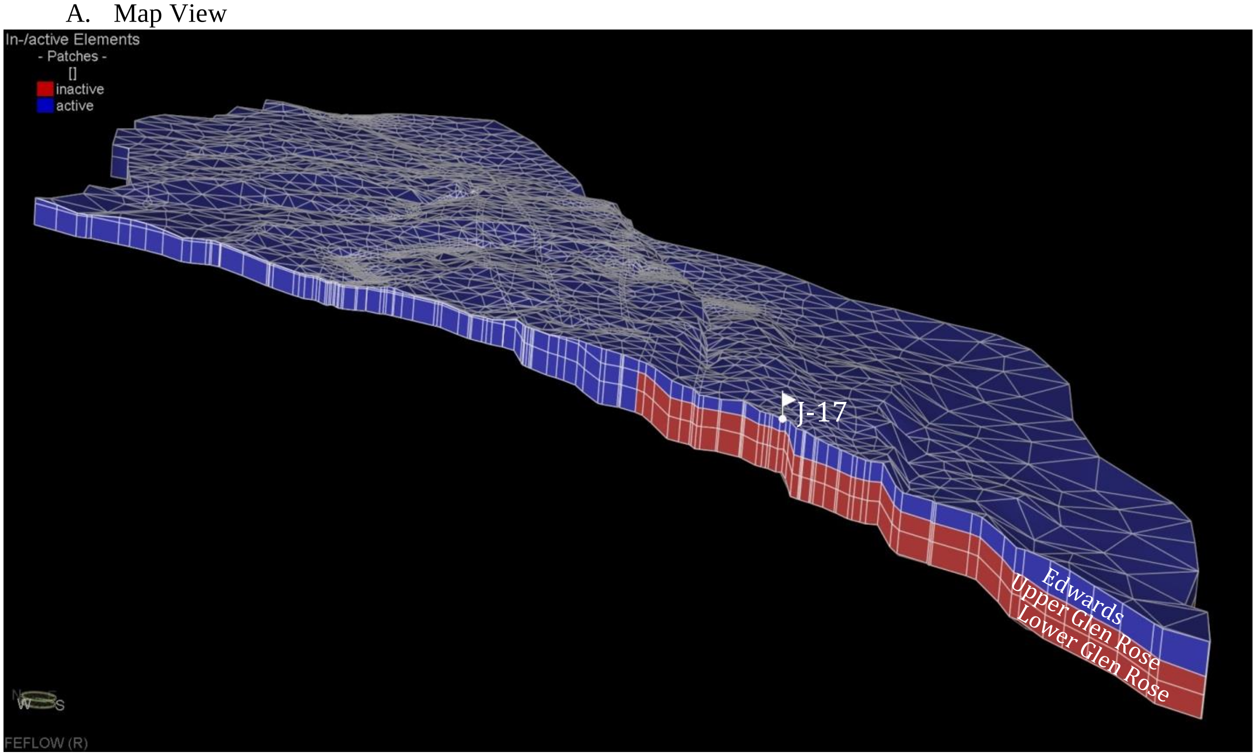
Figure 3-2. Finite-element grid of model domain.

3.1 Hydrostratigaphy

The model domain is represented by three layers in the Contributing and Recharge Zones and one layer in the Confined Zone (Figure 3.1-1). Inclusion of the lower two units was necessary to provide media through which recharge can flow from the upper reaches of the Contributing Zone, where the Edwards Aquifer and, in places, the Upper Glen Rose Formation are absent, to the Recharge Zone. Without the inclusion of these two units, there is no physical pathway for groundwater flow from the Contributing Zone to the Recharge and Confined Zones. Inclusion of the Upper and Lower Glen Rose Formations into the Confined Zone was not necessary because the full thickness of the Edwards Aquifer was present and available for conveyance of groundwater.



A. Map View



B. Three-dimensional View

Figure 3.1-1. Extent of Layer 2 (Upper Glen Rose) and Layer 3 (Lower Glen Rose) in the model domain. A. Map view. B. Three-dimensional representation of the eastern portion of the model with north-south vertical section at well J-17. Vertical exaggeration is 10x.

The Contributing and Recharge Zones were treated as water-table aquifers. The Confined Zone was obviously treated as a confined aquifer. FEFLOW allows for specific storage and specific yield to be designated by adjusting porosity and the medium and fluid compressibility. Both properties were adjusted during calibration. Specific yield was approximated as porosity in the Contributing Zone (Figures 3.1-2–3.1-4).

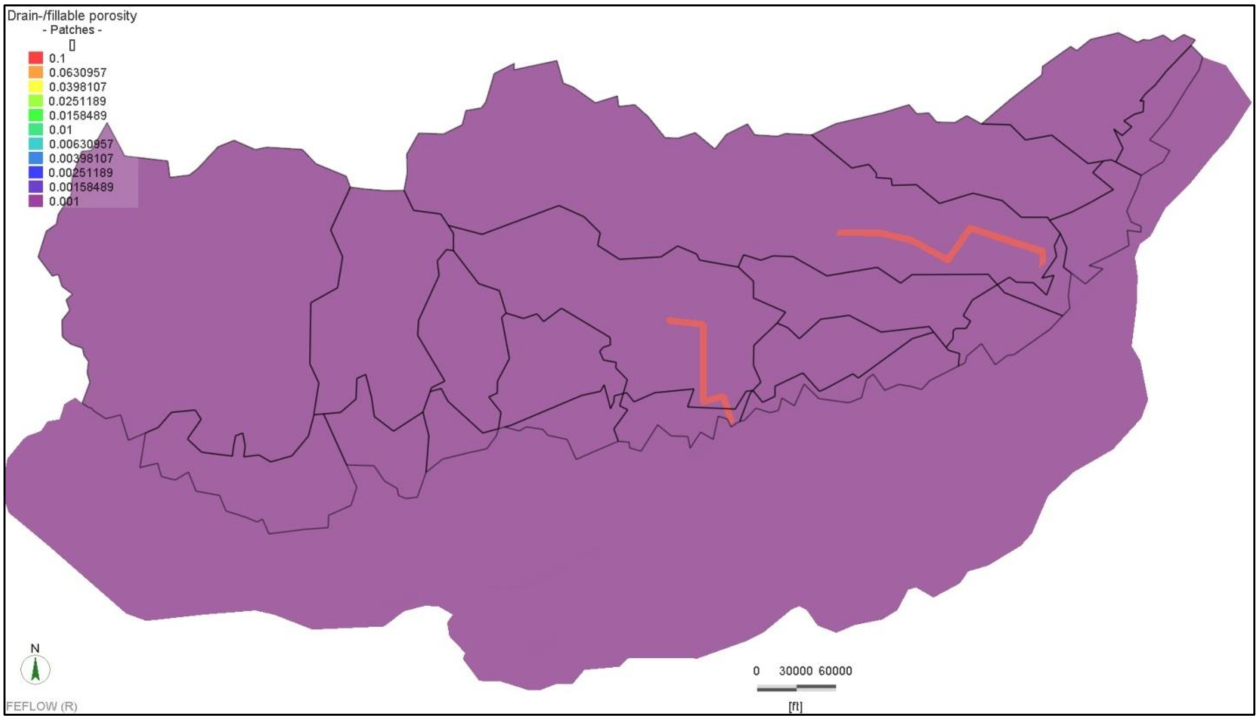


Figure 3.1-2. Specific yield was approximated as porosity in Layer 1 (Edwards Aquifer)

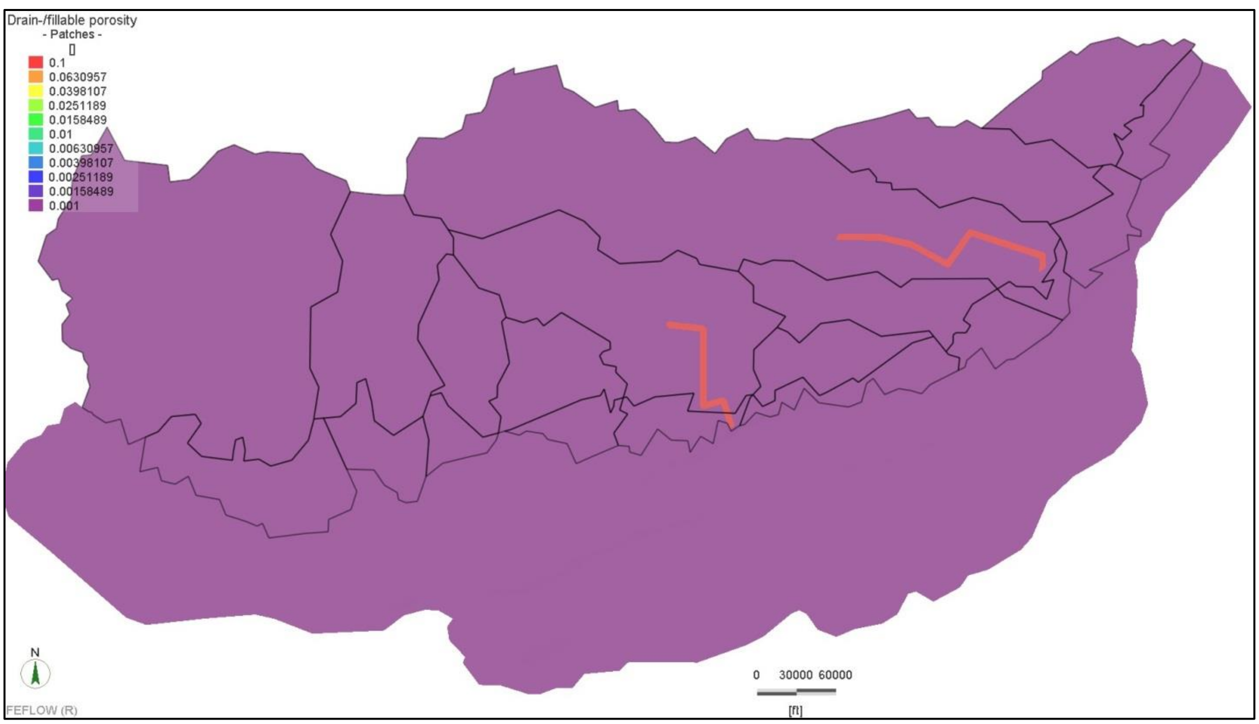


Figure 3.1-3. Specific yield was approximated as porosity in Layer 2 (Upper Glen Rose Formation) in the Contributing Zone

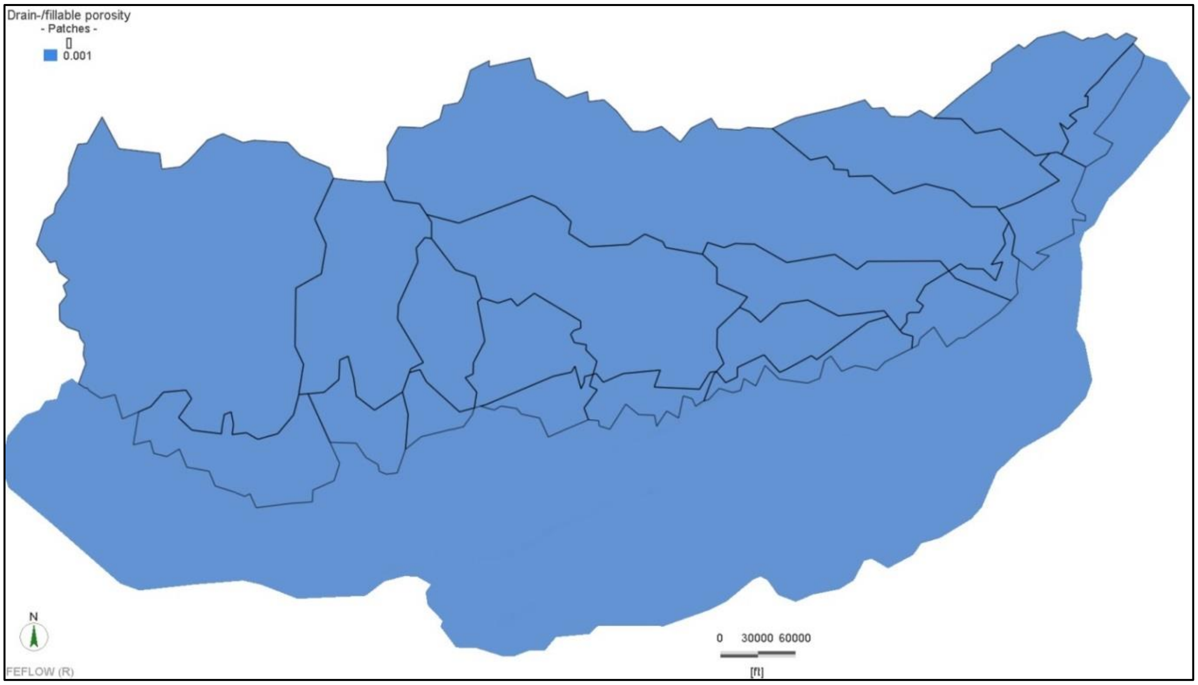


Figure 3.1-4. Storage was approximated as porosity in Layer 3 (Lower Glen Rose Formation) in the Contributing Zone.

Compressibility was reduced to low values in the Confined Zone to enable the model to propagate flashy recharge input in the Contributing and Recharge Zones to the Confined Zone (Figures 3.1-5–3.1-7).

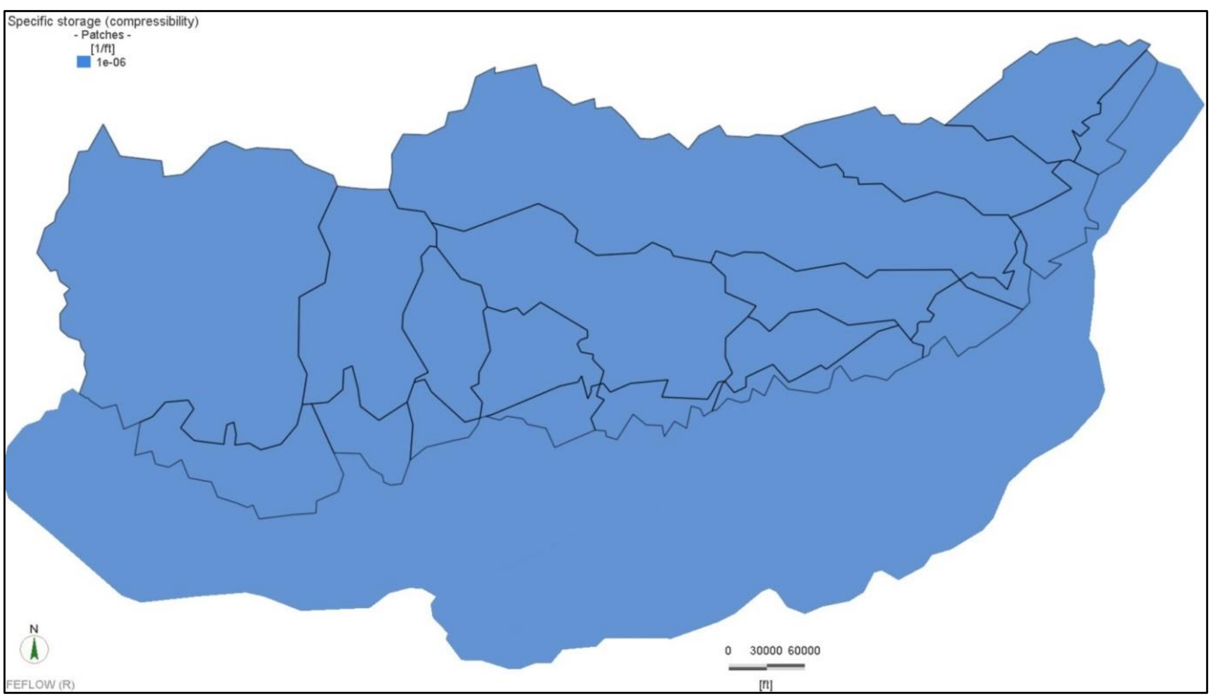


Figure 3.1-5. Storage was approximated as compressibility in layer 1 (Edwards Aquifer) in the Artesian Zone.

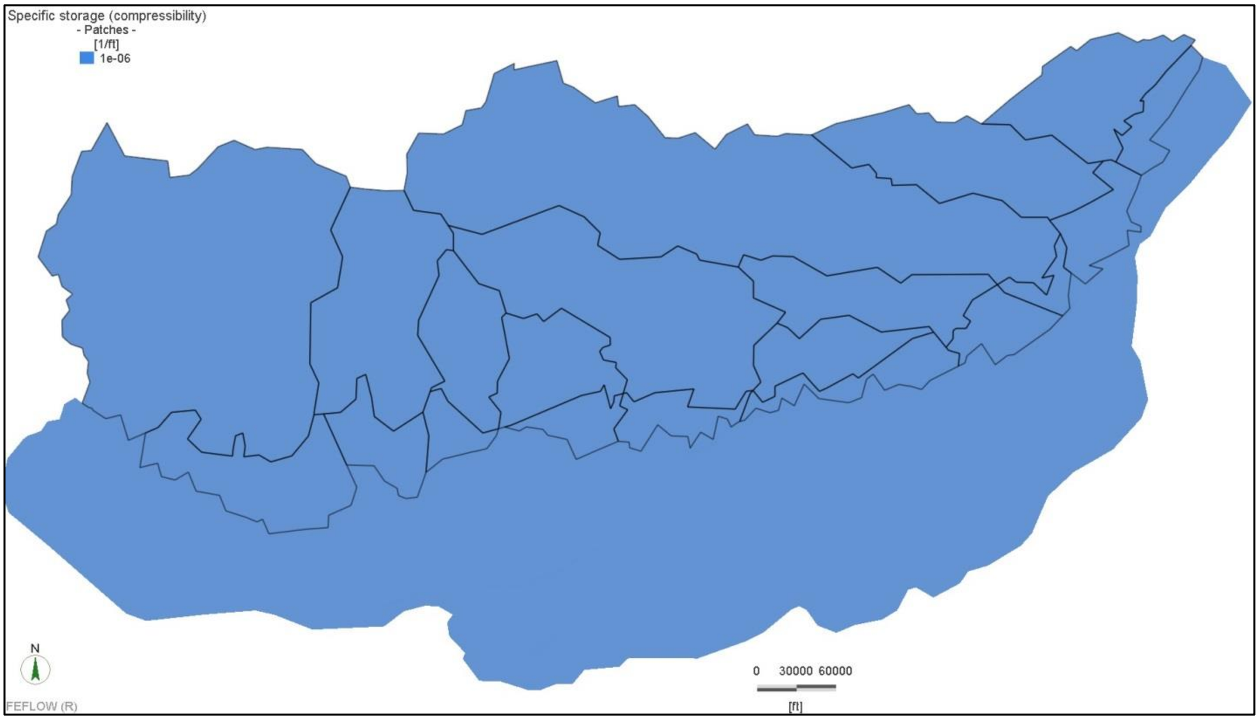


Figure 3.1-6. Storage was approximated as compressibility in Layer 2 (Upper Glen Rose Formation) in the Artesian Zone

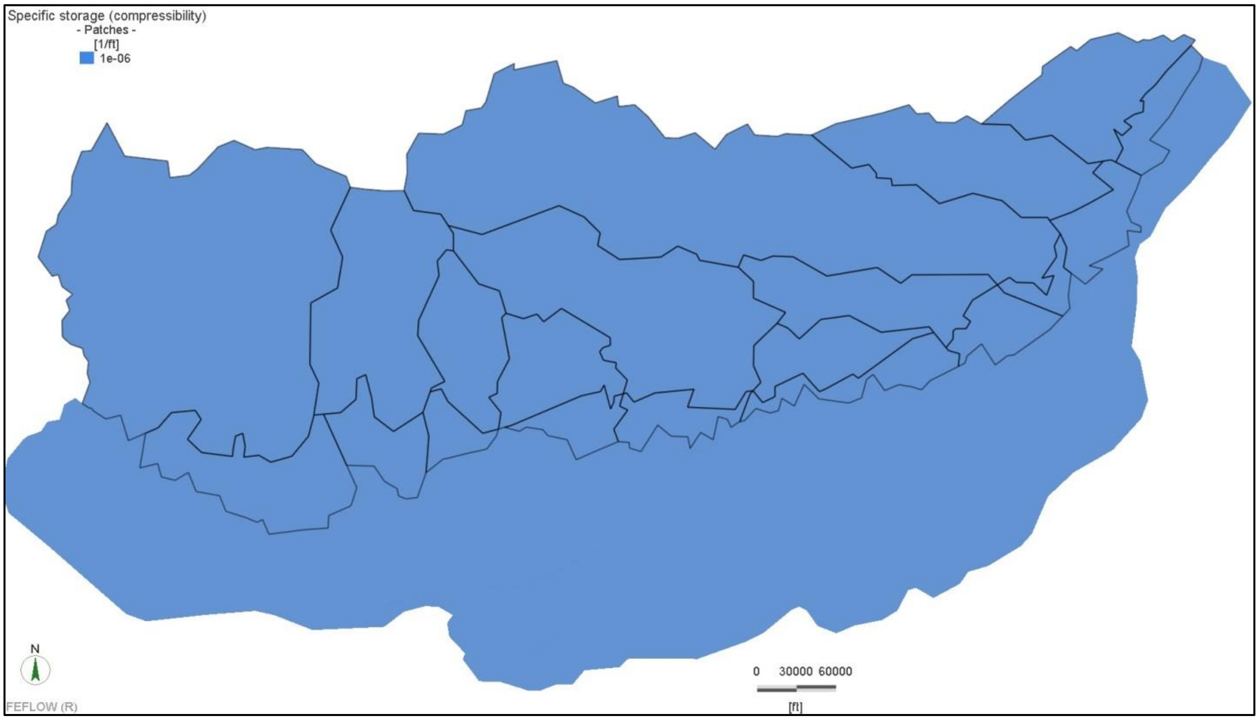


Figure 3.1-7. Storage was approximated as compressibility in Layer 3 (Lower Glen Rose Formation) in the Artesian Zone.

Hydraulic conductivity values were adjusted during calibration (Figure 3.1-8–3.1-10). The hydraulic conductivity of the model area between Barton Springs and the groundwater divide separating Barton and San Marcos Springs and was specified to be very low to effectively remove this area from the model domain. The area separating the Kinney and Uvalde Pools also was specified as low based on well assessments that indicate that no wells in this area have pumping capacities above 5 gpm (Green et al., 2006).

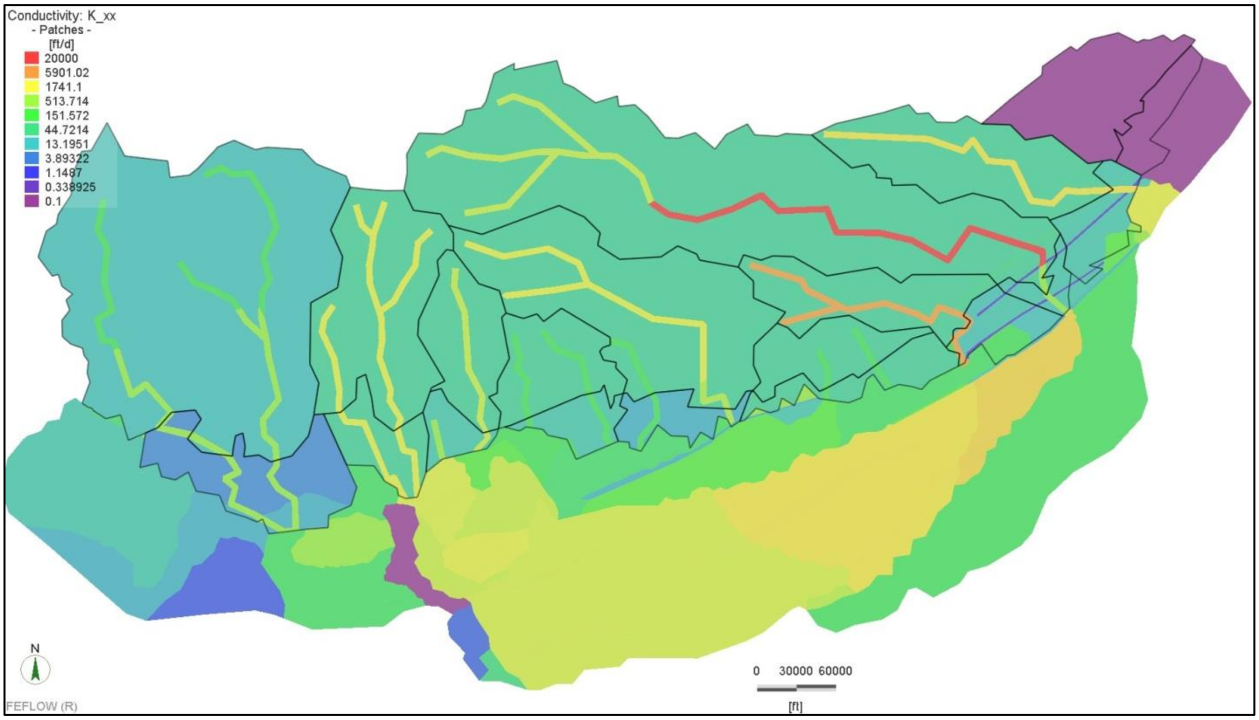


Figure 3.1-8. Hydraulic conductivity values assigned to Layer 1 (Edwards Aquifer) (ft/day).

Several starting datasets were evaluated during calibration including the dataset prepared using Bayesian inversion (Painter et al., 2002, 2007; Jiang et al., 2004), the final calibration from the 2004 MODFLOW model (Lindgren et al., 2004), and a dataset independently prepared using the TRANSIM software package (Medina and Carrera, 1996, 2003). The Confined Zone was divided into approximately 30 zones. This level of discretization allowed for some degree of heterogeneity of the aquifer, but was sufficiently coarse to avoid over parameterization.

Watersheds associated with the major rivers in the Contributing Zone in the model domain were characterized as hydraulically separate (Figure 2.1-3). This separation precludes surface water and groundwater from flowing from one basin to an adjoining basin which is not believed to occur except possibly where the basins are especially deep. Given that the basin boundaries are restricted to the Contributing Zone, basins are not deep, thus interbasin flow is conceptualized to be minimal. From west to east, these are identified as the West Nueces/Nueces, Dry Frio/Frio, Sabinal, Sabinal-Medina interbasin, Medina, Medina-Cibolo interbasin, Cibolo, Guadalupe, and Blanco Contributing Zone Basins.

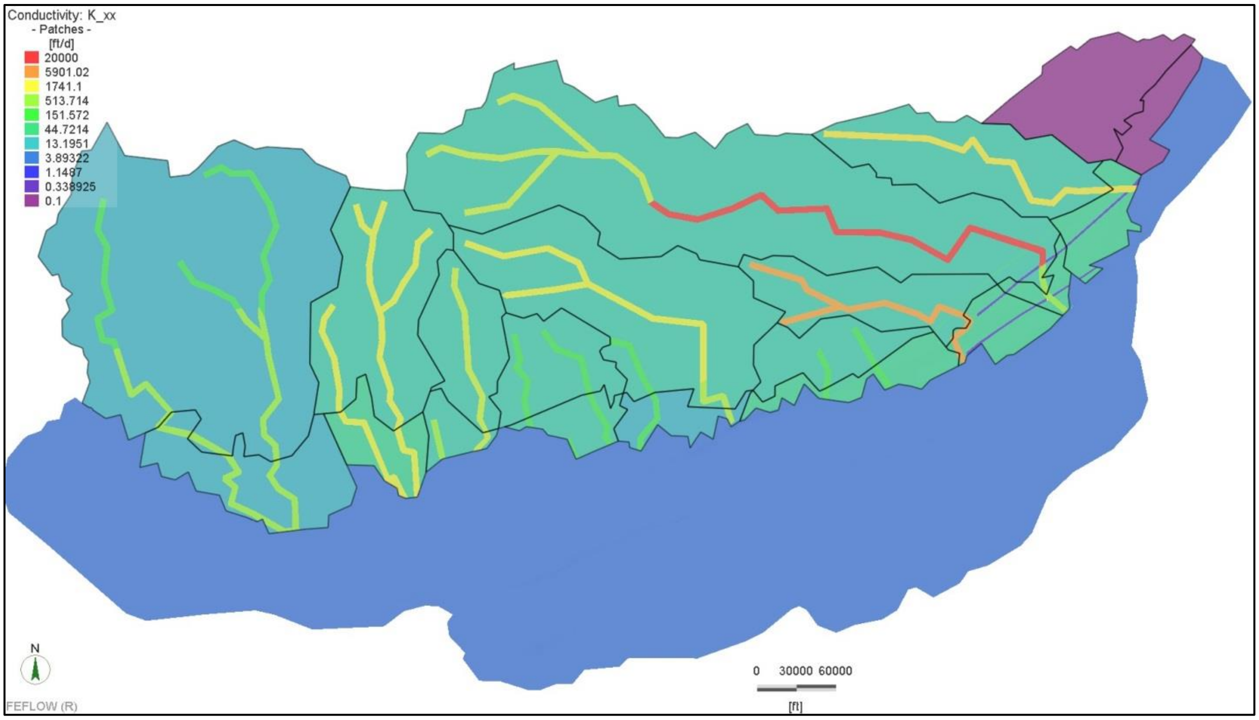


Figure 3.1-9. Hydraulic conductivity values assigned to Layer 2 (Upper Glen Rose) (ft/day).

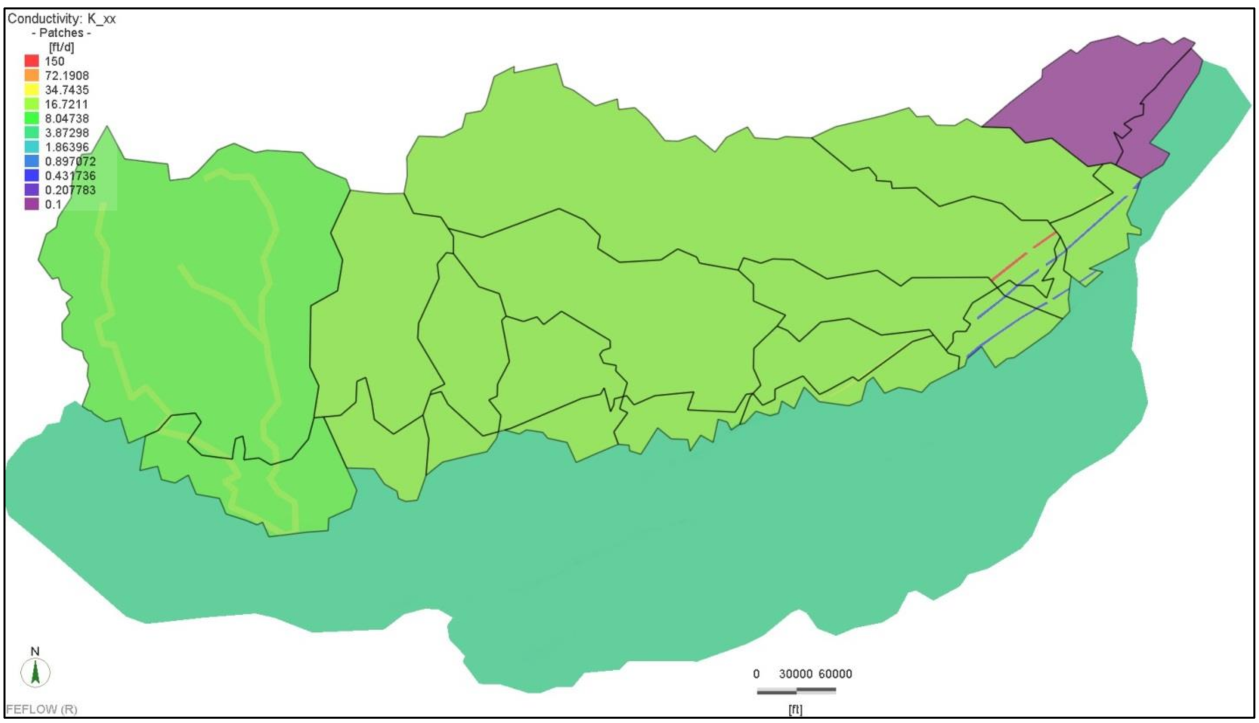


Figure 3.1-10. Hydraulic conductivity values assigned to Layer 3 (Lower Glen Rose) (ft/day).

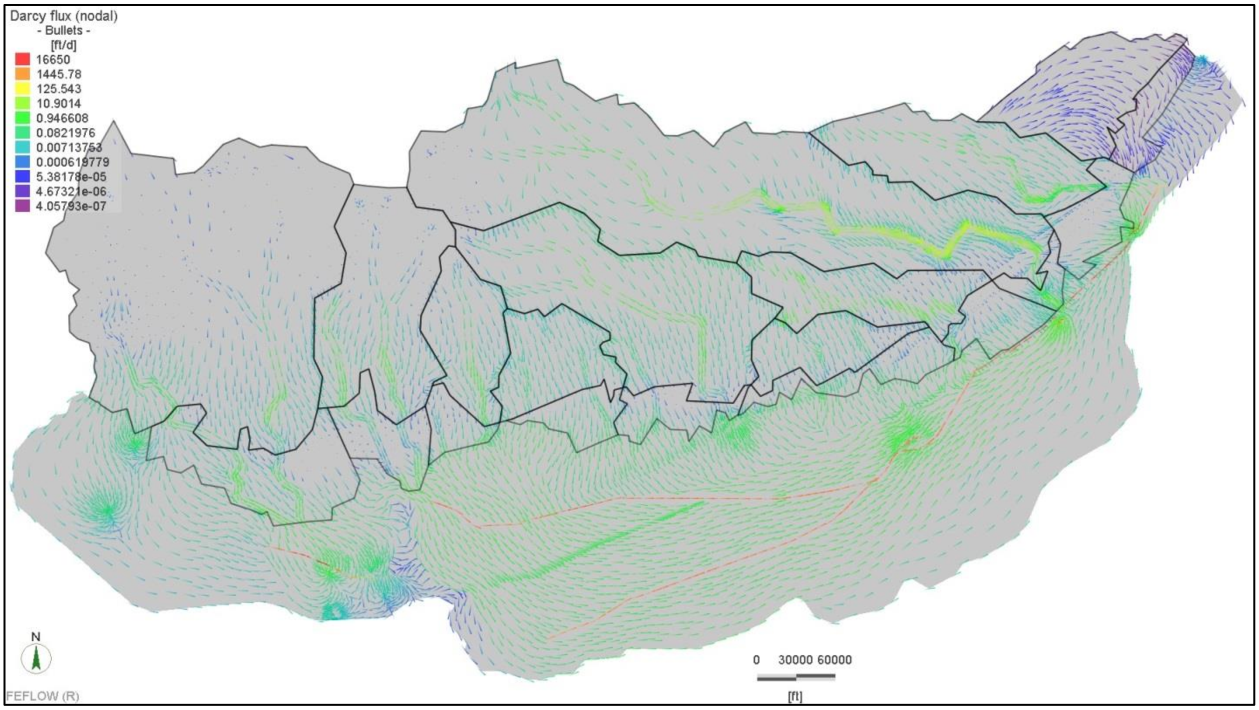


Figure 3.1-11. Groundwater flow vectors generated using the pseudo-steady-state potentiometric surface illustrated in Figure 2.3.3-5.

Each basin was characterized as hydraulically separate from each other. This is illustrated using groundwater flow vectors developed from the initial hydraulic head values (Figure 2.3.3-5), which illustrate that groundwater flow honors this conceptualization (Figure 3.1-11). With limited exceptions, the groundwater regime in each basin operated independently of each other. To impose this trait on the model, transmissivity zones associated with each river were calibrated so that groundwater watershed boundaries approximated the same boundaries as surface watershed boundaries.

Although groundwater basin and surface watershed boundaries do not necessarily have to be coincident, which is often the case in karst terrains (White and White, 2001; White, 2006), the surface and groundwater basin boundaries were designated as coincident in this model in the absence of any evidence to demonstrate this assumption was not valid. Pirating in the lower reaches of adjacent basins in the Contributing Zone was initially recognized by Woodruff (1974, 1977). Examples where strict demarcation between adjoining groundwater basins may not occur are between the Sabinal-Medina River Interbasins and Medina River Basin and between the Cibolo Creek Basin and Medina River-Cibolo Creek Interbasin (Figure 2.1-3). In addition, the groundwater basin boundary between the West Nueces and Nueces Rivers may be farther west than the surface-water divide.

Scenario testing during calibration suggested that comingling of groundwater flow between adjoining basins may be possible, particularly in the lower reaches of basins which are particularly deep. Although this phenomenon may be possible in limited situations (i.e., groundwater flow from the Kinney Pool to the Uvalde Pool under high stage conditions), groundwater basin boundaries should be considered static unless compelling evidence to the contrary is available.

3.1.1 Preferential Flow Using High Transmissivity Zones

Groundwater flow aligned with rivers in the Contributing Zone was initially represented as conduits using the discrete feature option in FEFLOW (Diersch, 2014). This approach resulted in numerical instability in the downgradient portion of the Contributing Zone which exhibits the largest hydraulic gradients. The large hydraulic gradients coupled with the abrupt change in the hydraulic properties of the matrix versus the discrete features (i.e., conduits) resulted in a numerically stiff system of equations. The numerical instability is attributed to the stiffness in the governing flow equations. FEFLOW does not offer a Newton-Raphson-type numerical solver for groundwater flow which may have resolved the numerical instability. Groundwater flow aligned with river channels in the Contributing Zone was therefore represented as zones with elevated transmissivity to reduce the stiffness in the governing flow equation and impose numerical stability to this portion of the model domain. Transmissivity values were uniformly assigned to all reaches of each river, however, transmissivity values varied significantly from river to river (Table 3.1.1-1).

Table 3.1.1-1. Transmissivity values assigned to river channels

River Basin	Transmissivity (ft^2/day)	Width (ft)
West Nueces/Nueces	500	4,000
Dry Frio/Frio	1,500	4,000
Sabinal	1,000	4,000
Sabinal-Medina interbasin	100	4,000
Medina	10,000	4,000
Medina-Cibolo interbasin	100	4,000
Cibolo	5,000	4,000
Guadalupe	20,000	4,000
Blanco	2,000	4,000
Onion	0.1	4,000

Transmissivity values assigned to groundwater flow aligned with rivers channels varied from low values of 100 ft^2/day assigned to the focused flow channels in the Sabinal-Medina Interbasin and Medina-Cibolo Interbasin to a high of 20,000 ft^2/day assigned to the focused flow channel in the Guadalupe River watershed. The focused-flow channels represent both surface flow and subsurface flow in each river channel. This representation is believed appropriate because essentially all rivers in the model domain are ephemeral in the lower reaches of the Contributing Zone and most of the Recharge Zone, indicating that all surface flow is lost to the surface through these reaches. Guadalupe River is an exception to this generalization. The Guadalupe River is mostly perennial from its headwaters through the Recharge Zone and into the Confined Zone. For this reason, the Guadalupe River was represented differently in the model from the other rivers.

Transmissivity values were determined during calibration. Values were adjusted until groundwater flow regimes approximated surface watershed boundaries, with the limited exceptions noted above, and that simulated hydraulic heads in the Contributing Zone approximated observed heads. For example, assigning transmissivity values less than 20,000 ft^2/day to the preferential flow channel in the Guadalupe River watershed did not restrict the Guadalupe River groundwater flow regime to remain within the boundary of the Guadalupe River watershed. The assignment of transmissivity values less than 20,000 ft^2/day to the Guadalupe River focused-flow channel resulted in smearing and comingling between the groundwater basins of the Guadalupe and Cibolo River watersheds, a flow feature not believed present in the Edwards Aquifer Contributing Zone (Green and Bertetti, 2010a; Green et al. 2012b, 2014). Conversely, assigning transmissivity values too high resulted in unrealistically low hydraulic head vales in the Contributing Zone. Matching both criteria constrained the assigned transmissivity values.

The zones of high transmissivity traced the major river channels from their headwaters to the point where the rivers exited the Recharge Zone. At that point, the transmissivity zones abutted with higher-transmissivity zones within the Confined Zone containing conduits represented by discrete features. This allowed water to be rapidly and continuously conveyed from the Contributing Zone through the Recharge Zone and into the Confined Zone, thereby retaining the flashy nature of recharge from the location it enters the subsurface to downstream locations in the Confined Zone where it was observed in monitoring and calibration wells. Apparently, the lower hydraulic gradients in the Confined Zoned ameliorated stiffness in the governing equations that was experienced when attempting to represent preferential flow in the river channels in the Contributing Zone using discrete features.

3.1.2 Preferential Flow Using Fault Zones and Discrete Features

FEFLOW offers the capacity to include discrete features in the flow regime. This capability was employed to represent conduits inferred to be in the Confined Zone of the Edwards Aquifer (Figure 3.1.2-1).

Analyses by Hovorka et al. (2004) and Worthington (2004) were used as the initial estimates of conduit locations. Conduit locations and properties were refined during calibration. The manner in which faults are incorporated by FEFLOW is graphically illustrated in Figure 3.1.2-2. Faults are represented by elements, not discrete features.

3.2 Recharge

As discussed in Section 1.4, existing numerical models of the Edwards Aquifer span only the Recharge and Confined zones and do not include the Contributing Zone (Kempt et al., 1979; Maclay and Land, 1988; Lindgren et al., 2004). Although most water recharged to the Edwards Aquifer is derived from the Contributing Zone, these models input this recharge into the model at the upgradient boundary of the Recharge Zone. Thus total recharge to these earlier models is the sum of precipitation that falls on the Contributing Zone and is accumulated before being provided as input on the upgradient boundary and from precipitation that falls directly on the Recharge Zone.

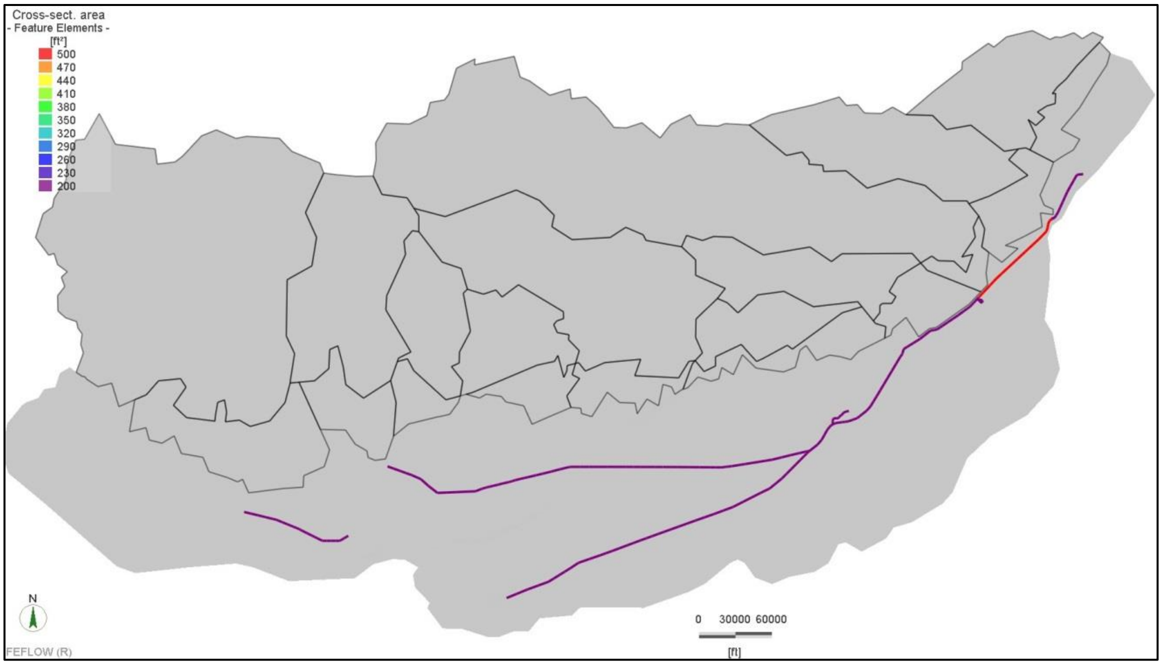


Figure 3.1.2-1. Map of model domain with colored lines to illustrate the locations of conduits included in the model. Line color is assigned to indicate cross sectional area of conduits.

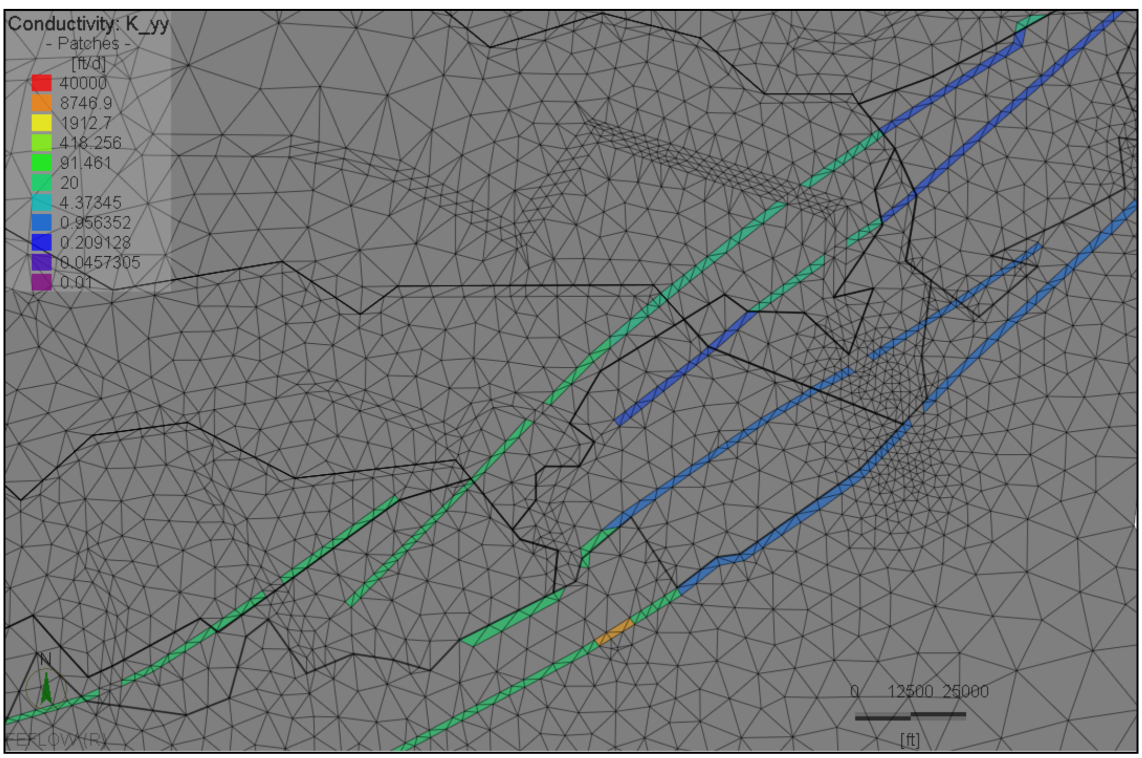


Figure 3.1.2-2. Faults are represented in the model domain by zones of elements and locally more-dense discretization. FEFLOW does not allow faults to be incorporated as discrete features.

To date, the quantity of recharge derived from the Contributing Zone has been determined using calculations provided by the U.S. Geological Survey and model results prepared using HSPF.

Both methods rely on surface-water flow measured where streams and rivers enter and exit the recharge zone. HSPF also incorporates watershed properties in its model predictions. The resulting calculations are typically provided as time-series recharge assigned to boundary elements. The input quantities are based on physical measurements, but can be adjusted during calibration. Limitations to both methods are that neither accommodates recharge that occurs in the Contributing Zone. Both methods only recognize recharge provided to the Recharge Zone as surface flow. Recharge by river underflow or interformational flow in the subsurface has to be discretely included as input to be part of the water budget. This approach poses a dilemma when modeling the Edwards Aquifer because river underflow and especially interformational flow are difficult to measure and quantify. In actuality, the transition from the Contributing Zone to the Recharge Zone is not distinct. The U Glen Rose Formation exhibits properties more like the Edwards Aquifer than the lower Glen Rose, particularly in the eastern half of the model domain. Thus, specifying the exact points where rivers exit the Contributing Zone and enter the Recharge Zone is difficult because the transition is not distinct.

Inclusion of the Contributing Zone in the alternative model obviates the need for discretely adding recharge by river underflow or interformational flow in the subsurface. Recharge is a direct function of precipitation. Coefficients assigned to each basin are calibrated independently. By including the Contributing Zone in the model domain, both underflow and interformational flow in the subsurface are included in the model. This accommodation enables the alternative model to simulate aquifer performance based solely on precipitation. The following sections discuss how recharge is accommodated in the alternative model and how this method compares with how recharge was accommodated in previous models (Kempt et al., 1979; Maclay and Land, 1988; Lindgren et al., 2004).

3.2.1 Recharge from the Trinity Aquifer

Groundwater from the Trinity Aquifer can recharge the Edwards Aquifer in two ways: (i) as subsurface cross-formational inflow across the updip margin of the Balcones Fault Zone where the Trinity Aquifer is juxtaposed with the downfaulted Edwards Aquifer and (ii) as upward flow from the Trinity Aquifer into the Edwards Aquifer along faults, fractures, and dissolution enhanced conduits. In addition, there is water that enters the Edwards Aquifer Recharge Zone from the Trinity Aquifer as surface flow. The volume of inflow as groundwater is difficult to determine and is typically estimated or constrained using numerical groundwater flow models and water-balance calculations.

There has been continued refinement in estimates and calculations of how much recharge to the Edwards Aquifer is sourced from the Trinity Aquifer. This refinement is due, in part, to improved conceptualization of the Trinity-Edwards Aquifer interface based on a variety of perspectives including multi-well testing (Smith and Hunt, 2009, 2010, 2011), tracer testing (Johnson et al., 2010, 2012; Schindel and Johnson, 2011), gain-loss studies (Slade et al., 2002; Green et al., 2011), enhanced characterization of the geologic structure and hydrogeology (Ferrill et al., 2003, 2004, 2005, 2008), and refinements in groundwater models that include the Trinity Aquifer-Edwards Aquifer interface (Klemt et a., 1979; Maclay and Land, 1988; Lindgren et al., 2004). These refinements support the conceptualization that the upper Glen Rose exhibits hydraulic properties that are more like the Edwards Aquifer than the rest of the Trinity Aquifer.

Early estimates of Trinity-Edwards Aquifer interformational flow of 53,800 acre-ft/yr (Lowry, 1955) and 107,000 acre-ft/yr (Bader et al. 1993) included only the Cibolo Creek watershed. Interformational flow from the Trinity Aquifer to the Edwards Aquifer was not included in the model by Klemt et al. (1979). Subsequent models by Maclay and Land (1988), and Lindgren et al. (2004) did include inflow from the Trinity Aquifer as a source of groundwater. The domain of the model by Kuniansky and Holligan (1994) and Kuniansky and Ardis (2004) incorporated the Edwards-Trinity, Trinity, and Edwards aquifers, thus interflow was inherently included in the model. Maclay (1995) identified two areas of groundwater inflow along the updip limit of the San Antonio segment of the unconfined Edwards Aquifer, one area is northeastern Medina County and the other is in Comal County (Maclay and Land, 1988). The Maclay and Land (1988) model did not indicate significant inflow from the Trinity Aquifer to the Edwards Aquifer in either Kinney or Uvalde counties.

Steady-state simulation using the 2004 Edwards Aquifer groundwater availability model (Lindgren et al., 2004) calculated that inflow through the northern and northwestern model boundaries contributes 6.5 percent of total recharge to the Edwards Aquifer. Of this, 87.9 percent of the flow into the model area occurs through the northern boundary (Lindgren et al., 2004). For an annual recharge of 699,400 acre-ft/yr for the years 1939–2013 (Tremallo et al., 2014), this equates to approximately 40,000 acre-ft/yr of inflow from the Trinity Aquifer to the Edwards Aquifer.

Kuniansky and Holligan (1994) estimated that 53 percent of average annual recharge to the entire Edwards Aquifer, which equates to 360,000 acre-ft/yr, is from the upper Glen Rose Formation of the Trinity Aquifer. Mace et al. (2000) contended that the Kuniansky and Holligan (1994) estimate of contributions to the Edwards Aquifer from the Trinity Aquifer is excessive. Mace et al. (2000) used the Hill Country Trinity Aquifer groundwater availability model to estimate that 59,000 acre-ft recharged the Edwards Aquifer from the Trinity Aquifer as inter-formational flow based on conditions representative of 1975. The Hill Country portion of the Trinity Aquifer only extends to the Dry Frio/Frio River watersheds to the west, excluding the West Nueces/Nueces River watersheds. The Hill Country Trinity Aquifer model refined by Jones et al. (2011) calculated that total groundwater flow through the Trinity Aquifer is approximately 321,000 acre-ft/yr. Of this flow, about 60 percent discharges to streams, springs, and reservoirs, and 35 percent or 111,000 acre-ft/yr, discharges through cross-formational flow to the Edwards (Balcones Fault Zone) Aquifer. The model by Jones et al. (2011) parsed out the cross-interformational flow rates as 660 acre-ft/yr in the west, 2,400 acre-ft/yr in the central area, and 350 acre-ft/yr in the east of the model domain (Figure 3.2.1-1).

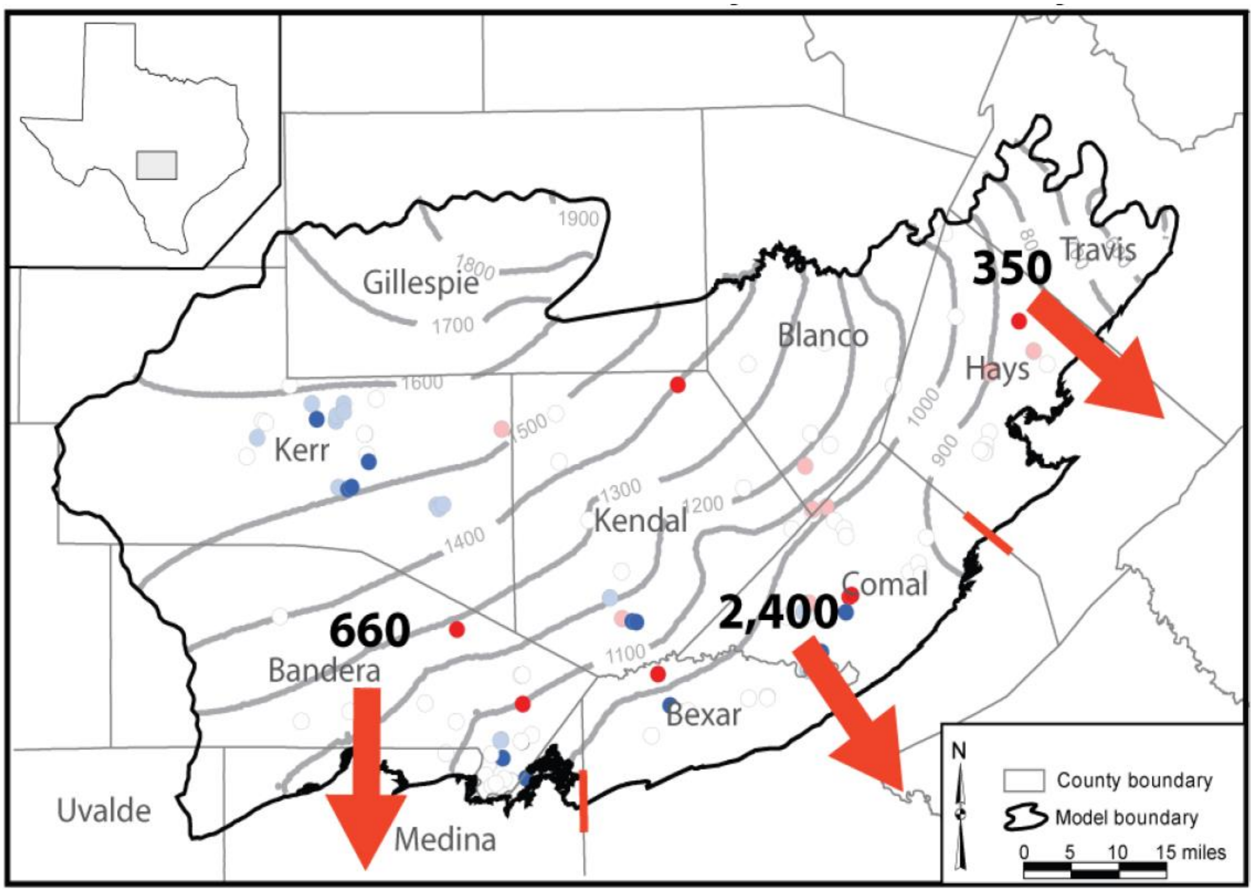


Figure 3.2.1-1. Cross-formational flow from the Trinity Aquifer to the Edwards Aquifer (acre-ft/yr) (Jones et al., 2011).

3.2.2 Recharge Calculated Using HSPF

The EAA maintains a joint funding agreement with the U.S. Geological Survey to provide recharge estimates by drainage basin using a water-balance that relies on precipitation and stream-flow measurements across the region. The U.S. Geological Survey estimates that annual recharge for the period of record (1934–2013) ranged from 43,700 acre-feet in 1956 to 2,486,000 acre-feet in 1992. The median annual recharge for 1934–2013 is 556,950 acre-feet. These estimates do not include the Guadalupe River watershed because the historical method of estimating recharge is based on the interpretation that the Guadalupe River Basin watershed does not recharge the Edwards Aquifer (Tremallo et al., 2014).

The EAA is also calculating recharge using the HSPF model (LBG-Guyton Associates and Aqua Terra Consultants, 2005; Clear Creek Solutions, 2009, 2012, 2013). HSPF modeling performed indicates similar historical total recharge relative to the traditional U.S. Geological Survey method; however, differences by basin are significant. The EAA does not include recharge by aquifer interflow (e.g., from the Trinity Aquifer) in these estimates (Tremallo et al., 2014).

The current Edwards Aquifer groundwater availability model (Lindgren et al., 2004) relies on estimates of recharge based on U.S. Geological Survey field measurements and HSPF calculations. In essence, these two methodologies integrate the cumulative recharge that enters the upgradient boundary of the Recharge Zone. The cumulative sum is input into the models as a time series. A notable shortfall of this approach is that these methodologies risk missing recharge that enters the Edwards Aquifer Recharge as either interformational flow or as underflow in the river channels that provide surface water for recharge. The magnitude of this underassessment has not been determined, but is recognized as significant (see Section 3.2.1).

3.2.3 Recharge Calculated Using Precipitation

Recharge from precipitation was applied as diffuse input into the Contributing and Recharge Zones of the model. Alternative models were tested which included a percentage of recharge designated as focused recharge and input directly into the closest point on a major stream; these approaches incorporating focused recharge did not show any significant differences in simulation results from diffuse recharge only. Once added, diffuse recharge was allowed to flow through the subsurface in response to the hydraulic conductivity field and the hydraulic gradient. The ability to replicate the temporal lag between the time of precipitation and the time at which the recharge event was transmitted as a hydraulic impulse through the aquifer and expressed during spring discharge was successfully accommodated using diffuse-only recharge in the Contributing Zone.

Recharge is calculated directly from precipitation data representative for the Contributing and Recharge Zones. NEXRAD (Next-Generation Radar) precipitation data acquired from RainVieux radar data are available for the most of the study area starting in 2003 (Figure 3.2.3-1) with added coverage in 2005 (Figure 3.2.3-2). NEXRAD is a network of 160 high-resolution S-band Doppler weather radars operated by the National Weather Service.

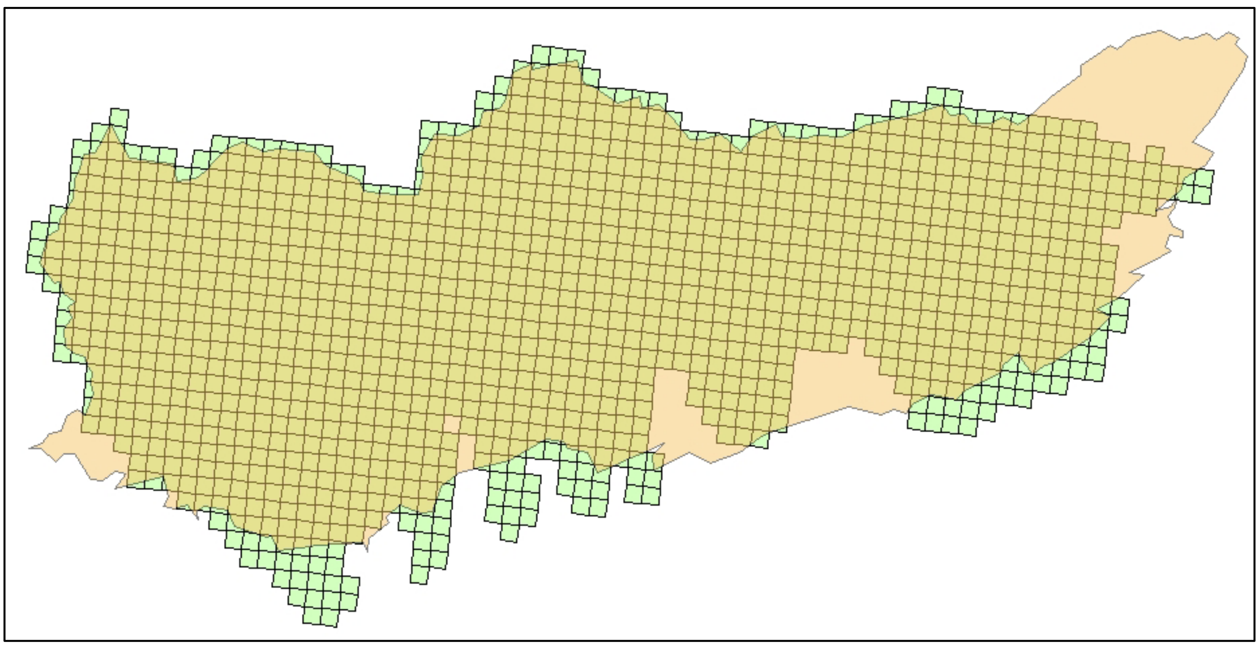


Figure 3.2.3-1.Pixel coverage of NEXRAD precipitation data 2002–2003.

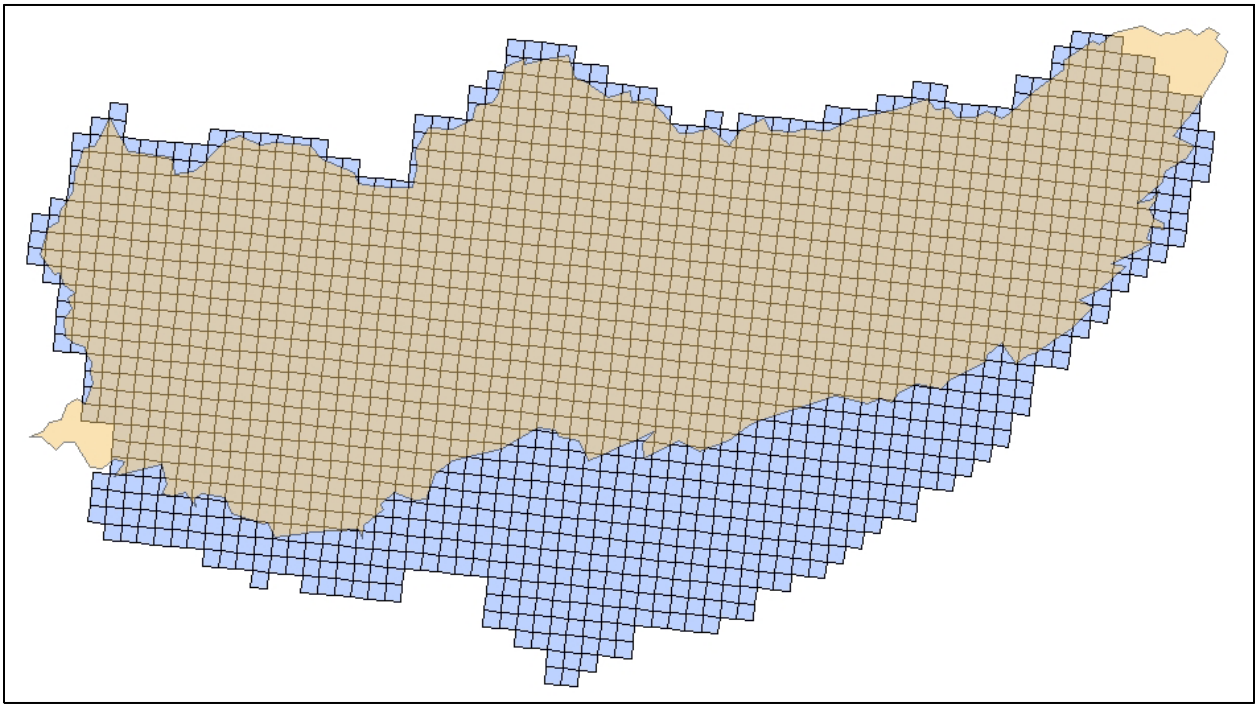


Figure 3.2.3-2. Pixel coverage of NEXRAD precipitation data post-2003.

Unfortunately, NEXRAD data are not available for the first two years of the calibration period, 2001–2002. For the period 2001–2002, precipitation data at the same spatial density as the NEXRAD data had to be generated using rain gauge data that are available for this two-year period (Figure 3.2.3-3). Unfortunately, the spatial density of the rain-gauge data is significantly less than the resolution of the NEXRAD data.

For the period 2003–2011, NEXRAD precipitation data were acquired from RainVieux radar data at approximately 3,800-m × 3,800-m resolution in the Edwards Aquifer Contributing and Recharge Zones. The precipitation data, P_i, consisted of separate shapefiles for each month of daily precipitation totals in the coverage area. The shapefiles were imported into ArcMap, projected from *NAD-1983_StatePlane_Texas_South_Central_FIPS_4204 Feet* to *NAD83_UTM_Zone14N*, and then clipped to the Contributing and Recharge Zones. Radar-acquired precipitation totals were missing at a small number of cells typically near the model domain boundaries, but did not exceed 2 percent of the total number of cells in any year. At these cells, a distance-weighted interpolation scheme was implemented to estimate the missing precipitation totals using the precipitation totals at the closest neighboring cells.

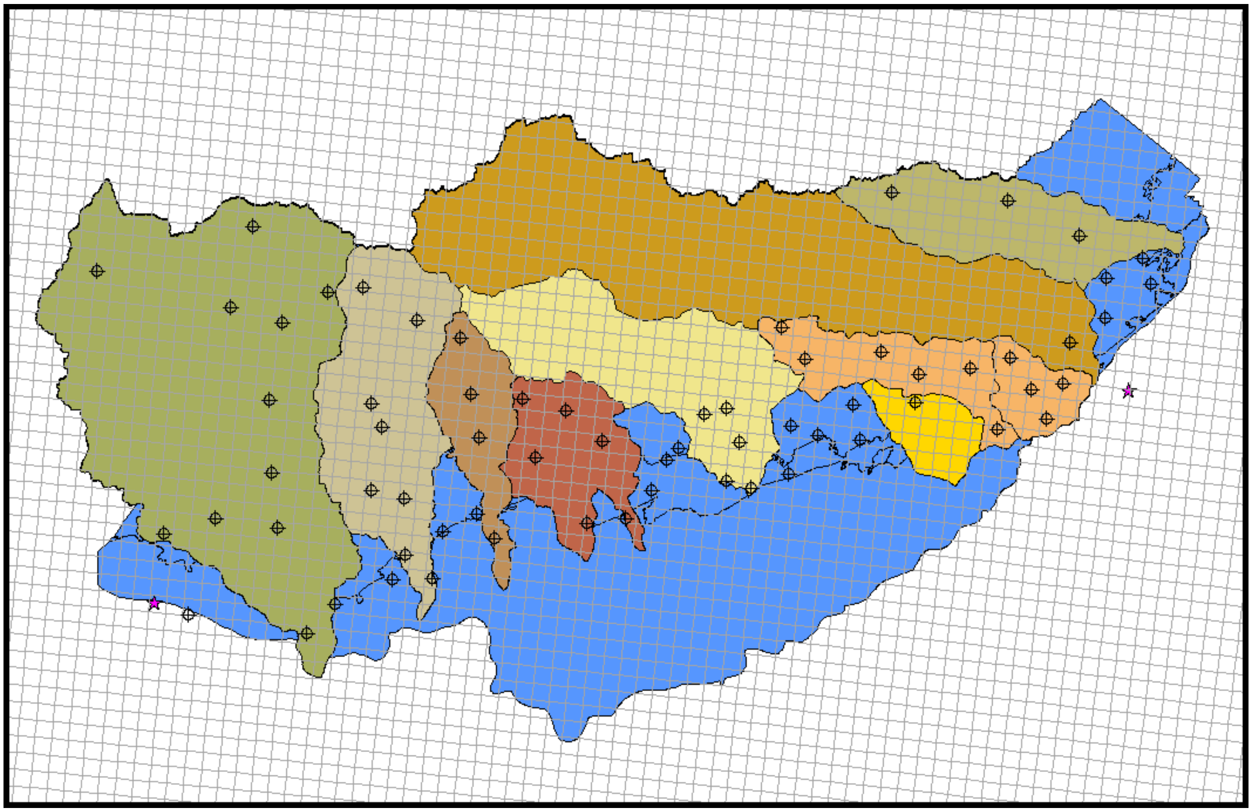


Figure 3.2.3-3. Radar 4x4-km grid and location of the two radars (stars) and rain gauges (crosshairs) relative to the Edwards Aquifer model domain.

There were data gaps and suspicious data in the precipitation dataset. These gaps and potentially erroneous data are problematic when attempting to perform correlation analyses. Attempts were made to resolve this deficiency to reduce uncertainties associated with missing or suspicious precipitation data. Precipitation across the study area usually occurs locally with distinct, but limited, spatial correlation. Hence, missing or suspicious precipitation data could be filled in or replaced by using the precipitation data at other rain gauges with highest correlations. Correlation strength, *r*, between precipitation at a particular rain gauge and precipitation at all other rain gauges was calculated as follows:

$$r = \frac{\sum_i (x_t - \mu_x)(y_t - \mu_y)}{\sqrt{\sum_i (x_t - \mu_x)^2 (y_t - \mu_y)^2}} \qquad \text{(Eq. 3.2.5-1)}$$

in which x_t and y_t are daily precipitation totals at two different rain gauges, and μ_x and μ_y are their time-averaged values. Higher *r* values imply higher cross-correlation among daily precipitation totals at the reference rain gauge and at other rain gauges. Cross-correlations computed among precipitation at different rain gauges are shown in Figure 3.2.3-4.

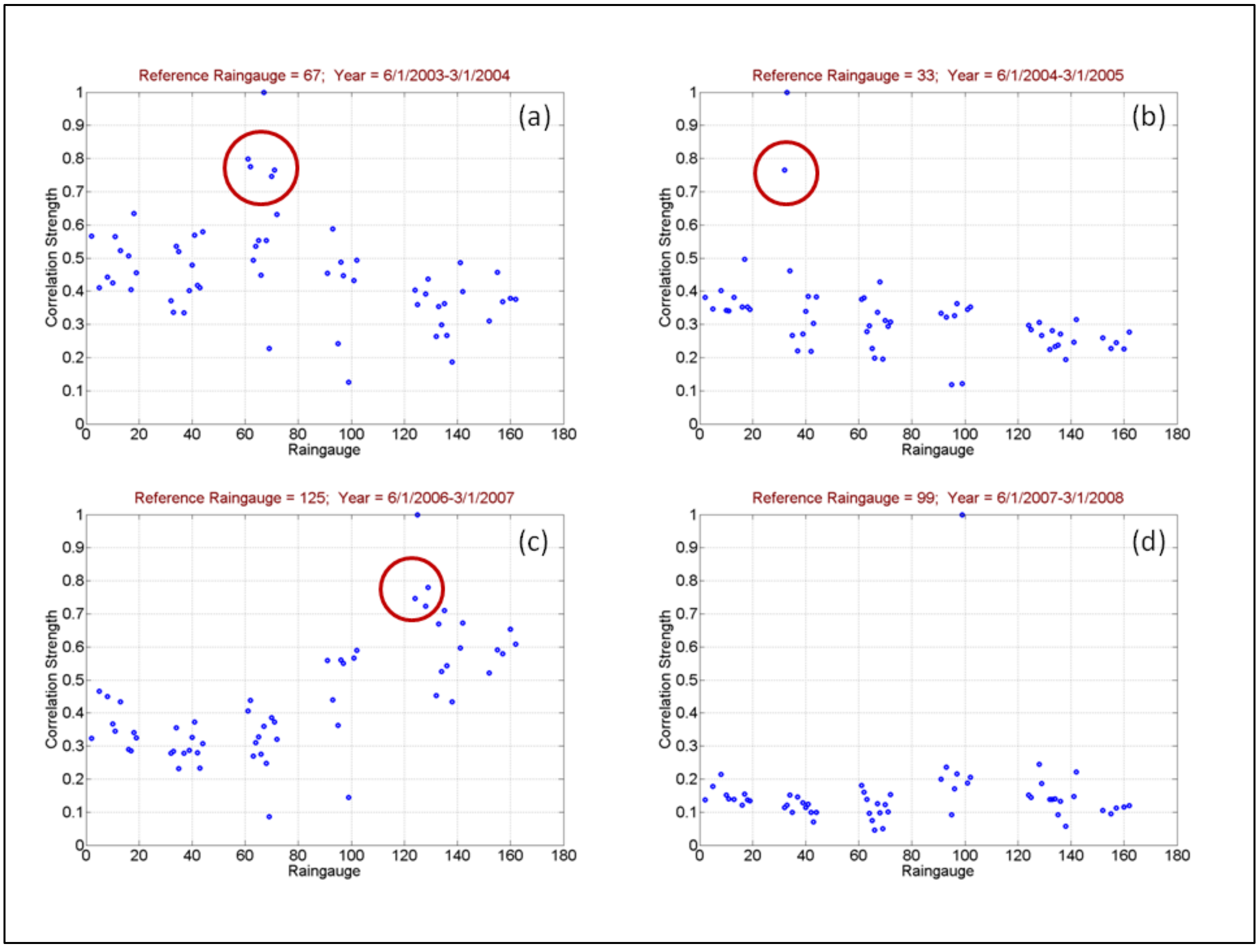


Figure 3.2.3-4. Cross-correlations among precipitation data at different rain gauges. Circles identify rain gauges that exhibit highly-correlated precipitation with the incomplete (but at least 90 percent complete) precipitation at the reference rain gauge.

Datasets for rain gauges with data gaps or suspicious data were filled or corrected as appropriate. Rain gauges with more than 10 percent missing precipitation data were omitted from the multi-variate cross-correlation analysis. Datasets with less than 10 percent missing data or suspicious data were filled or corrected in one of three ways.

- For cases in which 3 or 4 neighboring rain gauges exhibited a cross-correlation with the reference rain gauge greater than 0.5, the data were averaged to replace the missing or suspicious precipitation data [i.e., (a) and (c) in Figure 3.2.3-4].

- For instances in which there was only one rain gauge with missing or suspicious precipitation measurements and the data exhibited a correlation with the reference rain gauge above 0.5, then missing daily precipitation data at the reference rain gauge were replaced by the daily precipitation measurement at the highly-correlated rain gauge [i.e., (b) in Figure 3.2.3-4].

- Missing or suspicious precipitation measurements that did not exhibit significant correlation with neighboring rain gauges were replaced by the average precipitation rate of the preceding and proceeding days (i.e., data for rain gauges 69, 99, and 138) [i.e., (d) in Figure 3.2.3-4].

Precipitation is converted to recharge using an algorithm that accounts for antecedent moisture and seasonal variability. The conversion of precipitation-to-recharge algorithm accounts for the fact that recharge is greater in the winter than in the summer due to decreased evapotranspiration during the winter. Losses due to evapotranspiration are calculated from the average of monthly gross-lake evaporation rates calculated by the Texas Water Development Board for the period 2001–2011 (http://www.twdb.texas.gov/surfacewater(http://www.twdb.texas.gov/surfacewater /conditions/evaporation/index.asp accessed on August 20, 2014). Data are provided for one-degree latitude by one-degree longitude quadrangle 808 that is centered over Real, Uvalde, Bandera, and Medina counties. Average lake evaporation by month varies from a high of 7.29 inches in August to a low of 2.43 inches in December and January (Table 3.2.3-1). A scaling factor is applied to the lake evaporation for each watershed. The scaling factor is 0.4 for the Nueces, Frio, and Sabinal, and Medina River watershedss and Sabinal River-Medina River Interbasin, and 0.6 for the Medina River-Cibolo Creek Interbasin, Cibolo Creek, and Guadalupe and Blanco River watersheds.

Table 3.2.3-1. Average pan evaporation, E_i, by month for Texas Quadrangle 808

J	F	M	A	M	J	J	A	S	O	N	D
2.43	2.76	4.01	4.87	5.51	7.09	6.92	7.29	5.35	4.57	3.33	2.43

Antecedent moisture is accommodated by accounting for precipitation that occurred during the five months prior to the month for which recharge is calculated. *A priori* monthly precipitation is weighted for each of the five previous months by assigning less weight to months farther in the past. Weighting factors vary from a range of 32.5×10^{-5} to 0.0078 for the monthly precipitation that occurred five months prior to the month for which recharge is calculated, Φ_{i-5}, to a weighting factor of 0.1 to 0.33 assigned to the precipitation that occurred during the subject month, Φ_i. Weighting factors for the six-month averaging period are illustrated in Table 3.2.3-2.

Table 3.2.3-2. Weighting factors, Φ_i, to account for antecedent moisture

Watersheds	Φ_{i-5}	Φ_{i-4}	Φ_{i-3}	Φ_{i-2}	Φ_{i-1}	Φ_i
All watersheds, Contributing and Recharge Zones	2.51E-05	0.000167	0.0011137	0.007425	0.0495	0.33
Nueces River Contributing Zone	0.000486	0.00162	0.0054	0.018	0.06	0.2
Medina River Contributing Zone	1.52E-05	0.000101	0.000675	0.0045	0.03	0.2
Guadalupe River Contributing Zone	0.007776	0.01296	0.0216	0.036	0.06	0.1
Blanco River Contributing Zone	0.007776	0.01296	0.0216	0.036	0.06	0.1

The antecedent moisture weighting factors were adjusted during calibration. The amplitudes of the weighting factors were adjusted so that the volume of recharge results in the correct spring discharge quantities when pumping rates are known. The relative weightings among the six weighting factors were adjusted to provide the appropriate degree of flashiness in the hydraulic response observed in the Confined Zone.

Lastly, the temporal duration represented by the algorithm (in this case the duration is set at six months) is adjusted so that the length of time that a precipitation event continues to contribute to recharge is consistent with the “hydraulic memory” of the combined karstic Edwards Aquifer and Trinity Aquifer component in the Contributing Zone. The memory of this hydraulic system is obviously also a function of the conduit/matrix hydraulic responsiveness of the entire Contributing/Recharge/Confined Zone system, however a six-month length in the weighting algorithm implies that the Edwards Aquifer has a “hydraulic memory” no longer than 6 months. This estimate for the “hydraulic memory” is consistent with precipitation/hydraulic response correlation calculations of the Edwards Aquifer by Başağaoğlu et al. (2014) in which the preponderance of hydraulic impulse from precipitation was shown to dissipate within 2-4 months of the precipitation event. Başağaoğlu et al. (2014) also showed that the hydraulic signal in the Confined Zone in response to recharge in the Contributing Zone is stage dependent with shorter response times observed when aquifer stage is high.

A maximum threshold for monthly precipitation was applied to limit the size of the precipitation event allowed to recharge the aquifer. The maximum threshold was 8 inches for all watersheds. Using the NEXRAD precipitation data with the assigned seasonal and antecedent weighting factors, recharge for each month is calculated for each 3,800-m × 3,800-m pixel in the Contributing and Recharge zones using the following equation:

$$R_i = \sum_i^{i-5} \Phi_\mathrm{i} \left(Min(P_i, MaxP) - aE_i\right) \qquad \text{(Eq. 3.2.3-1)}$$

where:

- R_i = recharge during month i
- P_i = precipitation during month i
- E_i = average pan evaporation for month i
- Φ_i = weighting factor for antecedent moisture for month i
- a = Evapotranspiration scaling factor
- i = month indicator
- $MaxP$ = Maximum monthly precipitation allowed to recharge the aquifer

The weighting factor for antecedent moisture provides four levels of calibration flexibly associated with recharge. First, the number of months included in Equation 3.2.3-1 can be increased or decreased to reflect the duration over which antecedent moisture has measurable impact. Second, the amplitude of the antecedent moisture weighting factors can be adjusted to match recharge to the targeted discharge. Third, relative weighting among the antecedent moisture weighting factors can be modified to adjust the lag between the time of the recharge event and the time at which the recharge impulse is observed in the Confined Zone. Fourth, the maximum monthly precipitation threshold can be changed to control the impact of very large precipitation events.

3.3 Discharge

Groundwater is discharged from the Edwards Aquifer in the model domain via surface and subsurface springs. Surface springs include Pinto and Las Moras Springs in Kinney County; Leona Springs, Soldier Camp Springs, and other unnamed springs on the Nueces River in Uvalde County; San Pedro and San Antonio Springs in Bexar County; Hueco and Comal Springs in Comal County; and San Marcos Springs in Hays County (Figure 3.3-1). Subsurface discharge from the Edwards Aquifer within the model domain occurs in the Leona Formation gravel in the Leona and Medina River channels. Subsurface discharge also occurs in the Leona Formation gravel in Seco, Parker, Live Oak, Verde, Hondo, Elm, and Quihi Creeks in Medina County; however, this water is discharged from the Austin Chalk and is not included in the Edwards Aquifer water budget (Green et al., 2012b).

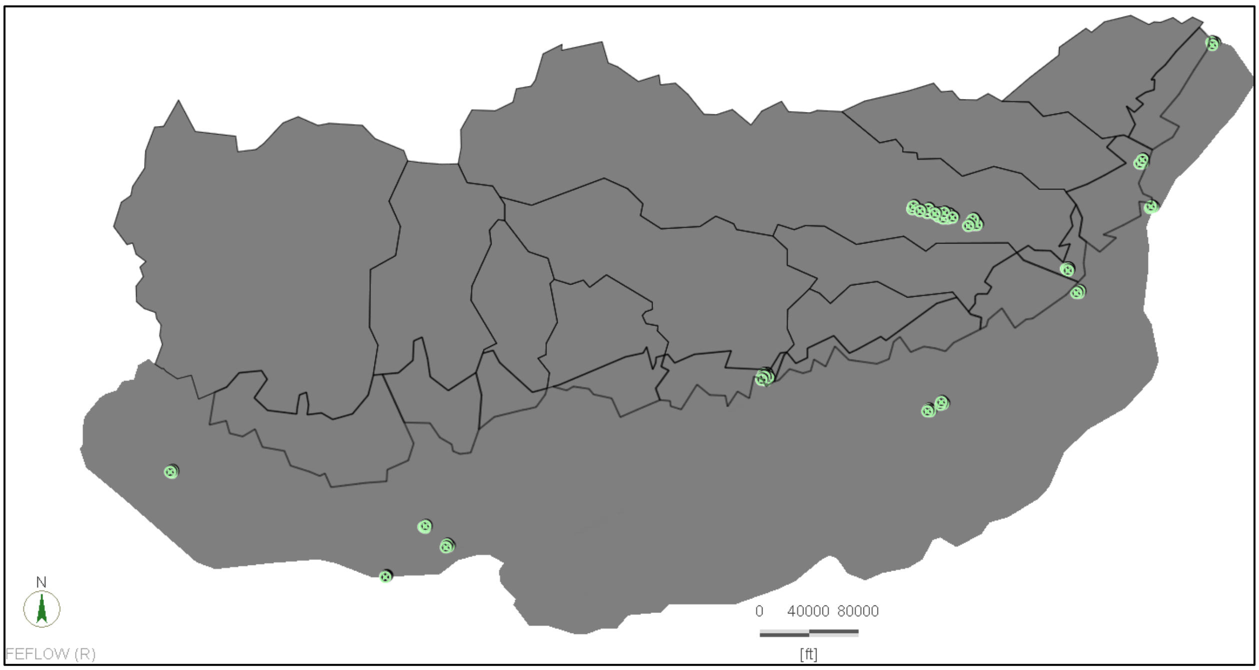


Figure 3.3-1. Locations of outflow features. Included are Pinto and Las Moras Springs (modeled together), springs located on the Nueces River, Leona Springs, Leona River channel gravels, Medina River channel gravels, Medina River discharge, San Pedro Springs, San Antonio Springs, Hueco Springs, Comal Springs, San Marcos Springs, Pleasant Valley Springs, and points of discharge on the Guadalupe River.

3.3.1 Springs

The major springs in the model domain are described in this section. Representing the springs as singular features in the model is challenging because springs to have multiple points of discharge often with different elevations. As a result, the different points of discharge can cease flowing as groundwater elevations drop. Elevations used for guidance are referred to as reference elevations due to this physical ambiguity. Initial spring reference elevations were adjusted during calibration. Initial reference elevation, calibrated elevation, and calibrated conductivity of springs and points of discharge for the major springs are summarized in Table 3.3.1-1. As shown in the table, the difference between the calibrated elevation and the initial reference elevation was 5 ft or less at four of the springs (San Marcos, San Pedro, Las Moras, and Leona Springs), within 5-10 ft at two springs (Comal Springs, Pinto Springs), within 15 ft at three springs (San Antonio Springs, Medina River and underflow, and Nueces River springs), 22 ft at Hueco Springs.

Table 3.3.1-1. Initial reference elevation, calibrated elevation and calibrated conductivity of springs and points of discharge.

	Initial Reference Elevation (ft, msl)	**Calibrated Elevation (ft, msl)**	**Calibrated Conductivity (ft/day)**
San Marcos Springs	573	570	1
Comal Springs	609	600	1
Hueco Springs	652	630	0.3
San Antonio Springs	670	685	2
San Pedro Springs	660	655	0.02
Pinto Springs	1150	1160	0.1
Las Moras Springs	1105	1105	1E-06
Medina River/Underflow	845	860	0.02
Leona Springs/Underflow	811/839	811/839	0.03
Nueces River springs	795	810	3

The source water for springs can be complex, particularly spring systems with multiple points of discharge. It has proven to be beneficial to parse-out source areas using tools such as water chemistry, tracer experiments, and water-budget analyses. Identifying source areas can be made more complicated if the sources of discharge vary with stage. These complications appear to be more common with larger spring systems such as Comal and San Marcos. Smaller spring systems with a limited number or even a single point of discharge are easier to conceptualize. Within the study area, Pinto, Las Moras, San Pedro, San Antonio, and Hueco Springs are conceptualized as systems with limited complexity due to a limited extent of discharge points and a relatively simple source area. The paleo-spring in the Medina River floodplain on the downdip side of Haby Crossing Fault appears to have a single source although this conceptualization may prove to be more complex as it is better defined. Leona Springs has slightly increased complexity with discharge from the Edwards, Buda Limestone, and Austin Chalk Aquifers (which are hydraulically connected in the Uvalde pool) and a separate source of recharge from the terrace deposits in the Leona River.

Comal and San Marcos Springs are not only the largest spring complexes in the study area (and the State of Texas), but they exhibit significant complexity in terms of discharge features, apparent source areas, and variability in discharge with change of stage. Simply stated, discharge at each spring is a combination of regional and local sources

$$Q_T = \sum_{i=1}^{n} Q_i^R + \sum_{i=1}^{m} Q_i^L \qquad \text{(Eq. 3.3.1-1)}$$

where n is the number of regional sources and m is the number of local sources of recharge for the springs. An additional level of complexity into this conceptualization can be incorporated if the sources vary with stage.

$$Q(t)_T = \sum_{i=1}^{n} Q(h)_i^R + \sum_{i=1}^{m} Q(h)_i^L \quad \text{(Eq. 3.3.1-2)}$$

Of course, implementing such a characterization scheme is only as realistic as the level of data support.

Past investigations of San Marcos Springs provide a basis to engage this conceptualization. Water chemistry and water-budget analyses indicate that local sources provide about 25-40 percent of total flow. The principal local sources are the Guadalupe River and Blanco River watersheds. The regional source is the cumulative flow in the Confined Zone as it flows from Bexar County through Comal County and eventually to Hays County. If appropriate, Equation 3.3.1-2 can be recast in context of San Marcos Springs as the following.

$$Q(h)_T = Q(h)_R + Q(h)_{L-Guadalupe} + Q(h)_{L-Blanco} \text{(Eq. 3.3.1-3)}$$

The regional source of recharge is a lower frequency contribution to spring discharge. The local sources are higher frequency and provide the flashiness exhibited in San Marcos Springs discharge. Identifying the individual contributions to the regional source of recharge has been discussed in some detail in Section 2, however, parsing out the time-varying individual contributions to the regional source of recharge is a challenge. Contributions to the regional source can be stated (with some simplification) as follows

$$Q(h)_R = Q(h)_{R-Nueces} + Q(h)_{R-Frio/DryFrio/Saabinal} + Q(h)_{R-MedinaInterbasin} + Q(h)_{R-Medina} + Q(h)_{R-SanAntionInterbasin} + Q(h)_{R-Cibolo} \text{(Eq. 3.3.1-4)}$$

Calculating the cumulative contributions of each of these watersheds is obviously a challenge which is best accomplished with a distributed model, such as the 2004 MODFLOW model or the alternative model discussed in this report. Nonetheless, complementary analyses can provide insight that can help constrain this problem. Analyses that evaluated the change of correlation between precipitation events (a surrogate for recharge) and aquifer response (i.e., spring discharge and head measurements) in the Edwards Aquifer provide some insight (Başağaoğlu et al., 2015). The correlation of precipitation on the Contributing Zone with the aquifer hydraulic response at J-17 is observed to vary between high and low stage. During low stage that occurred during the periods of July 2003 to March 2004 and July 2004 to March 2005, there is negligible correlation between the western portion of the Edwards Aquifer and J-17 (Figure 3.3.1-1). There is an observable correlation between recharge that occurred over the eastern Frio River/Dry Frio River/Sabinal River watershed and the western interbasin area immediately to the east.

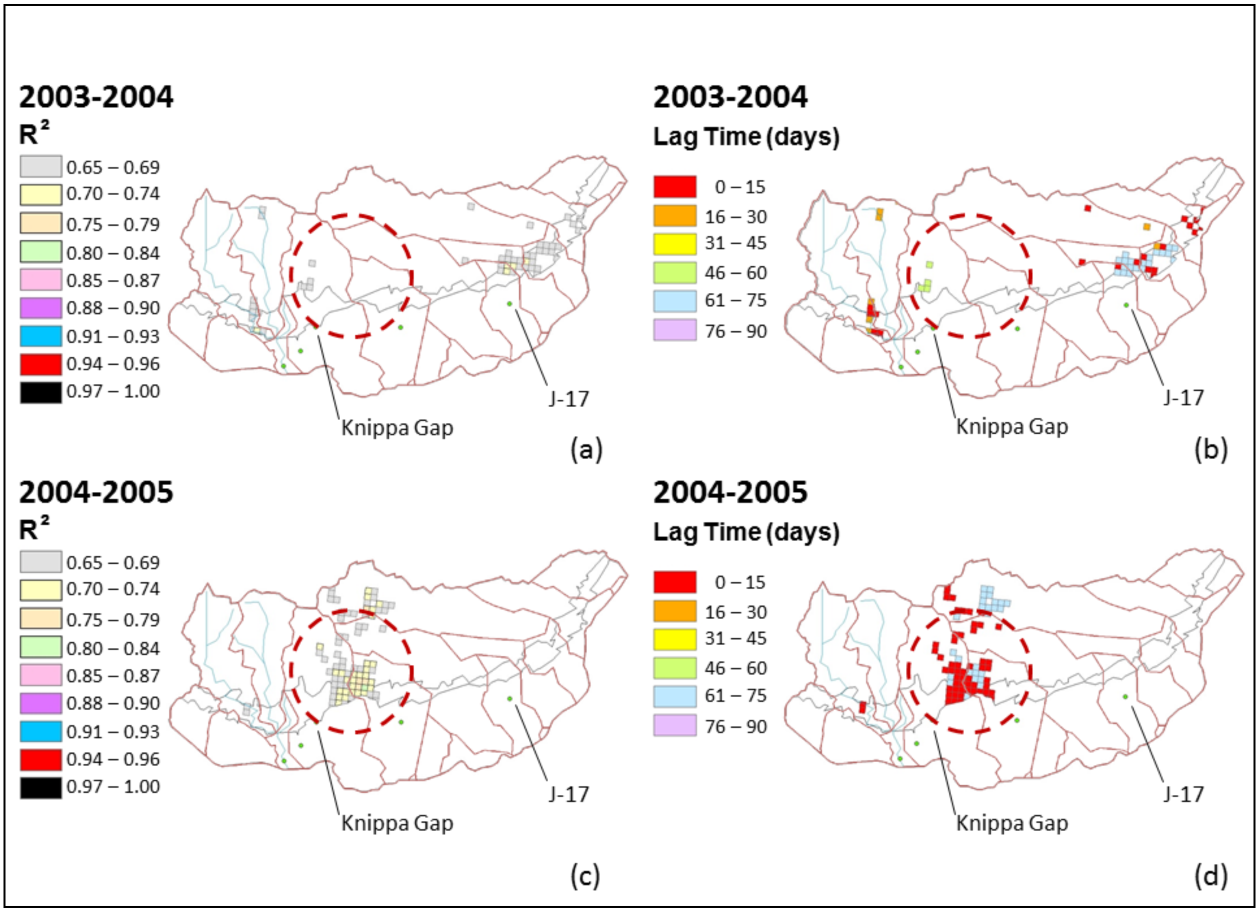


Figure 3.3.1-1. Correlation and lag time between precipitation in the Contributing Zone and hydraulic response observed at index well J-17 observed during the periods July 2003 and March 2004 and July 2005 and March 2005, two relatively dry periods.

Conversely, during high stage, which occurred during July 2007 to March 2008, there was high correlation between precipitation that occurred in the West Nueces/Nueces River watershed and the hydraulic response observed at J-17 (Figure 3.3.1-2). In addition, the hydraulic lag in the response was relatively short, less than two weeks. This analysis provides evidence the upgradient portion of the aquifer places an active and prominent role in regional flow observed downstream and that this response is more pronounced and quicker during high stage compared with low stage.

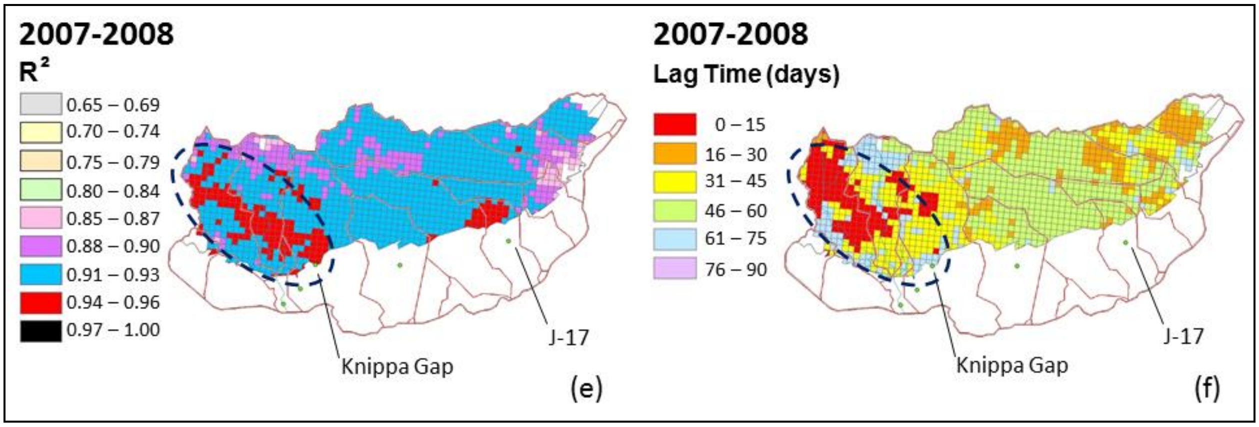


Figure 3.3.1-2. Correlation and lag time between precipitation in the Contributing Zone and hydraulic response observed at index well J-17 observed during the period July 2007 and March 2008, a relatively wet period.

3.3.1.1 Las Moras and Pinto Springs

Las Moras and Pinto Springs, as the Kinney Pool is conceptualized here, are the only natural points of discharge from the Kinney Pool (Figure 3.3.1.1-1).

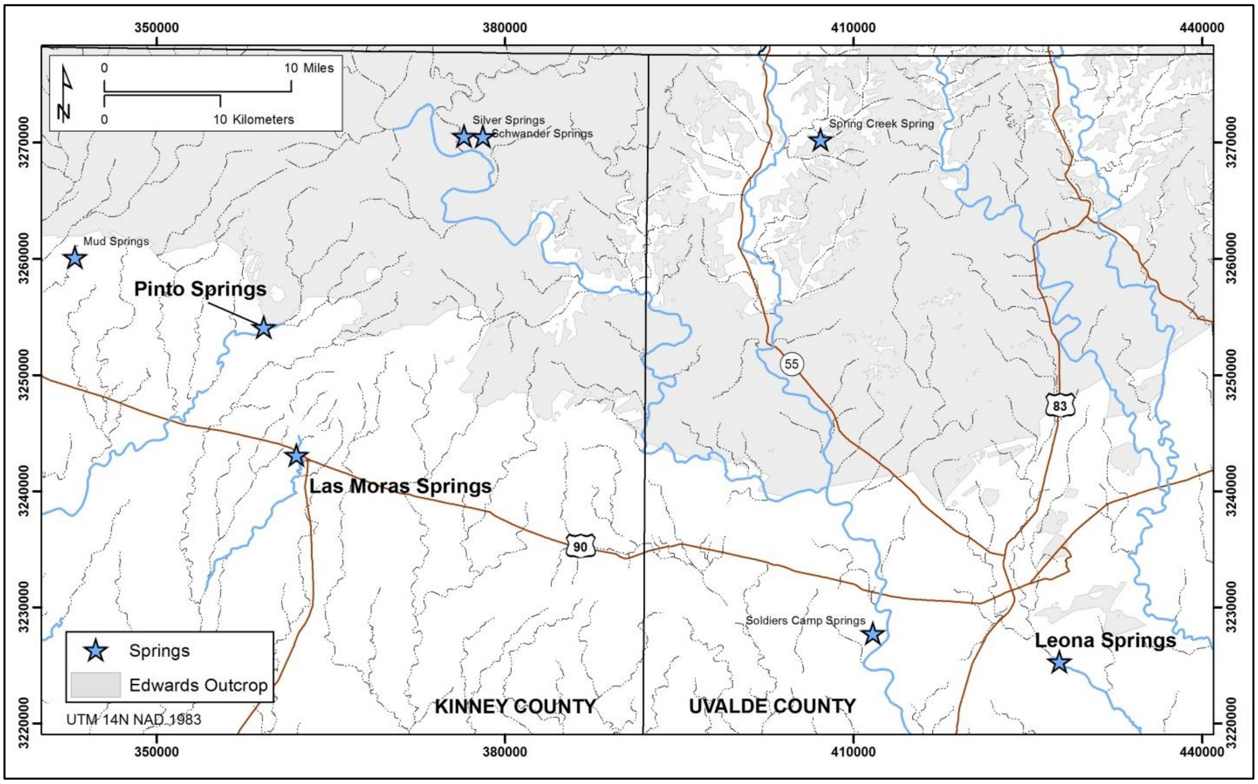


Figure 3.3.1.1-1. Map view of Las Moras and Pinto Springs in the Kinney Pool and Leona Springs in the Uvalde Pool.

The largest capacity spring in Kinney County, Las Moras Springs, discharges at a point where the top of the Edwards Aquifer is at a depth greater than 400 ft below ground level (Welder and Reeves, 1962). Although there is faulting at Las Moras Springs, there is no indication that there is sufficient vertical structural offset to juxtapose the Edwards Aquifer with the Austin Chalk or any other permeable unit located closer to the surface. Bennett and Sayre (1962) described Las Moras Springs as an artesian spring that discharges after passing through the Grayson Shale (local equivalent of the Del Rio Clay), Buda Limestone, Eagle Ford Shale, and Austin Chalk. It is possible that the Buda Limestone and the Austin Chalk aquifers contribute to discharge at Las Moras Springs.

Discharge at Las Moras Springs is variable, with measured flow rates that have ranged from a maximum of 60 cfs recorded on June 30, 1988 to periods of no flow. Based on 155 recorded measurements for Las Moras Springs provided in Bennett and Sayre (1962) during the period of 1895 to 1956, discharge averaged 23.1 cfs, which equates to an annual average discharge of 16,724 acre-ft. Using measurements from September 1939 to October 1940, Bennett and Sayre (1962) calculated the cumulative discharge from Las Moras, Pinto, and Mud springs to be 23,000 acre-ft/yr of which discharge from Las Moras and Pinto springs is approximately 21,000 acre-ft/yr. As discussed in Section 2.1.1, Mud Springs and Mud Creek are outside the model domain.

3.3.1.2 Leona Springs

Leona Springs consists of a number of seeps emerging from terrace deposits within the Leona River channel near where the river crosses Highway 90 in Uvalde County (Figure 3.3.1.1-1). This discharge provides for flow in the Leona River. The channel deposits consist of Uvalde Formation and Leona Formation gravels. Leona Springs are at approximately 865-875 ft msl. The Leona Formation at the headwaters of the Leona River is at about 835-845 ft msl. This suggests that the source of water for Leona Springs is the Uvalde Gravel, not the Leona Formation.

The Leona River appears to directly overly the Buda Limestone and Austin Chalk proximal to Hoag Dam near Fort Inge. Thus, Edwards Aquifer water may be indirectly discharged to the Leona River via channel deposits or via the Buda Limestone and Austin Chalk which are hydraulically connected, via juxtaposition by faults, to the Edwards Aquifer (Green et al., 2008a). U.S. Geological Survey measurements for Leona Springs are representative of discharge from Uvalde Gravel. Discharge via the Leona Formation gravel is considered subsurface discharge and discussed in Sections 2.3.2.3 and 2.3.2.4.

3.3.1.3 San Pedro and San Antonio Springs

San Antonio and San Pedro Springs in Bexar County discharge groundwater that rises along a major fault (Figure 3.3.1.3-1). A structural horst near the fault blocks ground-water flow in a complex graben and diverts flow around its northern and southern margins, some of which emerges as springflow (Maclay, 1995; Lindgren et al., 2004). San Antonio Springs has had intermittent flow since 1950 and flows only during periods when water levels in the aquifer are at a high stage. Increased pumpage from wells in San Antonio caused the interruptions of the springflow of San Antonio Springs and also has resulted in a cessation of flow from San Pedro Springs (Brune, 1981).

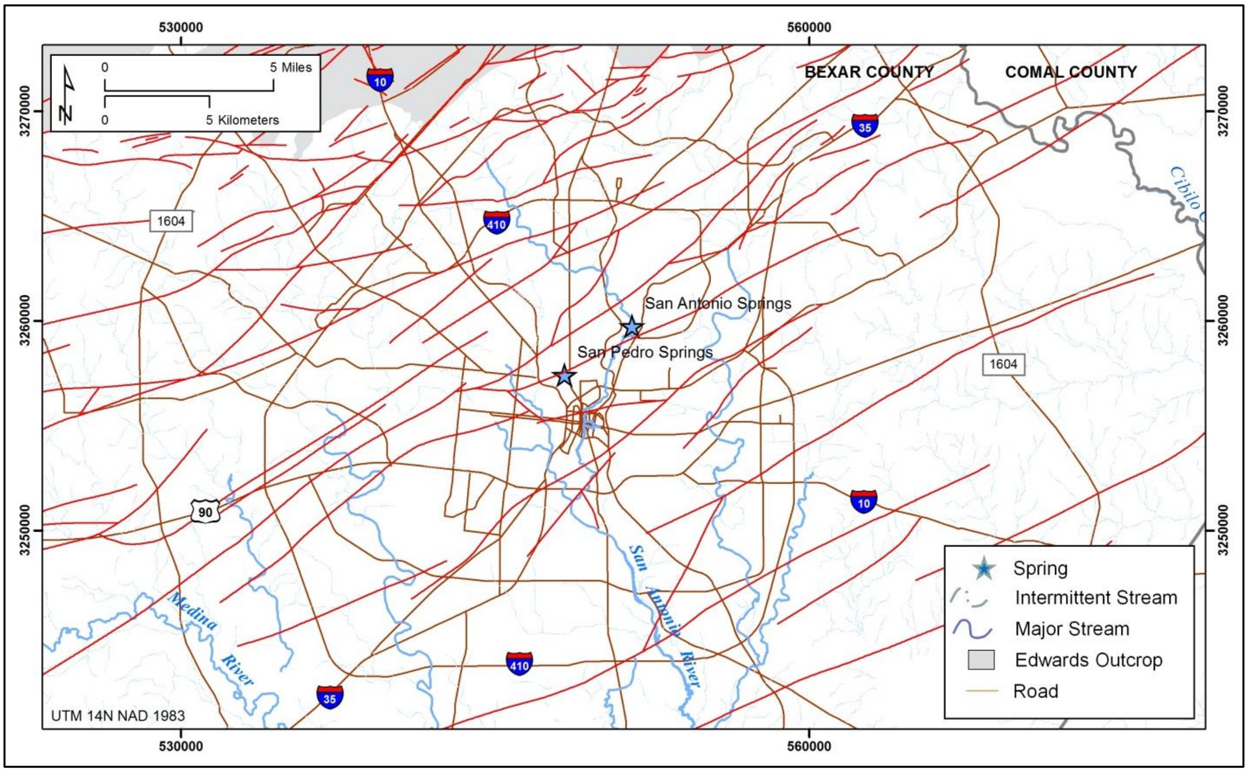


Figure 3.3.1.3-1. Map view of San Pedro and San Antonio Springs in the San Antonio segment of the Edwards Aquifer.

3.3.1.4 Comal Springs

Characterization of the hydrostratigraphic framework of Comal Springs is taken from Johnson and Schindel (2008). Comal Springs are located on the Comal Springs Fault which defines the downgradient side of the Comal Springs Fault block (Figure 3.3.1.4-1). Comal Springs Fault block does not contribute to discharge at Comal Springs during dry periods when the groundwater elevation in the Comal Springs Fault block is too low (Johnson and Schindel, 2008). During low stage, groundwater flow is from the Artesian Fault block, which is higher than the Comal Springs Fault block, flows through the Comal Springs Fault block to Comal Springs. LBG-Guyton Associates (2004) concluded that low TDS groundwater flow in the Artesian Fault block ends just north of Comal Springs. This may be an indication that a ramp structure allows water to flow from the Artesian Fault block to the Comal Springs Fault block (e.g., Ferrill and Morris, 2008).

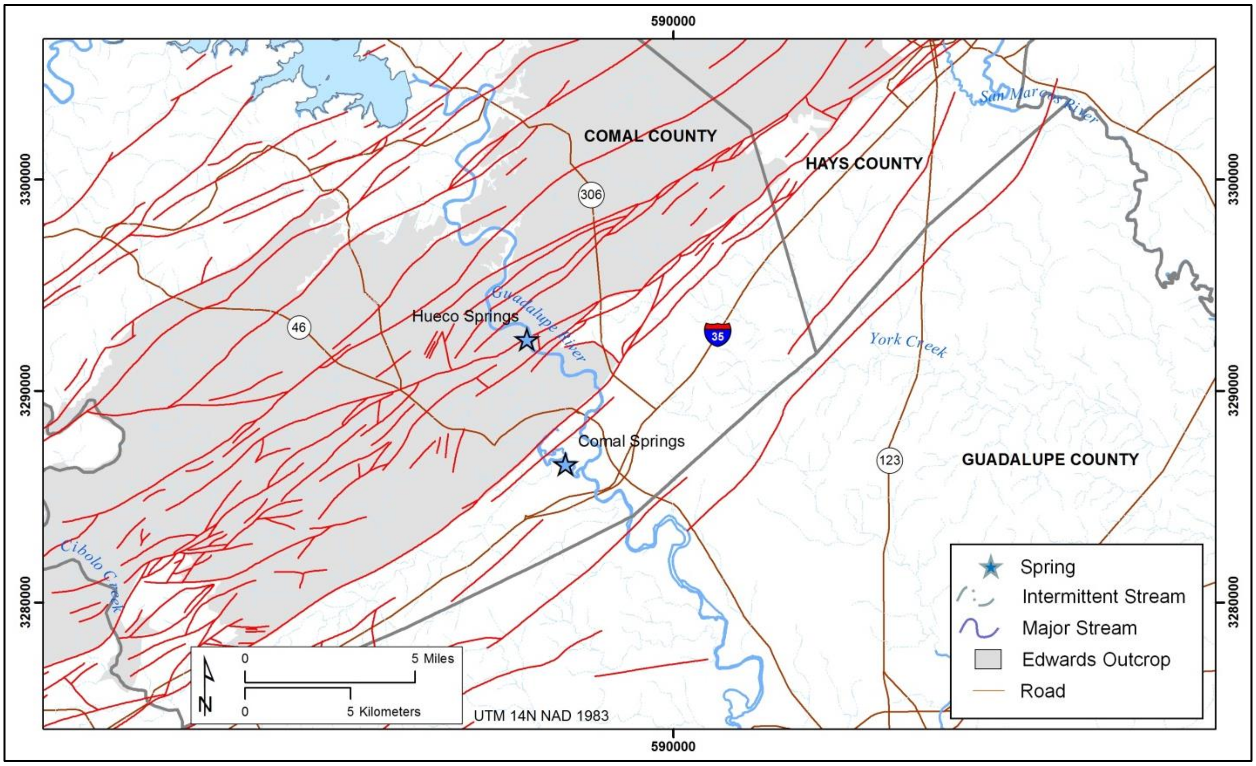


Figure 3.3.1.4-1. Map view of Comal and Hueco Springs in the San Antonio segment of the Edwards Aquifer.

During low groundwater elevations, a trough in the potentiometric surface forms in the Comal Springs Fault block. Groundwater flows to this trough and then flows past Comal to San Marcos Springs. Comal Springs discharge is typically less than 100 cfs when groundwater elevations in the Comal Springs Fault block are less than the elevation of the Comal Springs orifice (623 ft msl).

During high groundwater elevations, groundwater flows from the Comal Springs Fault block to both Comal and San Marcos Springs. Also at higher groundwater elevations, the Comal Springs Fault block is recharged by something other than the Artesian Fault block. Groundwater elevations in the Comal Springs Fault block to the northeast of Comal Springs are well correlated with discharge from San Marcos Springs.

Groundwater elevations in the Hueco Springs Fault block are higher than groundwater elevations in the Comal Springs Fault block. This suggests that the Hueco Springs Fault is a barrier to flow. Groundwater flow in the Hueco Springs Fault block is to the northeast toward San Marcos Springs.

With the exception of flow across the Comal Springs Fault near Comal Springs, most of the major faults (i.e., Bat Cave, Hueco Springs, Comal Springs) in Comal County and southern Hays County appear to act as barriers to flow. This is consistent with the observation that there are hydraulic head differences across the faults and groundwater flow appears to flow parallel to the strike of the faults (Johnson and Schindel, 2008).

3.3.1.5 Hueco Springs

Characterization of the hydrostratigraphic framework of Hueco Springs is taken from Johnson and Schindel (2008). Hueco Springs is on the upthrown Hueco Springs Fault block side of Hueco Springs Fault (Figure 3.3.1.5-1). There are two orifices, the lower orifice is at 652 ft msl. Hueco Springs discharge correlates with San Marcos Springs discharge, but not completely. Hueco Springs discharge can increase at times when San Marcos Springs discharge is stable. Potential sources of recharge to Hueco Springs that do not recharge San Marcos Springs include Cibolo Creek, Dry Comal Creek, and the Trinity Aquifer. Water discharged at Hueco Springs originates in the Edwards Aquifer with perhaps some contribution from the Trinity Aquifer.

The Cibolo River at the Selma gauge is dry 90 percent of the time. The Selma gauge is located in the Artesian Fault block. When there is no flow in the Cibolo River at Selma, Hueco Springs discharge averages 54 cfs. When Cibolo Creek is flowing at Selma, Hueco Springs discharge averages 100 cfs. This suggests flow in Cibolo Creek recharges the Hueco Springs Fault block only during high river flow periods. In addition, water from Dry Comal Creek may infiltrate into the Hueco Springs Fault block lock rather than cross the Hueco Springs Fault.

3.3.1.6 San Marcos Springs

Characterization of the hydrostratigraphic framework of San Marcos Springs is taken from Johnson and Schindel (2008). San Marcos Springs exhibits a number of orifices. The northern orifices, Cabomba, Hotel, Johnny (aka Weissmuller), and Divergent (aka Diversion), are recharged by Blanco River, Sink Creek and areas downgradient to the north, which is south of the groundwater divide near Onion Creek (Figure 3.3.1.6-1). The southern orifices, Deep and Catfish, are recharged by the Comal Springs Fault block, which is, in turn, recharged by the Artesian Fault block (Johnson and Schindel, 2008). Historically, during low flow conditions, groundwater continued to flow from the west to San Marcos Springs via the Artesian Fault block even when Comal Springs ceased to flow.

Johnson and Schindel (2008) noted that at high discharge rates, San Marcos Springs are recharged by water sourced from Cibolo, Dry Comal, and Sink Creeks and the Guadalupe River. They noted that the rate of contributed recharge is relatively small, but provided no estimate. At low discharge rates (i.e., when San Marcos Springs discharge is less than 100 cfs), Johnson and Schindel (2008) noted that Cibolo Creek, the Guadalupe and Blanco Rivers, and other creeks and streams in Comal and Hays counties contribute a small percentage of water to San Marcos Springs discharge.

Musgrove and Crow (2012) examined the hydrologic and geochemical variability of discharge from Comal, Hueco, and San Marcos Springs. Comal and Hueco Springs are representative of two endmember Edwards Aquifer spring types, with Hueco Springs predominantly affected by local flowpaths and locally sourced recharge. Comal Springs is predominantly affected by regional flowpaths and regionally sourced recharge.

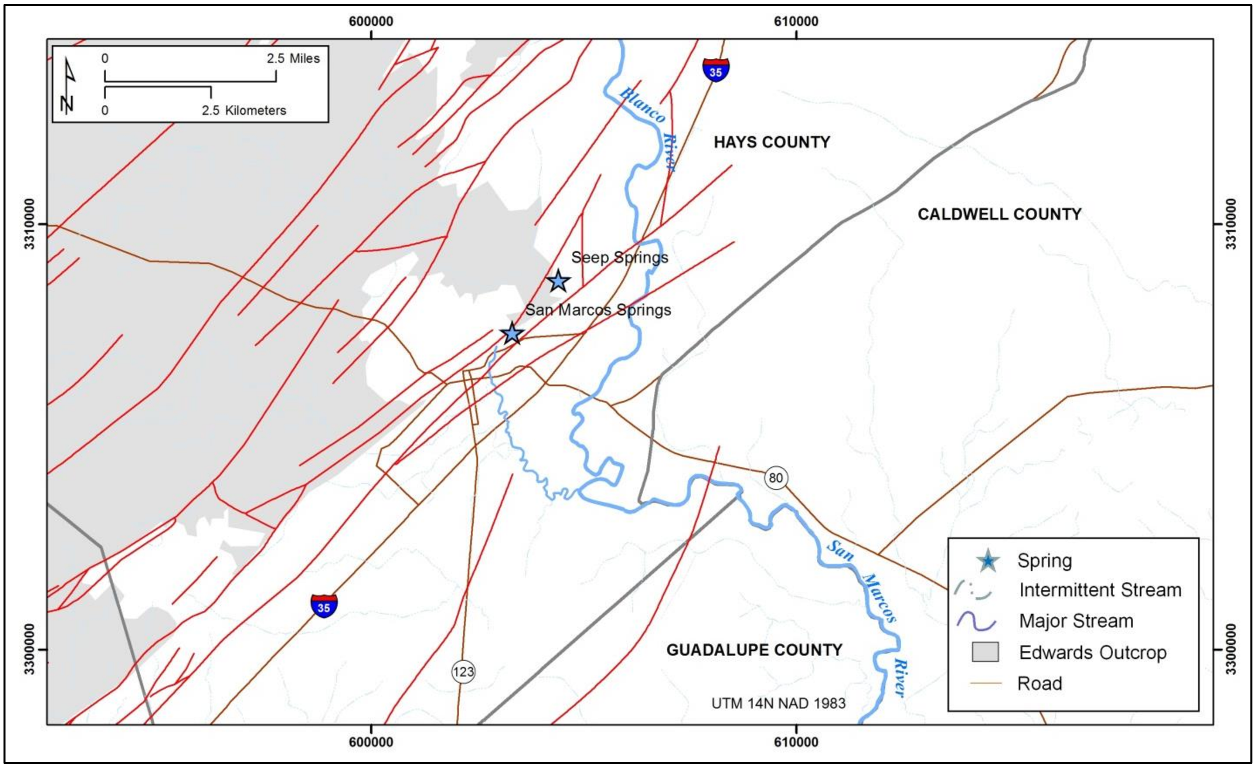


Figure 3.3.1.6-1. Map view of San Marcos Springs in the San Antonio segment of the Edwards Aquifer.

The geochemistry of discharge from Deep, Diversion, and Weissmuller orifices at San Marcos Springs is different. These differences in geochemistry are interpreted to indicate differences in the source of groundwater supplying the springs (Musgrove and Crow, 2012). During the dry period, discharge at Deep Spring exhibits a small component of saline groundwater. The geochemistry of Deep Spring is not responsive to changes in hydrologic conditions from the dry period to the wet period, indicating that Deep Spring is likely dominated by regional flow. Near San Marcos Springs, the Artesian Fault block contains saline water and does not contribute much recharge to San Marcos Springs, however, what regional flow discharges at San Marcos Springs is likely sourced by the Artesian Fault block.

Diversion Spring is more responsive to changes in hydrologic conditions, indicating that Diversion Spring is affected by some changes in discharge sources (Musgrove and Crow, 2012). From the dry period to the wet period, the geochemistry of Diversion Spring becomes more like that at Deep Spring; in that the saline component increased. Weissmuller Spring geochemistry is similar to that of Diversion Spring, indicating that Weissmuller and Diversion Springs are likely supplied by common, local flow paths.

3.3.3 Discharge by Pumping

Pumping discharge data were compiled by the EAA staff based on Annual Use Reports that are submitted each year by withdrawal permit holders. Exact locations of permitted pumping wells are known (Figure 3.3.3-1). Permit holders are required only to report total amounts pumped for each calendar year, thus presenting a challenge to estimate monthly pumping for input to the model. Fortunately, many permit holders make the effort to record and report their monthly use, including some of the largest users such as San Antonio Water System. In any given year, there are approximately 1,500 wells making permitted withdrawals throughout the aquifer region but monthly pumping data may only be available for several hundred. Monthly pumping must, therefore, be estimated for all of the other wells.

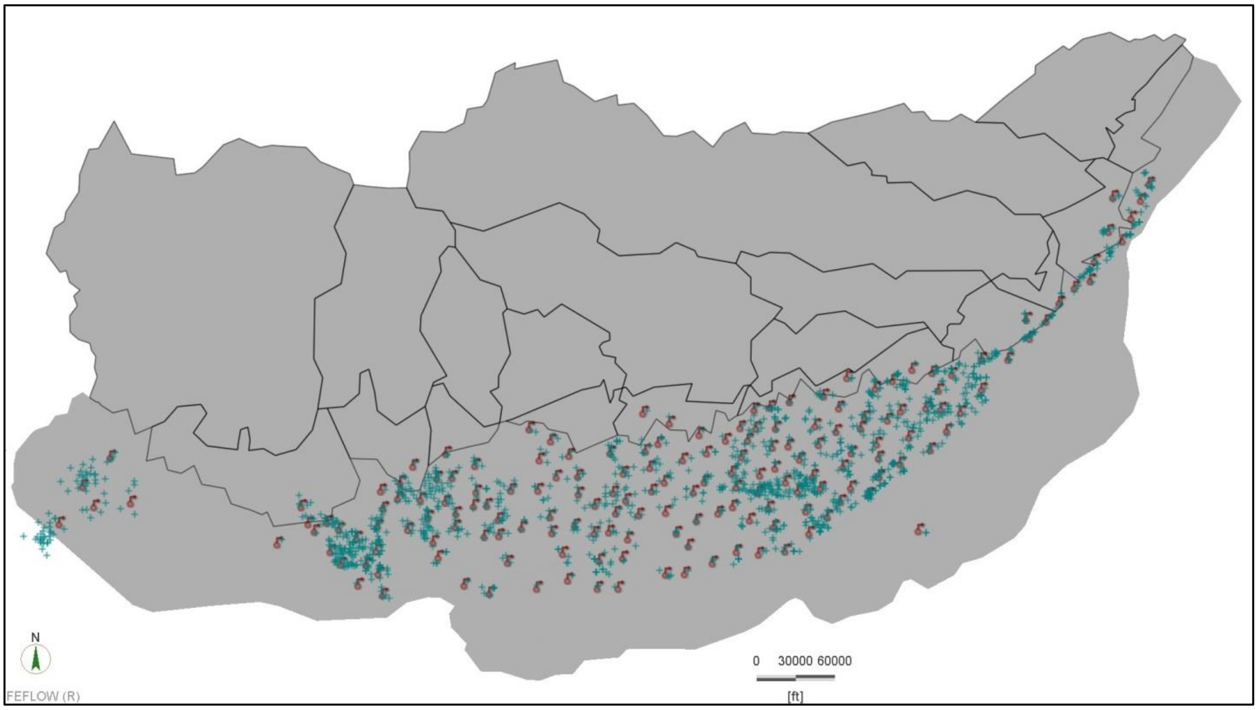


Figure 3.3.3-1. Locations of actual pumping well locations (blue-green) and pumping wells within the model (red).

To estimate monthly pumping, unit pumping curves were developed for each calendar year based on data from those permit holders who did report monthly pumping. Pumping curves were developed for three separate types of use: industrial, municipal, and irrigation. The curves were generated by summing the monthly totals for each use type and dividing the monthly use by the annual total use, such that the fractional pumping for each month will sum to 1.0 for the year. An example of a unit pumping curve for year 2001 is shown in Figure 3.3.3-2. The unit pumping curves for each use type were then used to estimate pumping for other wells of the same use type by multiplying the fractional pumping for each month by the annual total. This approach implies that the wells that do not report monthly pumping will, on average, follow a similar pattern of pumping as the wells that do report monthly pumping.

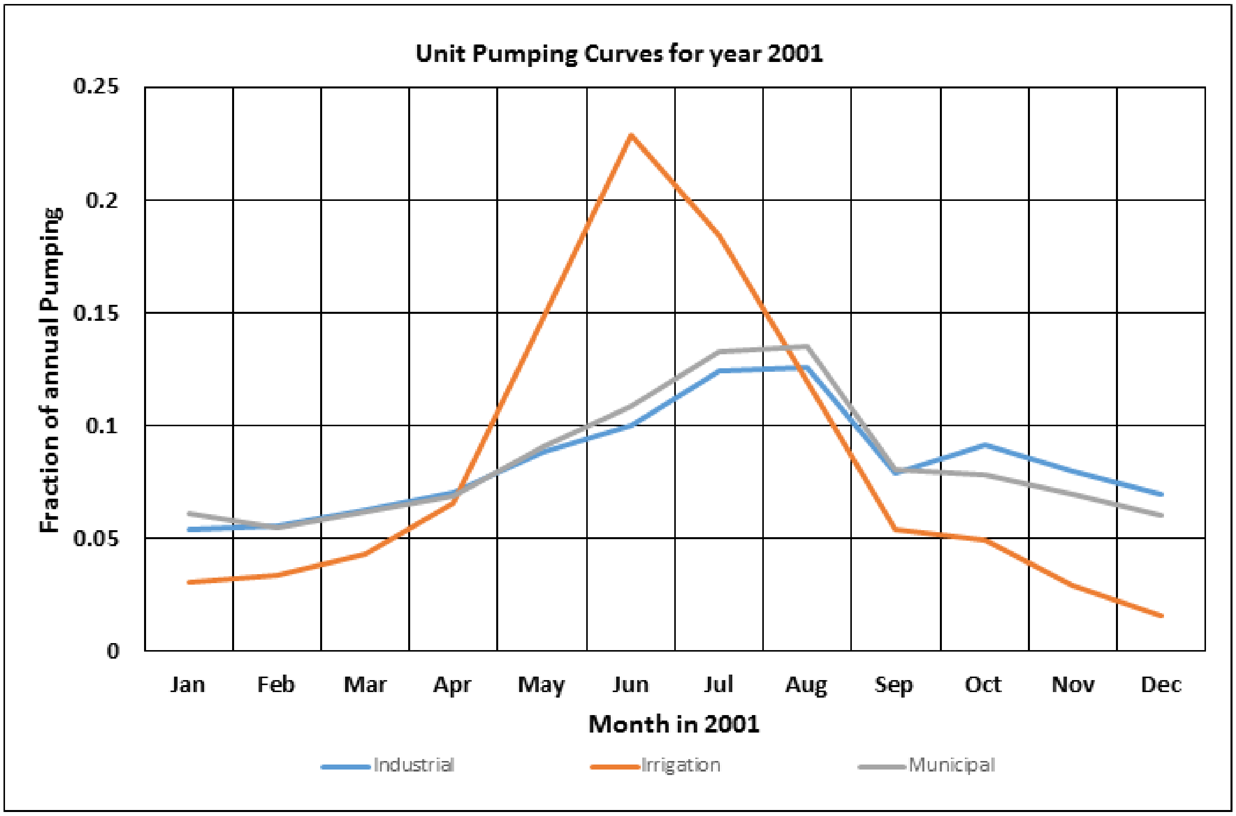


Figure 3.3.3-2. Unit pumping curves developed for industrial, municipal, and irrigation use for calendar year 2001.

Of the approximately 1,500 permitted well locations that report pumping in a given year, there will typically be several hundred that pump less than 10 acre-feet. To simplify the model input, the wells were sorted in order of total use for each year. The wells with the lowest use were selected until 1,000 acre-feet worth of low-use wells were identified. These low-use wells were then removed from the data set and the 1,000 acre-feet that they represent was then distributed among all other wells using a municipal unit pumping curve. This approach reduces the number of pumping wells considered in any year by about 300, although it varies from year to year. Thus, approximately 20 percent of the pumping wells that represent only about 0.3 percent of annual pumping were removed from consideration.

In addition to permitted pumping wells, there are estimated to be over 10,000 domestic and livestock wells throughout the region that are exempt from permitting and reporting requirements. The EAA estimates for total annual domestic and livestock pumping ranged from 13,000 to 13,800 acre-ft/yr during the 2001–2011 modeled period, which is on the order of 3 to 4 percent of total pumping. Because of the large number of exempt wells and lack of individual well data, the EAA annual estimates of domestic and livestock pumping were simply divided among and added to the permitted pumping wells using municipal type pumping curves.

The total modeled monthly pumping from the aquifer estimated via the foregoing procedure is shown in Figure 3.3.3-3. Summer pumping peaks are evident in all years except for 2007, which had a very wet summer, resulting in much lower total water demand. When input to the

FEFLOW model, wells in close proximity were summed and represented as a single pumping location.

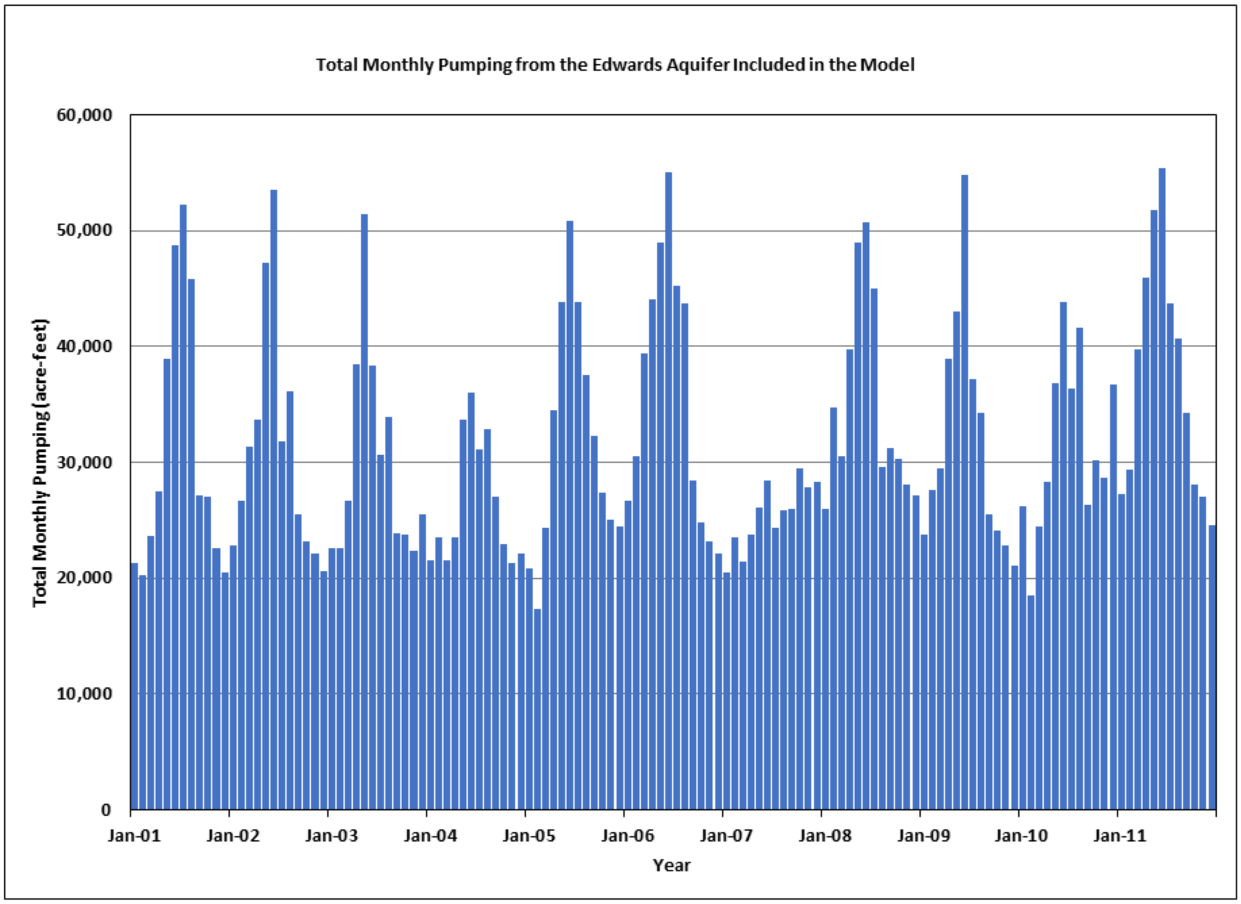


Figure 3.3.3-3. Total monthly pumping from the Edwards Aquifer included in the model for years 2001–2011.

3.4 Initial Conditions

The initial hydraulic heads were initial conditions were obtained by running a pseudo-steady-state simulation for 100 years with pumping and recharge conditions set to the average of the 11-year calibration period. A map view of the initial conditions is shown in Figure 2.2.3-5. Other choices for initial conditions were used, however, model performance was relatively insensitive to which set of initial conditions was used provided the set was comparable to the arithmetic averages. This insenitivity supports the conceptualization of the Edwards Aquifer as having a relatively ”short memory” as ascertained by Başağaoğlu et al. (2014). Porous media aquifers which are significantly slower to respond would have much longer memories and would therefore be much more sensitive to choice of initial head designation.

4. Numerical Model

The numerical model developed using FEFLOW (Diersch, 2014) was run on a PC with an Intel® Core™i7 CPU870@2.93Ghz processor with 4.00 GB of RAM and a 64-bit operating system. Run times vary with input, but typically require less than 30 minutes to simulate the 11-year calibration period with a 100-year lead-up period.

4.1 Calibration Period

The eleven-year period 2001–2011 was designated as the period of calibration. Although relatively short in terms of number of years, this period was selected because it included extended periods of high precipitation and high stage (2004 and 2007) when recharge to the aquifer was calculated to be in excess of 2,000,000 acre-ft/yr and also extended periods of low precipitation and low stage (2006, 2008, 2009. 2011) when recharge was calculated to be an order of magnitude less (Tremallo et al., 2014). The period 2010–2011 experienced record low levels of precipitation by several measures, although aquifer stage was not as low as during the drought of record experienced in the 1950s. Designation of the period 2001–2011 as the calibration period which did not include the drought of record was also motivated by the fact that precipitation and pumping records for times before 2000 are not complete. Pumping records and high-resolution NEXRAD precipitation have only been available post-2002.

4.2 Model Uncertainty

Uncertainty in the conceptual and numerical model is categorized at three levels. The highest level of uncertainty is attributed to the fundamental structure of the model. Model features included in this level of uncertainty include:

- Model domain boundaries
- Hydrostratigraphic structure
- Recharge structure and mechanism (assigning recharge to either the Contributing or Recharge Zones)
- Hydraulic characterization of channel flow from the Contributing Zone to the Recharge Zone
- Structural framework of the Kinney Pool and Uvalde Pool

Designation of model properties that determine these model features have the potential to alter the fundamental nature of the numerical model.

The second level of uncertainty is less important to model performance than the first level. Model features included in this level of uncertainty include:

- Algorithm used to convert precipitation to recharge
- Hydraulic property assignment to river channels in the Contributing and Recharge Zones and the matrix in either the Contributing, Recharge, or Confined Zones
- Designation of major faults as either barriers or conduits for flow (includes Haby Crossing Fault and four faults near Comal and San Marcos Springs)

- Inclusion of conduits in the Confined Zone near Comal and San Marcos Springs
- Designation of discharge rates at springs which have poorly constrained or no discharge measurements. Notable examples are Pinto Springs and the subsurface discharge via the Leona Formation in the Leona and Medina River floodplains

Designation of model properties that determine these model features have the potential to alter the calibration of the numerical model, but do not fundamentally affect the interpretation of aquifer response.

The third, and lowest level of uncertainty is less important to model performance than the second level. Model features included in this level of uncertainty include:

- Inclusion of conduits in the Confined Zone away from Comal and San Marcos Springs
- Incorporation of approximately 100 minor faults that do not act as barriers to flow
- Simulation of runoff to major stream trunks (application of recharge directly to streams

Designation of model properties that determine these model features do not have the potential to significantly alter the calibration of the numerical model.

Model stability proved to be a function of several model properties. The most significant of these properties included:

- Element size in the river channels in the southern Contributing Zone
- Hydraulic property assignment to the river channels in the southern Contributing Zone
- Spring elevations and conductance

4.3 Model Performance

Comparison of the alternative model with the conceptual model was discussed in detail in Chapter 2. To accomplish this in a meaningful and feasible manner, the model domain was divided into subdomains based on naturally occurring hydraulic boundaries, barriers, and other conceptually “convenient” features. The conceptual model of each subdomain was independently compared with available observations. Observations included a broad range of data, including chemical analyses, hydraulic heads, spring discharge, river flow, meteorological data, and correlation analyses. Using the ensemble of these data, the conceptual model developed as part of this numerical model was determined to be physically reasonable and representative of the model domain.

Performance of the FEFLOW model is evaluated using statistics of comparison of model predictions with aquifer observations. Five principal performance measures have been identified: water levels at two index wells (J-17 and J-27); water levels of all calibration wells; and discharge measured at Comal and San Marcos Springs. In addition, discharge from other points in the model domain was compared with conceptual model interpretations and data, when available. Performance of FEFLOW is compared with target goals and comparable values for the 2004 MODFLOW model calculated for the calibration period 2001–2011. The

EAA staff prepared the statistics for the 2004 MODFLOW model as part of the alternative model evaluation exercise. This data set was generated using a 2004 MODFLOW simulation identified as "run 7-2". Model performance statistics are summarized in Table 4.3-1.

Table 4.3-1. Model performance and statistics

	MODFLOW*	**Target Goals**	**FEFLOW**
J-27 (ft)			
Mean error	5.8	1.3	3.6
RMS error	9.4	5	8.2
Max absolute error	17.7	20	15.8
J-17 (ft)			
Mean error	-7.7	2	0.2
RMS error	10.1	7	7
Max absolute error	30.3	30	17.5
Comal Springs (cfs)			
Mean error	-11	3	-45.9
RMS error	38	50	55.6
Max absolute error	171	150 for 2 mths	111
San Marcos Springs (cfs)			
Mean error	40	3	-32.2
RMS error	60	35	57.6
Max absolute error	140	150 for 2 mths	203.9 (2 mths)
All Wells (ft)			
Mean error	-9.3	2	-1.5
RMS error	35.5	25	24.6
Max absolute error	271	-	146.1

*Based on MODFLOW verification model run designated as "run 7-2."

4.3.1 Spring Discharge

Nine springs are represented in the numerical model: Pinto, Las Moras, Nueces River, Leona, San Pedro, San Antonio, Comal, Hueco, and San Marcos. In addition, there are two points of subsurface discharge discretely incorporated into the numerical model, Leona River channel gravels and Medina River channel gravels. Discharge measurements for underflow in the Leona River channel gravels are included with Leona Springs discharge. Underflow in the Medina River channel gravels was accounted for by removing this amount from recharge to the Medina River Basin. Discharge measurements for each spring are graphically compared with simulated discharge for the calibration period. These comparisons are presented in Figures 4.3.1-1–4.3.1-9.

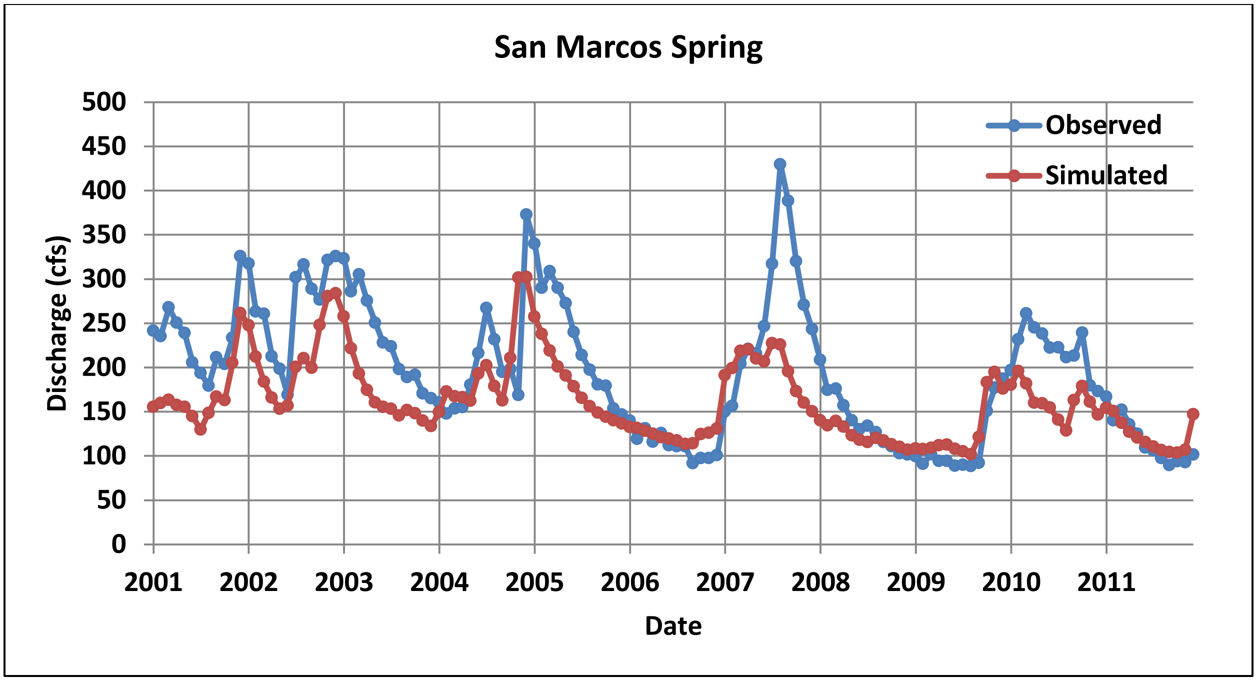


Figure 4.3.1-1. Observed (blue) and simulated (red) discharge at San Marcos Springs for the years 2001–2011.

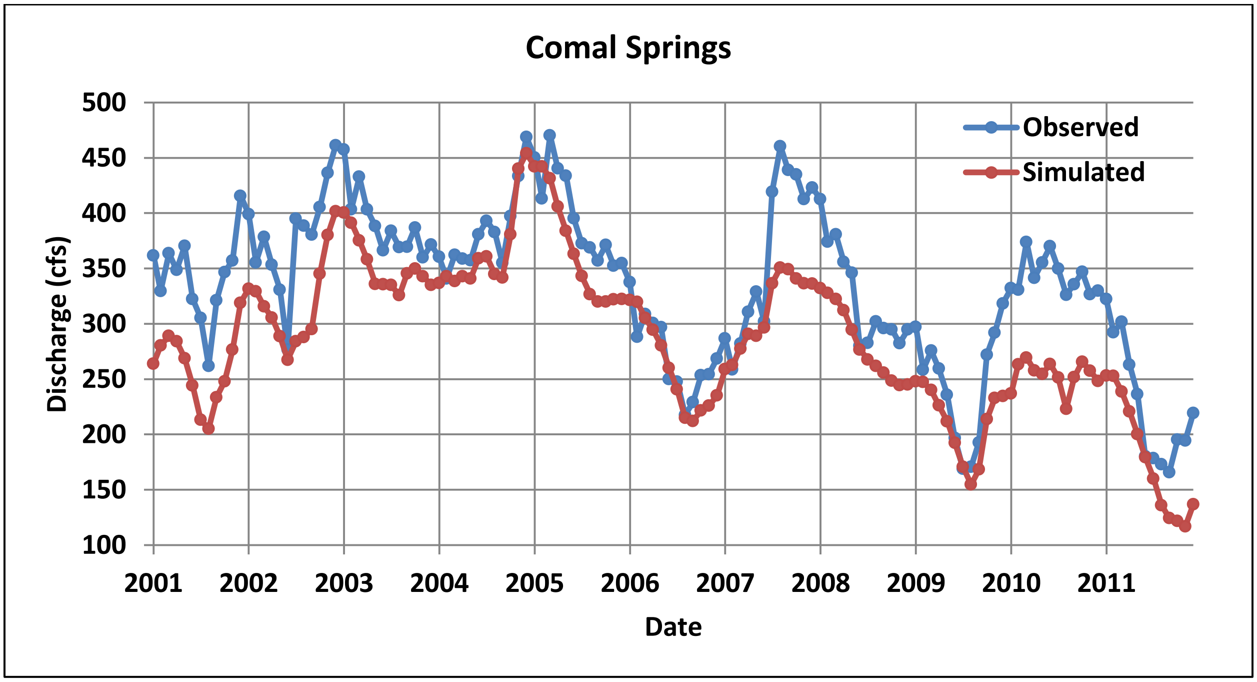


Figure 4.3.1-2. Observed (blue) and simulated (red) discharge at Comal Springs for the years 2001–2011.

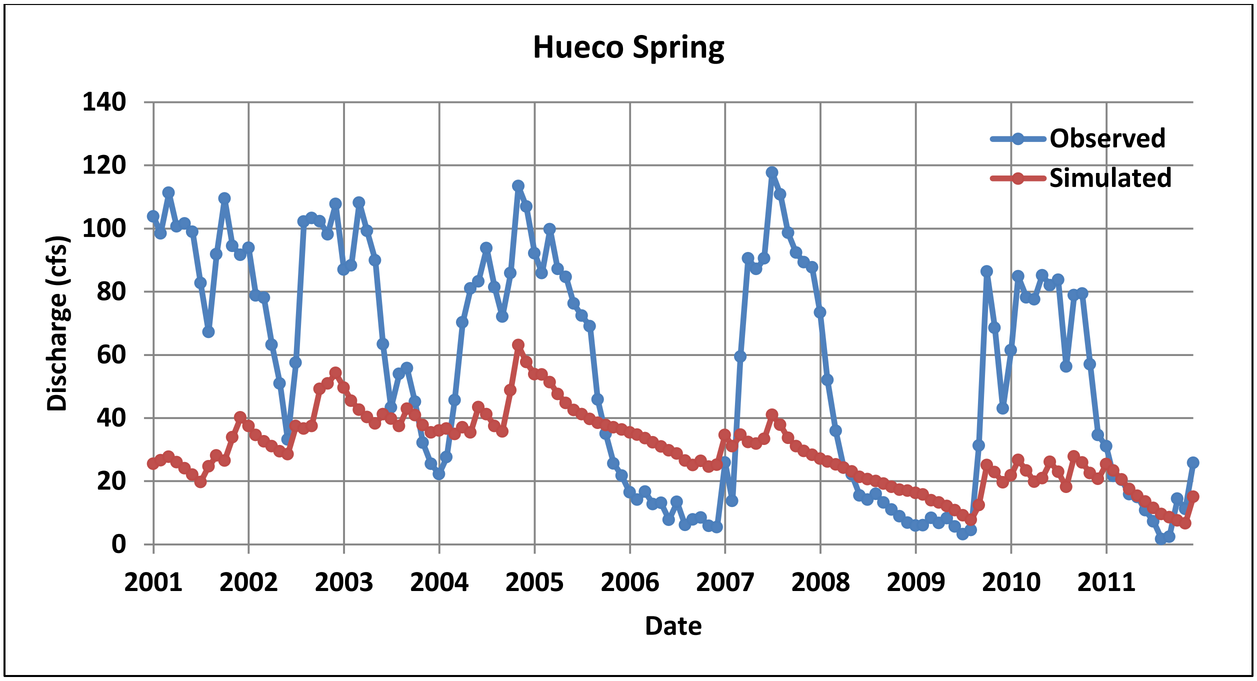


Figure 4.3.1-3. Observed (blue) and simulated (red) discharge at Hueco Springs for the years 2001–2011.

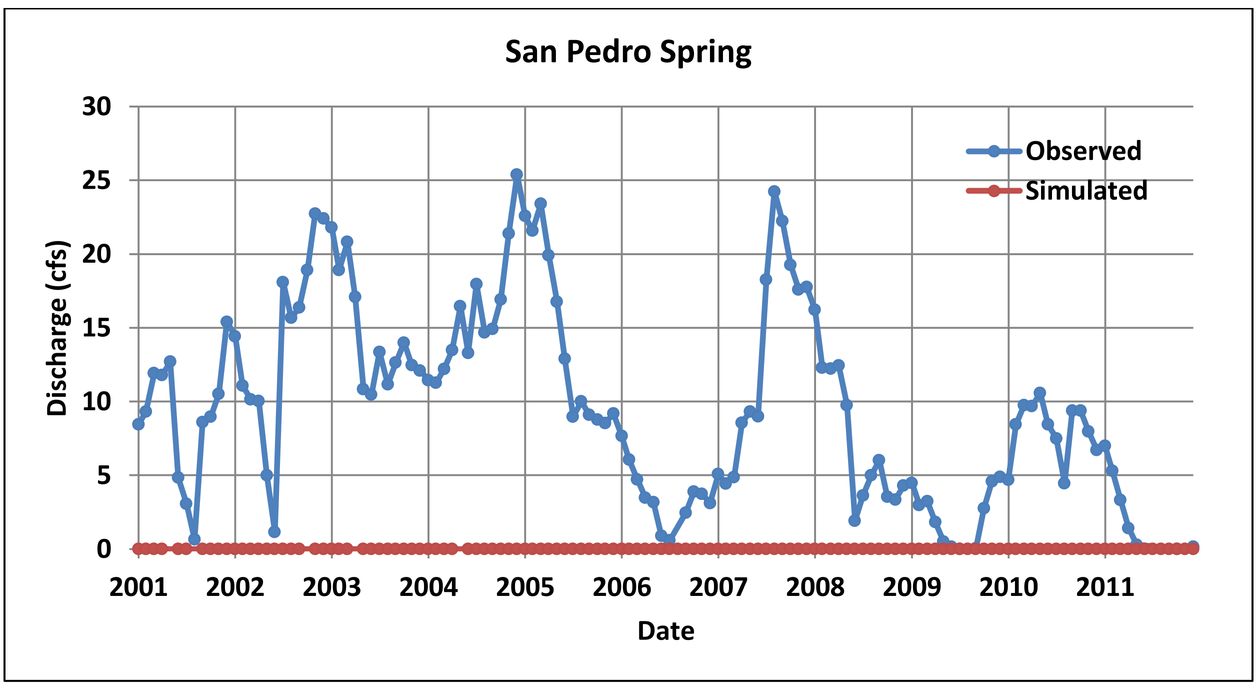


Figure 4.3.1-4. Observed (blue) and simulated (red) discharge at San Pedro Springs for the years 2001–2011.

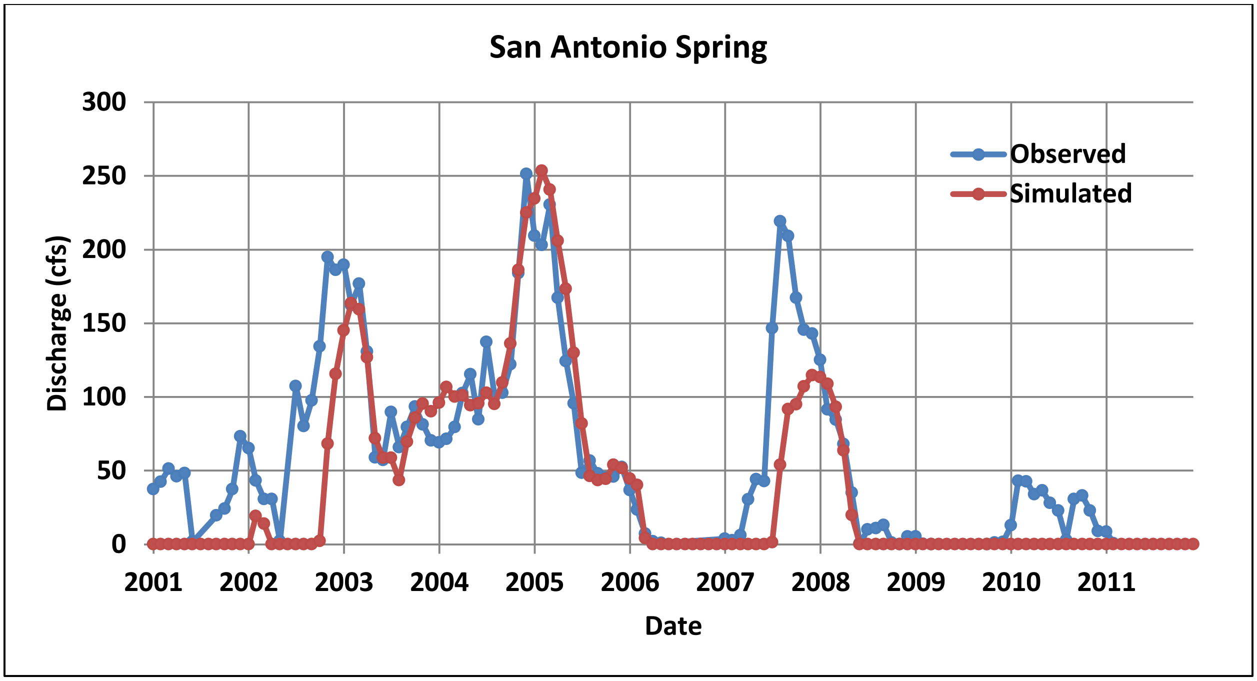


Figure 4.3.1-5. Observed (blue) and simulated (red) discharge at San Antonio Springs for the years 2001–2011.

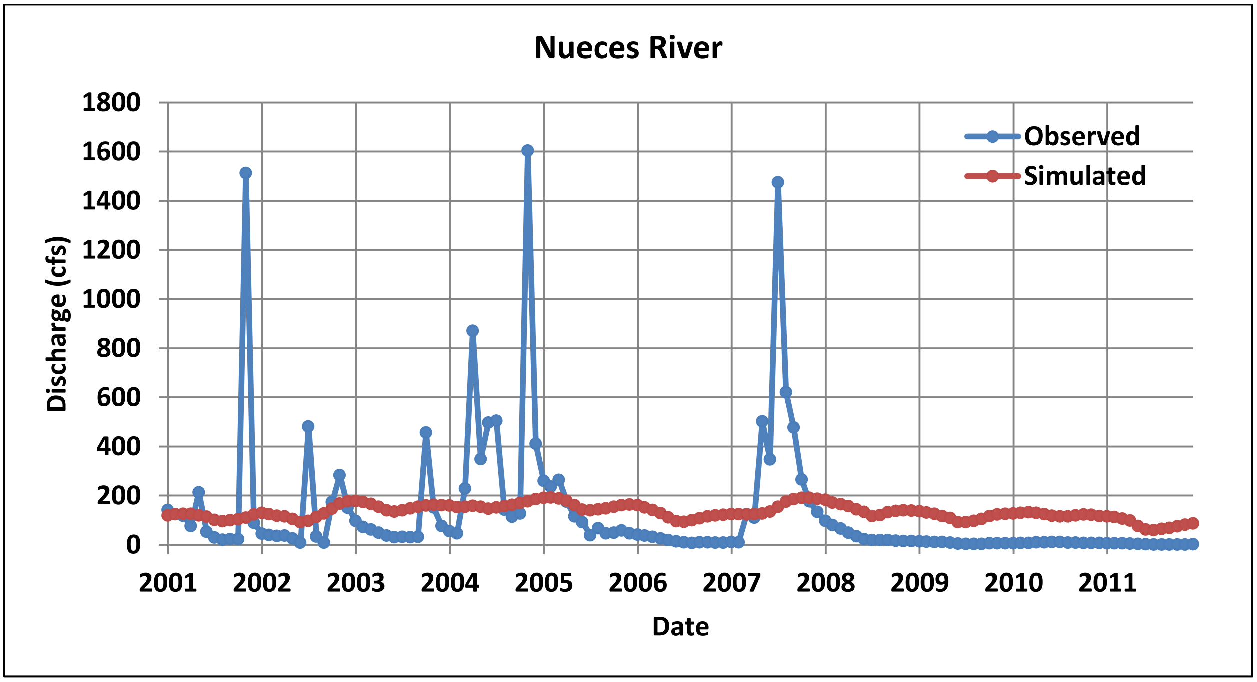


Figure 4.3.1-6. Observed (blue) and simulated (red) discharge at springs on the Nueces River for the years 2001–2011.

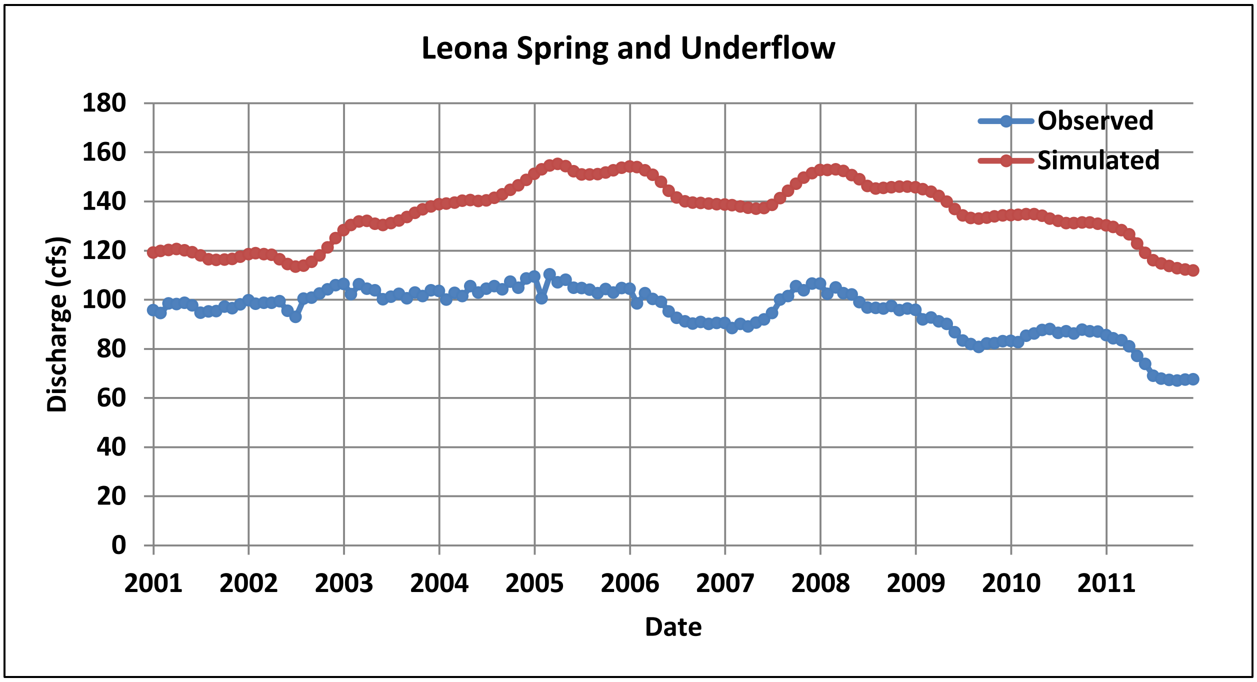


Figure 4.3.1-7. Observed (blue) and simulated (red) discharge at Leona Springs for the years 2001–2011.

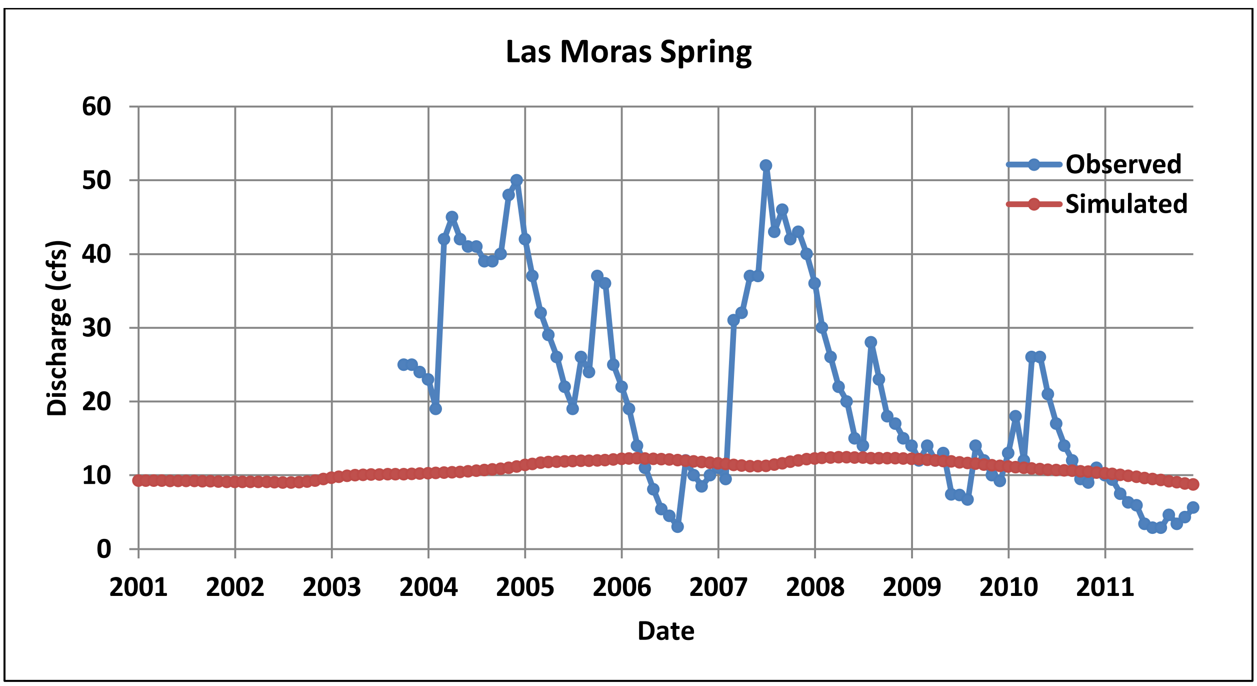


Figure 4.3.1-8. Observed (blue) and simulated (red) discharge at Las Moras Springs for the years 2001–2011.

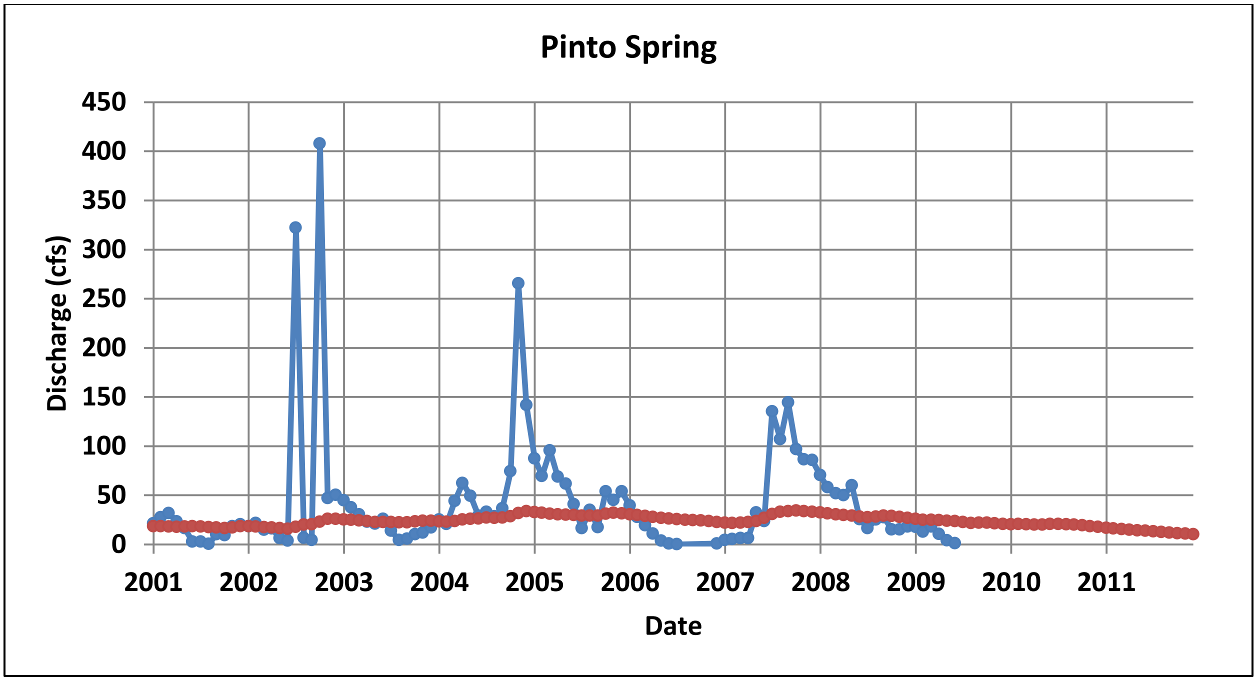


Figure 4.3.1-9. Observed (blue) and simulated (red) discharge at Pinto Springs for the years 2001–2011.

Model simulations of spring discharge are compared with measured discharge as an indicator of model performance. Simulated flow compared with measured flow is expressed in terms of mean error (ME), root-mean square error (RMS), and absolute error (Max Abs). The RMS error for cummulative discharge from all springs is 100 cfs. The RMS error means that, on average, the simulated cummulative discharge differs from observed cummulative discharge by about 100 cfs. The RMS error of discharge at Comal and San Marcos springs is 55.6 and 57.6 cfs, respectively. Spring performance statistics are summarized in Table 4.3.1-1.

Comal Springs and San Marcos Springs are the two largest spring complexes in Texas, not to mention the Edwards Aquifer. Correct representation of these two springs is central to the performance of any numerical model of the Edwards Aquifer. Simulated discharge is compared with observed discharge for Comal and San Marcos Springs in Figures 4.3.1-1 and 4.3.1-2. The mean error of -45 cfs between simulated and observed discharge at Comal Springs is considerably greater than the target goal of 3 cfs. The RMS error of 55.6 cfs, however, is close to the target value of 50 cfs. Lastly, the maximum absolute error of 111 cfs is well within the target goal of an absolute error of 150 cfs for two consecutive months (Table 4.3-1). Inspection of model performance of Comal Springs (Figure 4.3.1-1) illustrates that the model was better at matching low discharge than high discharge. The timing of simulated with observed lows was good with no apparent time lag between simulated and observed discharge. The greatest discrepancy between model results and observed discharge was during periods of significant recharge that occurred in 2007 and again in 2010. The model did not effectively simulate these large recharge events, although recharge events early in the calibration period and particularly in 2005 were effectively captured by the model.

Table 4.3.1-1. Discharge statistics for target springs.

	ME (cfs)	RMS (cfs)	Max Abs (cfs)	Average Simulated Flow (cfs)	Average Simulated Flow (acre-ft/yr)
Total	-11.8	100	278.1	819.6	594,000
Comal Springs	-45.9	55.6	111	287.7	208,418
San Marcos Springs	-32.2	57.6	203.9	162.4	117,674
Hueco Springs	-25.3	39.5	83.6	29.9	21,659
San Pedro Springs	-9.9	11.9	25.4	0	0
San Antonio Springs	-19.1	43	165.1	40.5	29,349
Leona Springs and Underflow	37.2	43.8	90.8	132.4	95,928
Nueces River	8.3	251.9	1,427.2	132.4	95,928
Las Moras Springs	9.6	9.6	10.4	10.8	7,825
Pinto Springs	-17	62.4	385.1	23.4	16,983

The model response at San Marcos Springs was similar to model performance at Comal Springs. Mean error was less at -32.2 cfs, but sill significantly greater than the target goal of 3 cfs. RMS was comparable with Comal Springs at 57.6 cfs (compared with a target goal of 35 cfs). The maximum absolute error for two consecutive months was 203.9 cfs, greater than the target goal of 150 cfs for two months. Simulated discharge was relatively effective in matching low discharge (Figure 4.3.1-2). There was no significant time lag between simulated and observed low discharge. The model under-predicted a period of high discharge in late 2007 by 200 cfs, which contributed to the high values for mean error and RMS. Additional periods of high discharge particularly during 2002, 2003, 2005 and 2010 were also under-predicted, however these discrepancies were no greater than 50-70 cfs.

The relatively stable simulated discharge at Hueco Springs was not reflective of the highly variable observed discharge (Figure 4.3.1-3). Simulated discharge only approximated two of the three periods when spring discharge was near zero. Observed peaks in discharge were not well approximated. Conceptualization of the model at Hueco Springs is not considered a sufficient representation of the hydraulics at this location.

Model simulated discharge for San Antonio Springs was similar to observed discharge (Figure 4.3.1-5). The model predicted more times when spring discharge is zero compared with observed discharge, but did not predict flow at any time when no discharge was observed. The model successfully simulated the correct time lag for the period of greatest discharge (2005), but exhibited a delay of 2-3 months when simulating the increase in discharge observed in 2003 and again in 2007. The model did not predict discharge at any time at San Pedro Springs during the calibration period (Figure 4.3.1-4). This limitation is not considered significant given that the maximum discharge at San Pedro Springs is only 25 cfs compared with an order-of-magnitude greater discharge at San Antonio Springs (i.e., 250 cfs). Stated differently, the simulated combined discharge from San Antonio and San Pedro springs was close to observed values of the combined discharge.

Simulated discharge via the springs on the Nueces River was compared with discharge measured by the U.S. Geological Survey at gauge 08192000 (Figure 4.3.1-6). The flow gauge at this location measures both discharge from the springs on the Nueces River (i.e., Soldiers Camp Springs and other unnamed springs) in addition to storm surge. The peaks in the observed flow are a reflection of the storm surge flow in the Nueces River. Simulated discharge from the springs during periods of baseflow in the Nueces River, however, are greater than what is measured at the river flow gauge.

Simulated discharge at Leona Springs and underflow is considerably different than the observed discharge (Figure 4.3.1-7). The principal reason for this discrepancy is that the conceptual model as described in the document (Sections 3.3.1.2 and 4.4.1.2), accommodates significantly more discharge via the Leona Formation gravel in the Leona River floodplain than reflected in U.S. Geological Survey measurements. The observed discharge values for the calibration period are relatively constant at about 100 cfs until a two-year period of low flow was observed starting in 2006 and then again when the current drought commenced in 2009. The total range in observed discharge values only varied by about 35 cfs during the calibration period. Conversely, the model simulates large variations in discharge from the Leona Springs and underflow, varying from a maximum of about 190 cfs which occurred in 2005 and again in 2007 to a low of about 55 cfs. The model simulation is believed to be closer to actual discharge from the combined surface-water and groundwater discharge that occurs via the Leona River floodplain.

The Kinney pool was essentially separated from the Uvalde Pool and the San Antonio segment of the Edwards Aquifer. As conceptualized here, recharge to the Kinney pool is less than previously conceptualized. The Kinney Pool has limited avenues for discharge, Las Moras Springs and underflow, Pinto Springs and underflow, and possibly inter-pool flow either to the west or east. Underflow via either Las Moras or Pinto Creeks or by way of inter-pool flow is believed minimal, thus discharge from Las Moras and Pinto Springs obviously must be comparable to recharge of Kinney Pool. The combined discharge of the two springs ranges from 25 to 35 cfs, which is consistent with long-term average discharge (Figures 4.3.1-8 and 4.3.1-9). Calibration of the internal hydraulics of Kinney Pool was not attempted in this model.

4.3.2 Well Hydraulic Head

A total of 118 wells in the model domain were identified as calibration targets. Calibration well locations are illustrated in Figure 4.3.2-1. Eleven wells were located in the area of the Barton Springs segment of the aquifer, which was essentially removed from the model. Several other wells originally selected as calibration targets were deselected or disqualified as targets during calibration. The principal reason was that water levels in the wells were determined to not be representative of the hydraulic head at their respective locations. This typically occurred in or near the Recharge Zone where the horizon in which the wells are completed may not be well known and the horizon that is monitored by the well may be perched. For example, wells 6935401, 6935602, and 6935804 are located in the Recharge Zone within the Frio River watershed basin. Hydraulic heads measured in these wells are 100–150 ft above the hydraulic heads expected in the Edwards Aquifer. In addition, the head values are intransigent over time. Both attributes support their reclassification as not being representative of the hydraulic state of the Edwards Aquifer.

There was also a well located in the Recharge Zone of the Blanco River watershed (well 6808701) and one in the Recharge Zone of the Medina River watershed (well 6932703) that were reclassified as not being representative of the hydraulic state of the Edwards Aquifer. Thus, 16 of the original 118 wells were eliminated from consideration, leaving a total of 102 wells qualified as calibration targets.

It was suggested that the simulated mean water level for each individual well should fall within the range of observed measurements for that well, and that the simulated amplitude for each well should be within ±50 percent of the observed amplitude. Of the 102 observation wells included in this study, 73 met the first requirement and 48 met the second requirement. Forty-nine observation wells had fewer than 33 data points out of 132 possible monthly data points during the calibration period. The calibration statistics for each observation well are presented in Table 4.3.2-2. Graphical comparison of simulated versus observed hydraulic head of the cumulative observations are presented in Figure 4.3.2-2. The 16 wells that were eliminated as calibration targets are not included in this graphic.

The root-mean squared (RMS) error for all wells included in calibration is 24.6 ft (Table 4.3-1). This RMS error is about 2 percent of the total hydraulic head drop across the modeled area, significantly within the 10 percent usually desired for model calibration. This RMS error did not include the Contributing Zone. The RMS error for well elevations in the Contributing Zone was 3.5 percent.

Three of the wells designated as calibration targets have elevated status as index wells. They are located in Uvalde (J-27), Medina (Hondo), and Bexar (J-17) Counties. Each well has a relatively long history as an index well and, accordingly, has a rich record of hydraulic-head measurements. Simulated hydraulic head at J-17 is compared with observed head in Figure 4.3.2-3. The mean error between the simulated and observed heads was 0.2 ft, which is less than the target goal (Table 4.3-1). The RMS of simulated heads is the same as the target goal of 7 ft. The maximum absolute error is 17.5 ft which is less than the target goal of 30 ft. There is a minor time lag between the simulated and observed heads of no more than 1-2 months, although there are periods with no observable time lag. The model accurately simulates two of the five most prominent periods of low head. The three periods that were not accurately simulated had predicted heads that were approximately 15, 10, and 7 ft higher than observed. Periods of high hydraulic head were relatively well simulated with two periods, one in 2008 and one in 2010, when the hydraulic head was under-predicated by about 10 ft.

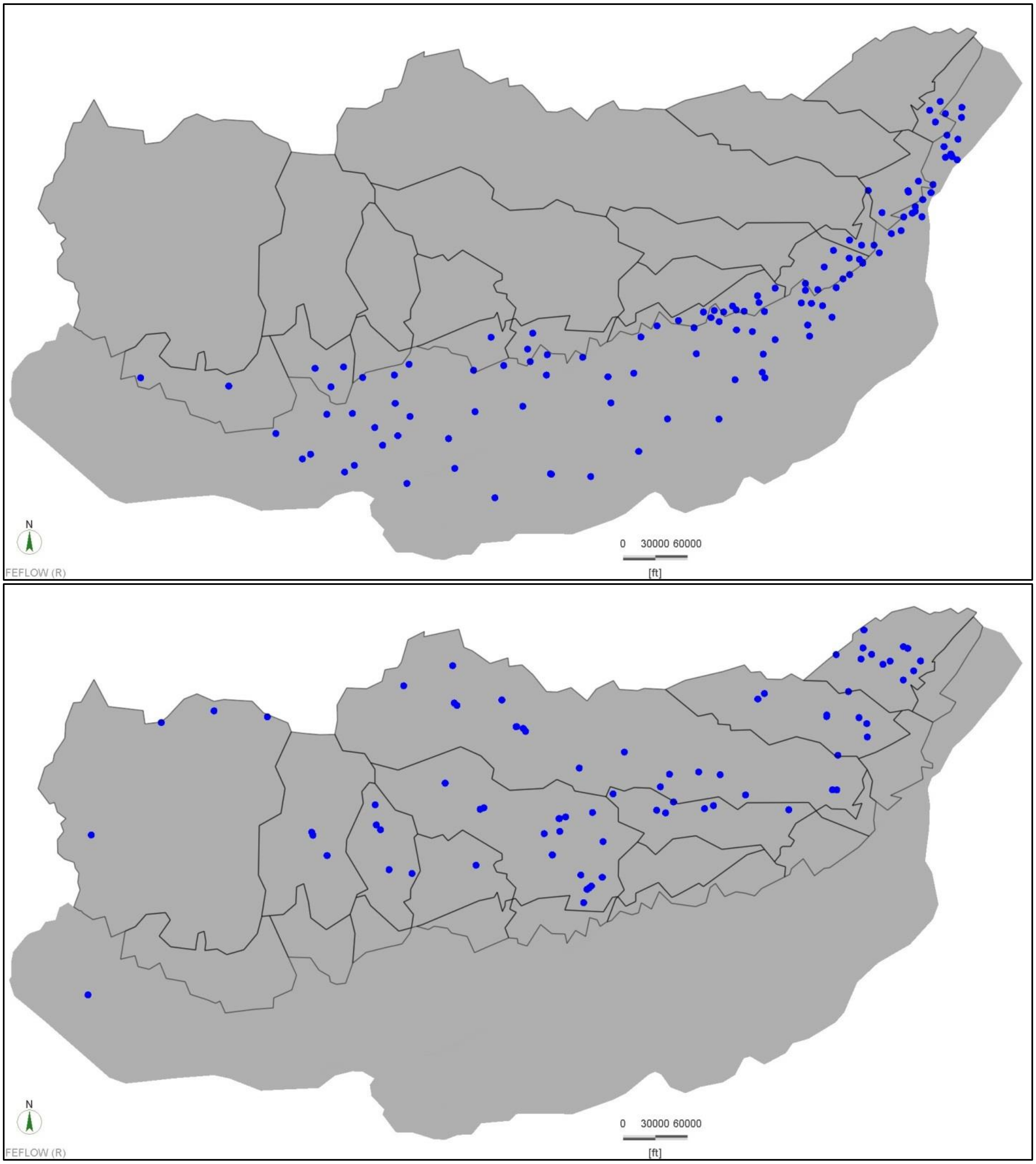


Figure 4.3.2-1. Locations of wells used in calibration. Top Figure. Location of wells designated as official calibration targets. Bottom Figure. Location of wells used to augment official calibration targets, for which close calibration was not attempted.

Table 4.3.2-1. Wells removed as calibration targets with justification

Well	Location	Reason for Elimination
O5849926	Barton Segment	Outside of calibrated model domain
O5857201	Barton Segment	Outside of calibrated model domain
O5857301	Barton Segment	Outside of calibrated model domain
O5857509	Barton Segment	Outside of calibrated model domain
O5857902	Barton Segment	Outside of calibrated model domain
O5857903	Barton Segment	Outside of calibrated model domain
O5858101	Barton Segment	Outside of calibrated model domain
O5858123	Barton Segment	Outside of calibrated model domain
O5858704	Barton Segment	Outside of calibrated model domain
O6701303	Barton Segment	Outside of calibrated model domain
O6701311	Barton Segment	Outside of calibrated model domain
O6808701	Blanco River Watershed	Perched
O6932703	Medina River Watershed	Perched
O6935401	Frio River Watershed	Perched
O6935602	Frio River Watershed	Perched
O6935804	Frio River Watershed	Perched

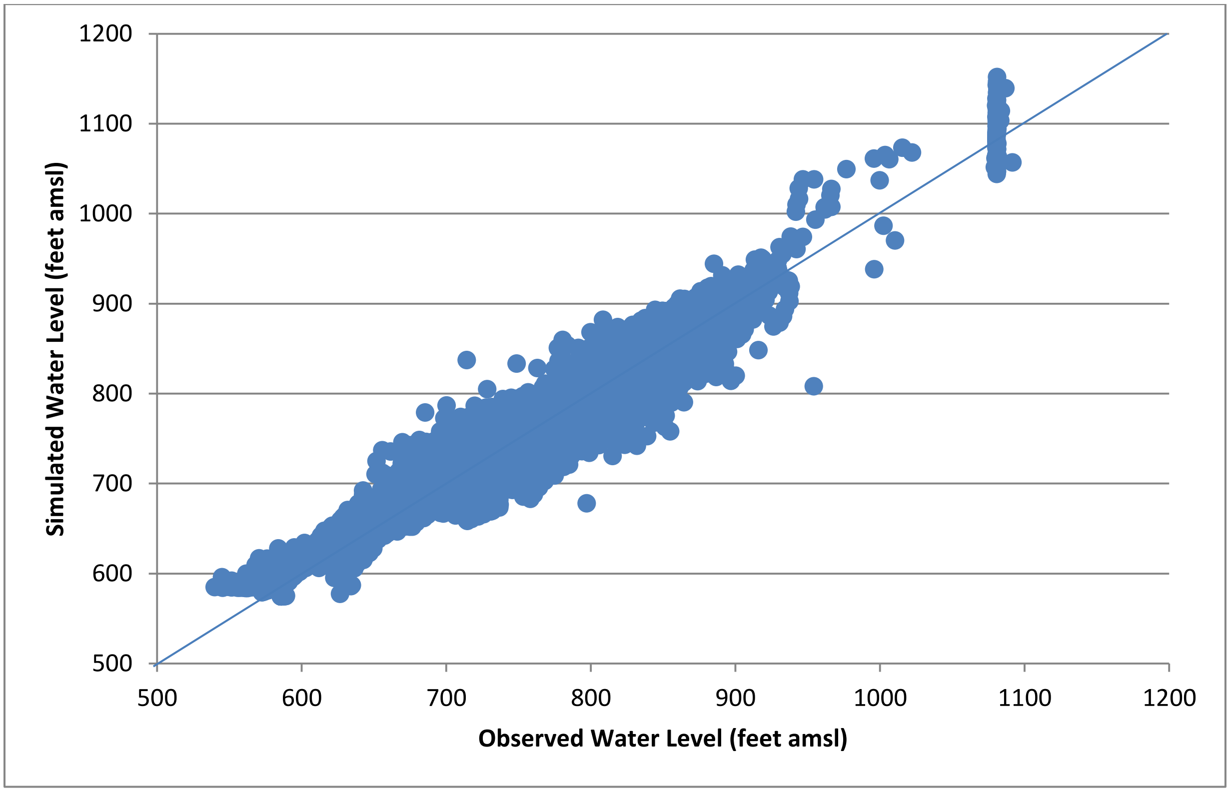


Figure 4.3.2-2. Simulated versus observed values of hydraulic head at 102 wells selected for calibration.

Table 4.3.2-2. Calibration statistics for individual wells. Italicized entries in bold are considered within the target goals.

Well	Mean Absolute Error (ft)	Root Mean Square Error (ft)	Maximum Absolute Error (ft)	Observed Range (ft msl)	Simulated Mean* (ft msl)	Observed Amplitude (ft)	Simulated Amplitude§ (ft)
O6837203 (J-17)	0.2	7.0	17.5	642.1-699.5	***675.0***	57.4	***59.0***
O6950302 (J-27)	3.6	8.2	15.8	849-886.8	***878.2***	37.7	25.9
O6947306 (Hondo)	29.6	31.8	56.5	669.8-773.5	***755.8***	103.7	***117.4***
O6701403	5.2	5.9	11.8	581.3-598.4	***594.7***	17.1	36.5
O6701809	7.7	8.0	13.6	572.7-584.9	***584.4***	12.2	***18.2***
O67018SMC	-12.2	12.3	14.1	585.6-589.2	574.9	3.6	1.6
O6702104	24.8	26.7	50.9	539.8-595.3	***593.3***	55.5	***33.4***
O6702106	18.9	20.4	40.6	551.6-592.1	593.1	40.5	***32.9***
O6708903	19.3	19.8	30.5	577.3-609.9	***607.0***	32.6	***48.2***
O6709101	18.4	18.6	27.1	576.2-593.3	600.9	17.1	32.3
O6709110	13.0	13.6	23.8	582.1-608.8	***602.2***	26.7	***31.0***
O6709113	23.8	24.2	43.7	576.8-589.5	604.5	12.6	32.4
O6709116	12.7	12.9	18.3	573.3-586.7	589.9	13.3	20.8
O6709401	5.8	6.0	10.0	588.4-595.6	597.1	7.3	***10.3***
O6808902	22.0	22.8	32.3	571.3-611	***608.1***	39.6	***50.1***
O6815809	59.6	61.4	80.8	651.8-702	728.1	50.2	86.3
O6815903	30.2	30.4	37.1	631.8-642.5	665.8	10.7	31.0
O6816202	16.6	19.2	34.6	661.9-672.5	701.2	10.6	111.4
O6816602	6.6	6.8	9.6	602.3-605.4	609.3	3.1	11.8
O6816603	26.8	27.3	40.6	577.1-595	608.5	17.9	34.0
O6816701	25.7	25.8	32.1	612.5-627.1	643.9	14.7	24.7
O6816801	4.8	7.1	14.0	603.9-647.2	***619.7***	43.3	***28.0***
O6821806	9.5	22.9	59.2	698.3-791.4	***744.9***	93.1	165.8
O6821903	11.3	18.6	42.3	691.6-763.4	***748.4***	71.8	174.2
O6822603	-17.8	47.6	119.3	669.7-797.2	***680.7***	127.5	***97.6***
O6822808	14.8	17.0	38.5	644.6-680	691.1	35.4	113.3
O6822810	7.7	16.9	35.6	661.2-715.3	***690.6***	54.1	111.3
O6822913	-55.3	56.0	63.6	714.2-753.2	673.7	39.0	85.0
O6823104	58.5	61.1	86.5	692.1-728.5	751.4	36.3	141.4
O6823302	7.9	14.9	38.4	622.7-632	634.9	9.4	75.2
O6823304	-11.5	17.4	49.4	626.7-652	***627.7***	25.3	86.7
O6823316	18.1	19.9	44.6	623.2-642.6	650.2	19.3	60.8
O6823317	6.9	10.1	21.4	637.4-641	666.6	3.6	77.5
O6823502	6.4	7.5	15.6	634.1-659.4	***650.1***	25.3	49.3

Well	Mean Absolute Error (ft)	Root Mean Square Error (ft)	Maximum Absolute Error (ft)	Observed Range (ft msl)	Simulated Mean* (ft msl)	Observed Amplitude (ft)	Simulated Amplitude§ (ft)
O6823504	10.6	11.2	17.1	638.9-660.4	***656.2***	21.5	57.9
O6823701	-7.5	9.3	26.7	615.7-673.1	***645.7***	57.4	***31.9***
O6824105	-4.7	5.0	8.5	625.5-636.3	624.1	10.8	***9.0***
O6826814	-13.0	27.8	65.8	721.5-855.8	***766.3***	134.3	***121.8***
O6827401	-8.1	48.3	146.1	739.8-954.3	***808.5***	214.5	***165.3***
O6827503	-23.7	29.6	83.0	723.3-900.3	***755.8***	177.0	***153.0***
O6827610	-13.8	18.9	35.8	700.4-807.1	***732.7***	106.7	***132.3***
O6828113	-35.4	41.7	65.0	743.7-853.8	***761.3***	110.1	***164.3***
O6828202	-25.8	33.3	54.8	722.8-799.8	***732.3***	77.0	152.4
O6828210	-51.8	55.5	97.2	753-854.9	745.7	102.0	158.8
O6828314	-16.0	26.3	53.5	706.6-778.7	***717.5***	72.1	144.2
O6828315	-5.7	24.7	90.0	717.1-831.9	***735.5***	114.8	***158.5***
O6828407	-23.1	31.8	54.9	736.8-814.5	736.8	77.7	145.4
O6828515	-10.3	18.5	41.1	698-753.2	***711.7***	55.1	131.5
O6828920	3.9	11.2	25.9	655.1-729.9	***689.9***	74.8	***96.7***
O6829103	2.0	17.1	54.4	678.3-750	***714.5***	71.7	131.3
O6829214	-1.5	13.7	30.1	667.8-734.2	***699.1***	66.4	109.4
O6829216	-12.0	20.7	35.7	700.1-784.2	***727.4***	84.1	145.0
O6829701	-1.2	8.8	22.7	640.2-706	***674.9***	65.8	***64.3***
O6829925	-3.0	8.3	20.9	640.3-700.1	***669.5***	59.9	***57.8***
O6830208	24.8	26.4	59.9	637.1-695.9	***690.7***	58.8	103.9
O6830314	-7.3	8.6	19.0	638.2-682.8	***653.7***	44.7	***40.3***
O6830315	-5.6	7.3	15.4	642.1-685	***656.6***	42.8	***43.8***
O6830510	-5.5	7.0	12.0	659-693.3	***660.8***	34.3	***47.9***
O6830807	-9.5	12.1	28.8	641.9-698.3	***662.2***	56.4	***48.9***
O6831403	-13.9	15.1	24.5	640.2-687.3	***653.6***	47.2	***39.7***
O6833102	-58.7	60.1	86.6	839.1-871.9	783.4	32.8	102.1
O6833604	23.0	25.9	49.2	671.8-757.1	***734.2***	85.3	***98.3***
O6834506	21.2	25.0	38.2	655.3-744	***723.7***	88.7	***94.8***
O6835315	18.7	18.9	23.5	647.3-677.4	698.7	30.0	88.3
O6836901	10.5	13.6	22.5	656.1-700	***688.8***	43.9	71.0
O6837522	9.1	12.0	26.6	642-700.8	***680.4***	58.8	***63.4***
O6837526	3.9	9.1	22.4	650.1-704.5	***679.3***	54.4	***62.4***
O6841301	21.1	25.6	59.8	662.5-742.7	***726.4***	80.1	***97.9***
O6843402	25.4	27.1	43.8	650.5-714.3	***712.9***	63.8	***89.5***
O6843607	23.2	24.5	32.5	657.4-696.6	700.3	39.3	79.9
O6849813	41.2	42.3	54.6	677.2-731.6	737.5	54.5	106.0
O6850201	47.2	48.7	66.8	642.5-706	722.5	63.5	95.6

Well	Mean Absolute Error (ft)	Root Mean Square Error (ft)	Maximum Absolute Error (ft)	Observed Range (ft msl)	Simulated Mean* (ft msl)	Observed Amplitude (ft)	Simulated Amplitude§ (ft)
O6931708	38.6	50.7	91.2	923.5-1022.2	***973.9***	98.8	236.4
O6936402	19.8	24.9	68.4	728-866.4	***823.6***	138.4	***170.2***
O6936601	12.2	24.7	73.4	746.2-889.9	***822.3***	143.8	***170.3***
O6937402	-10.5	20.8	41.5	765.7-899	***825.3***	133.3	***169.8***
O6938601	-21.8	28.7	74.1	856.1-938.3	***856.6***	82.3	167.9
O6939504	-20.9	31.6	59.1	835.3-996.1	***872.5***	160.8	***167.9***
O6940101	7.2	21.5	40.2	865.4-918.9	***893.4***	53.5	143.0
O6940102	4.6	24.7	43.4	823.2-884.3	***861.2***	61.1	135.3
O6940209	-24.9	30.2	51.3	840.6-883.9	***848.7***	43.3	123.4
O6940510	27.8	29.0	51.0	711.2-792.4	794.7	81.2	123.2
O6942709	-4.2	11.7	29.1	866.6-908.7	***892.3***	42.1	77.0
O6943409	-30.3	33.4	65.7	831.8-900.9	***844.3***	69.1	***82.2***
O6943607	18.4	23.4	51.9	727.2-859.9	***814.7***	132.7	***164.6***
O6944301	24.5	30.2	79.2	733.5-838.9	***804.4***	105.5	***157.5***
O6944804	15.0	20.9	37.9	735.9-849	***803.4***	113.0	***156.7***
O6944902	22.4	26.7	44.3	728.8-832.7	***794.4***	103.9	***149.1***
O6945401	22.6	26.7	46.7	745.7-837.4	***796.8***	91.6	150.8
O6946601	12.0	16.8	36.3	720.6-821.9	***778.3***	101.3	***133.2***
O6946702-B	13.5	18.7	31.8	716.1-822.9	***779.8***	106.8	***136.8***
O6950324	6.2	12.5	25.4	848.7-889.8	***879.0***	41.1	74.1
O6951602	-1.6	15.7	37.1	814.7-846.4	***832.2***	31.7	48.7
O6951606	25.3	35.2	123.0	685.4-833.3	***796.8***	147.9	***151.1***
O6952202	29.7	32.0	45.6	727.8-831.2	***795.8***	103.4	***150.2***
O6953701	8.4	18.1	24.6	775.7-823.9	***780.4***	48.3	137.5
O6954401	4.4	10.4	23.3	743.6-779.9	***772.2***	36.3	131.1
O6956507	9.6	15.3	27.7	720.6-781.9	***747.4***	61.4	112.9
O6956508	16.3	19.9	31.5	704.5-782.9	***747.6***	78.5	***113.0***
O6963103	16.5	19.6	35.6	702.7-788.1	***761.3***	85.4	***123.0***
O7038902	37.0	43.9	89.1	1186.9-1206.3	1232.7	19.4	126.4
O7040901	7.0	29.0	70.5	1079.5-1091.8	1078.3	12.3	151.6

* Target goal for individual wells – The mean simulated value for each well should fall within the observed range for that well.
§Target goal for individual wells – The simulated amplitude should be within ±50% of the observed amplitude.

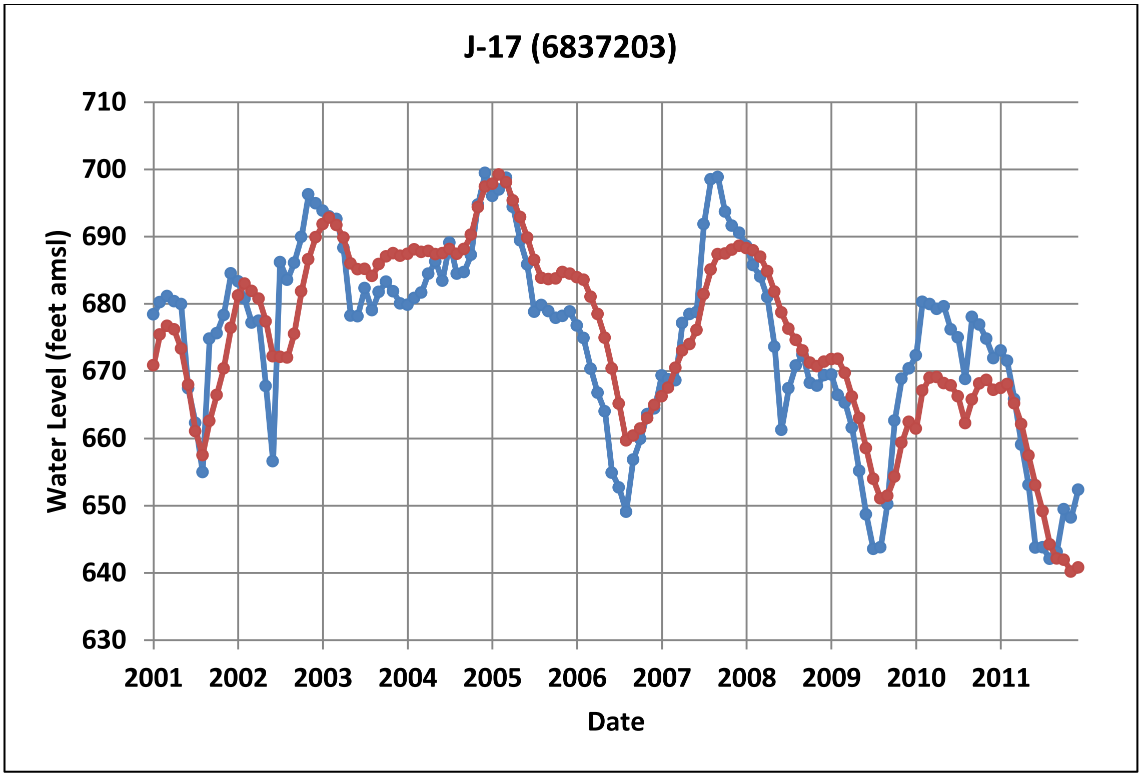


Figure 4.3.2-3. Observed (blue) and simulated (red) water elevations at J-17 for the years 2001–2011.

The correlation between San Antonio pool index well J-17 and discharge at Comal Springs is high (r = 0.978) (Kresic and Stevanovic, 2010). This high correlation is interpreted as a strong indication of high degree of hydraulic communication in the Confined Zone of the San Antonio pool from Bexar County to Comal Springs. The correlation between the simulated head at J-17 and discharge at Comal Springs was similarly high (r = 0.973) as graphically illustrated in Figure 4.3.2-4. This strong correlation between the simulated head at J-17 and simulated discharge at Comal Springs suggests that the hydraulics of the Confined Zone in this portion of the model are adequately captured by the model.

Simulated heads at index well J-27 accurately reproduce the impacts of pumping and variation in recharge (Figure 4.3.2-5). The model accurately simulates the amplitude of the observed head changes at J-27. The mean error (3.6 ft) is approximately twice the target goal of 1.3 ft. The maximum absolute error (15.8 ft) is less than the target goal (20 ft). The RMS error (8.2 ft) is marginally greater than the target goal (5 ft).

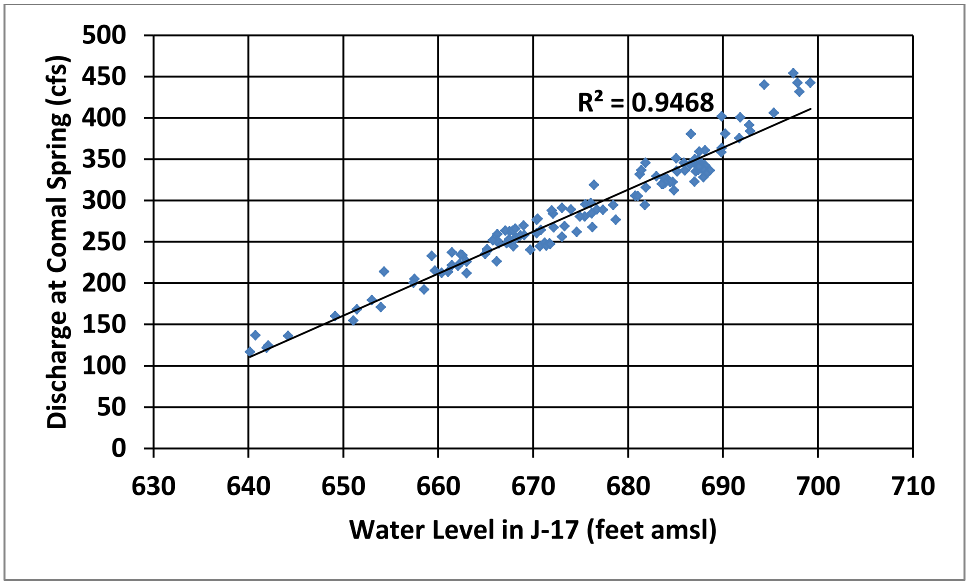


Figure 4.3.2-4. Correlation between the simulated head at San Antonio pool index well, J-17, and simulated discharge at Comal Springs.

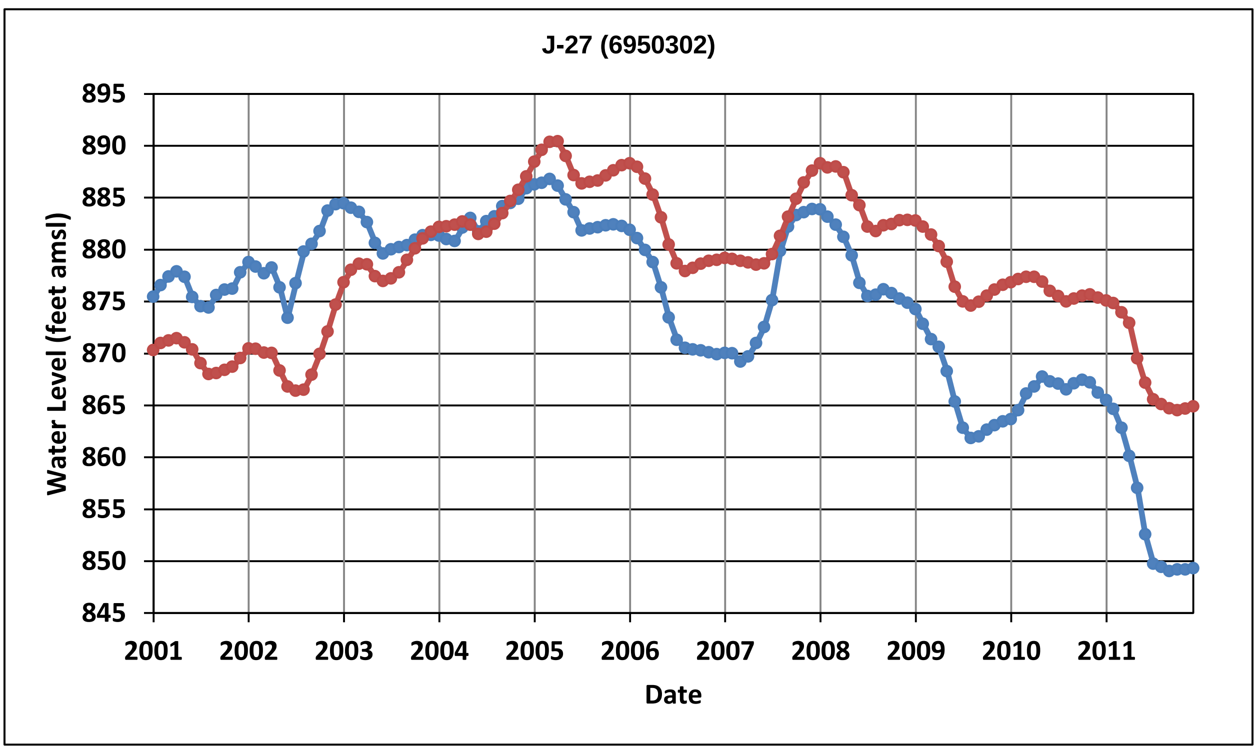


Figure 4.3.2-5. Observed (blue) and simulated (red) water elevations at J-27 for the years 2001–2011, 06950302.

The difference between the observed initial conditions and the simulated initial conditions increases the error between the simulated heads and the observed heads. As currently represented, the modeled Uvalde Pool does capture the long-term average discharge from the

Uvalde to the San Antonio Pool if the average head of the Uvalde Pool is a valid measure of how much water is contributed to the San Antonio Pool by the Uvalde Pool.

As discussed in Sections 2.4.2.3 and 2.4.2.4, the hydraulics of the Uvalde Pool, with three principal avenues for natural discharge, has a modulating effect on hydraulic head in the Uvalde Pool. The dynamic hydraulic relationship among the primary (and sole) source of recharge (i.e., surface flow and underflow from the Nueces River) and the three avenues of discharge as it is currently represented in the model requires further modification to replicate this modulated hydraulic response. The likely source of the discrepancy is either: (i) the recharge model (in terms of both the spatial extent and the precipitation/recharge correlation) of the West Nueces /Nueces River Basins; (ii) the manner in which the Knippa Gap is represented in the numerical model; or (iii) a combination of both. This ambiguity is not easily resolved because of the degree of freedom that was added to the conceptual and numerical models by the inclusion of the Contributing Zone recharge model.

4.3.3 Comparison of Results From the Alternative Model With the 2004 MODFLOW Model

EAA staff has continued to refine the existing Edwards Aquifer groundwater availability model, referred to as the 2004 MODFLOW model. Simulation results from the alternative model are compared with results from the 2004 MODFLOW that was run to simulate the Edwards Aquifer for the same calibration period, 2001–2011 with the same pumping data. The 2004 MODFLOW simulation used in this comparison is referred to as “run 7-2”. As discussed in detail in this report, the fundamental difference between the two models is the method used to input recharge into the model domain. Because of this fundamental difference in conceptualization, values of recharge in the alternative model are not directly comparable with recharge in the 2004 MODFLOW model.

Comparison of the statistics from the two models is summarized in Table 4.3-1. In general, the statistical performance of the alternative model was comparable with the 2004 MODFLOW model in terms of index well J-27, marginally better at J-17, not as good at Comal Springs, comparable at San Marcos Springs, but better overall in terms of statistics for all wells.

4.4 Water Budget

The water budget of each subdomain in the model simulated using the alternative model is compared with the conceptual models described in Chapter 2, calculations by the U.S. Geological Survey using river-gauge measurements, and values based on the HSPF model. Values for each are summarized in Table 4.4-1. The conceptual model values are not wholly independent from the U.S. Geological Survey calculations because the U.S. Geological Survey calculations were used, to some degree, in some of the conceptual-model assessments. The conceptual model, U.S. Geological Survey, and HSPF values are discussed with the values generated with the new alternative model in the following sections.

Simulated values of recharge by basin are graphically presented in terms of annual totals in Figure 4.4-1 and in terms of monthly totals in Figure 4.4-2. As illustrated, recharge values vary widely. This is a reflection of the recharge model which is based on monthly NEXRAD measurements which vary significantly both spatially and temporally. The significant differences between the mean and median values for most basins provide a quantitative assessment of the wide range in precipitation rates and frequency. This is consistent with extreme precipitation and flood patterns experienced in the Balcones Fault Zone (Asquith and Slade, 1995, 1997; Slade 1986).

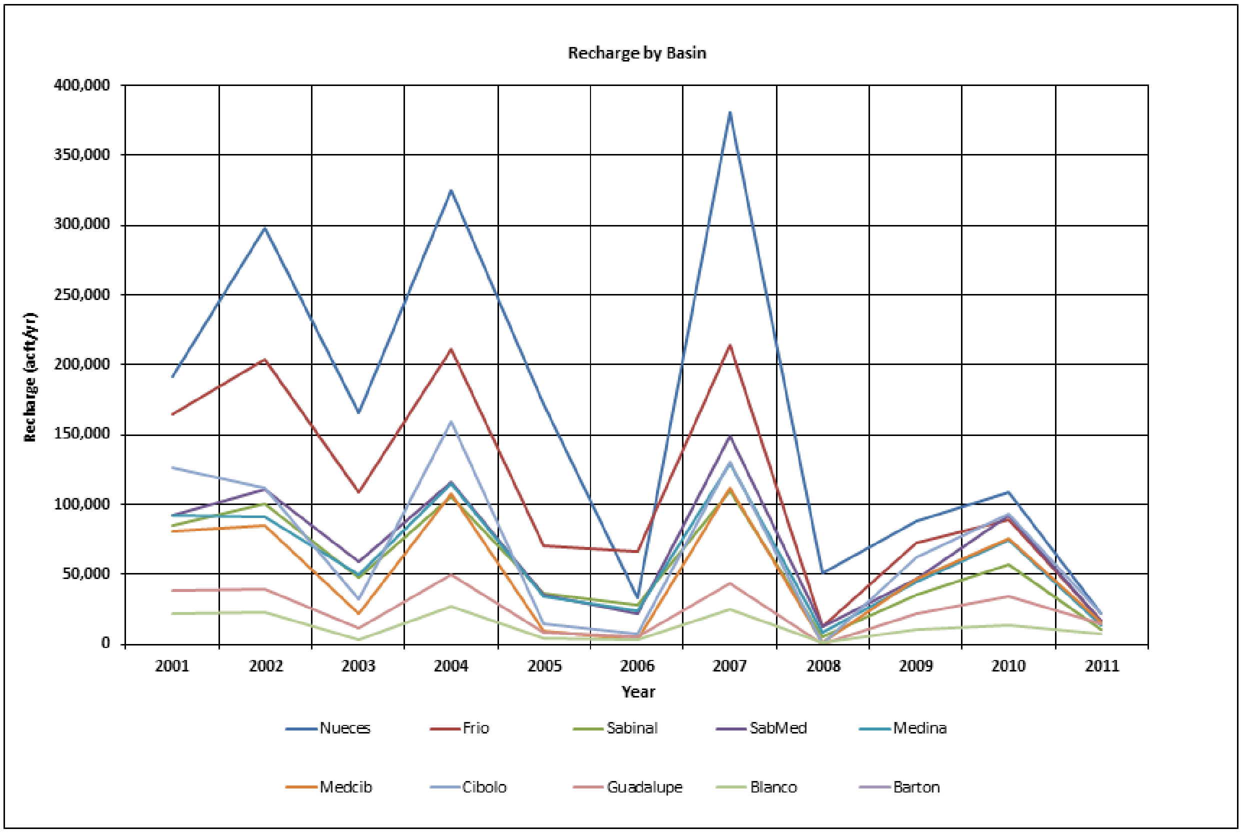


Figure 4.4-1. Simulated recharge by basin for the period 2001-2011. Recharge data are annual totals per basin.

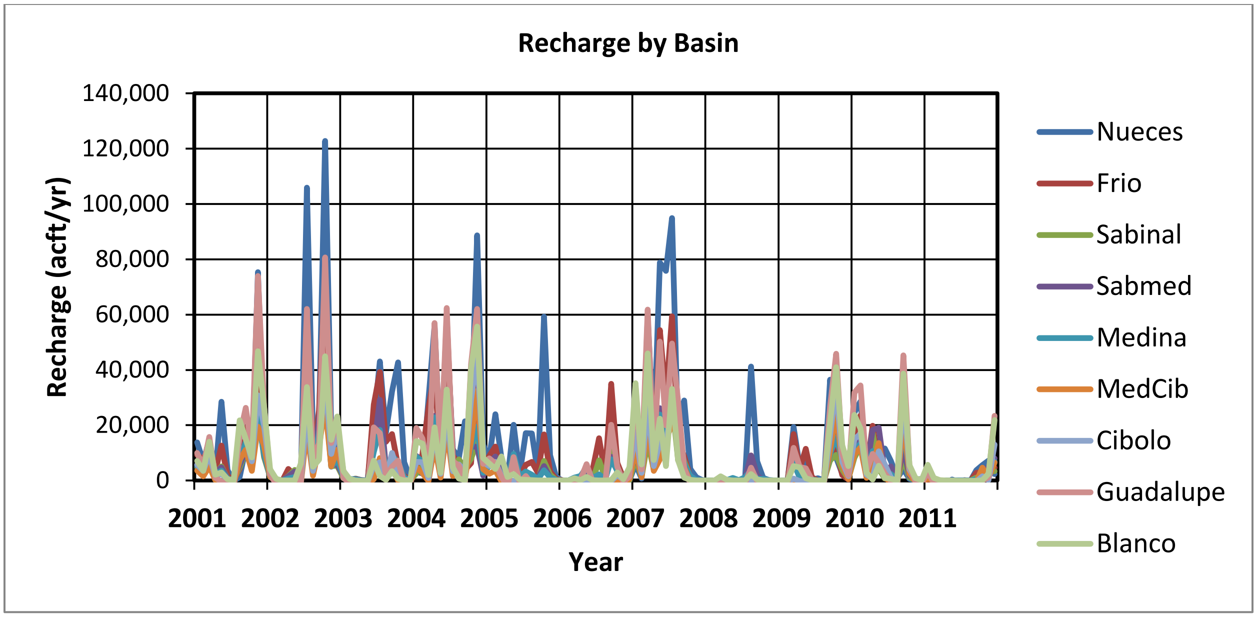


Figure 4.4-2. Simulated recharge by basin for the period 2001-2011. Plotted data are monthly totals per basin.

Table 4.4-1. Comparison of basin recharge values determined based on the conceptual model described in Chapters 2 and 3, measurements by the U.S. Geological Survey, HSPF model calculations, and simulations using the alternative model (FEFLOW). Values are expressed in 1,000 acre-ft/yr.

	Conceptual Model	USGS*		HSPF§	FEFLOW	
Basin		**Mean**	**Median**	**Mean**	**Mean**	**Median**
Kinney pool	>23.0	172.1	105.5	171.8	166.8	52.7
Nueces River	50.0-329.3					
Dry Frio River/Frio River	165.4	158.7	112.2	164.1	111.7	41.1
Sabinal River		44.3	31.7	34.4	56.3	20.8
Sabinal-Medina Interbasin	-	143.9	79.1	103.5	68.2	24.6
Medina River	173.9	71.1	75.2	75.7	61.5	25.2
Medina-Cibolo Interbasin	-	87.8	81.4	78.7	50.9	9.7
Cibolo Creek	37.8	155.6	140.4	98.5	69.0	11.6
Guadalupe River	36.0	0.0	0.0	10.6	137.6	43.8
Blanco River	10.9	72.4	59.9	80.7	85.6	13.4
Total	-	905.9	764.0	818.0	807.6	242.9

*Tremallo et al., 2014, includes years 2001–2011; §Clear Creek Solutions, Inc., 2012, 2013, Scenario 1 with the exception of Guadalupe River Basin which is from Scenario 2.

4.4.1 Western Hydrogeology

4.4.1.1 Kinney Pool Water Budget

The refined conceptual model of the Kinney Pool is that recharge of the Kinney Pool is less than historical estimates (Sections 2.4.2.1 and 2.4.2.2). This assessment is contingent on the conceptualization that the Kinney Pool has minimal hydraulic communication with the Uvalde Pool. If the concept of the Kinney Pool is valid, then discharge from the two embayments of the Pool (Grass Valley and Pinto Valley embayments) is limited to outflow as surface water and groundwater via Las Moras and Pinto Creek channels. Interformational flow from the Kinney Pool to either the groundwater basin to the west that includes Mud Springs or the groundwater basin to the east, the Uvalde Pool, is conceptualized to be minimal.

Unfortunately, limited groundwater-elevation data or water-chemistry analyses are available to delineate the upstream boundary of the Kinney Pool. In the absence of this constraining information, the location of the upstream boundary in the numerical model was arbitrarily specified so that hydraulic heads within the Kinney Pool and discharge from Las Moras and Pinto Springs were reasonable and that interformational flow west or east out of the Kinney Pool is minimal. The upstream boundary of the Kinney Pool may be shown to more of a north-south orientation, than the east-west orientation as its currently conceptualized. If valid, then the boundary between the West Nueces and Nueces River groundwater basins may have the same orientation as the watershed boundary, but the groundwater basin boundary would be located significantly west of the watershed boundary.

The simulated water budget for the Kinney Pool is illustrated in Figure 4.4.1.1-1.

Recharge is indicated by the blue line. Discharge by pumping and via Pinto and Las Moras Springs is in pink. Discharge from Las Moras and Pinto Springs in Kinney Pool was simulated at 24,800 acre-ft/yr. This value is close to the long-term average discharge of 23,000 acre-ft/yr. Total outflow is in dark red. The remaining discharge which ranges from about 3,000–6,000 acre-ft/yr, is leakage out the Kinney Pool. Because the internal hydraulics of the Kinney pool operates separately from that part of the Edwards Aquifer that flows to the major springs in the east of the model (i.e., Comal and San Marcos springs), matching spring hydrographs in the Kinney Pool (Figures 4.3.1-1 and 4.3.1-2) was considered to be of secondary importance when comparing model predictions to observations.

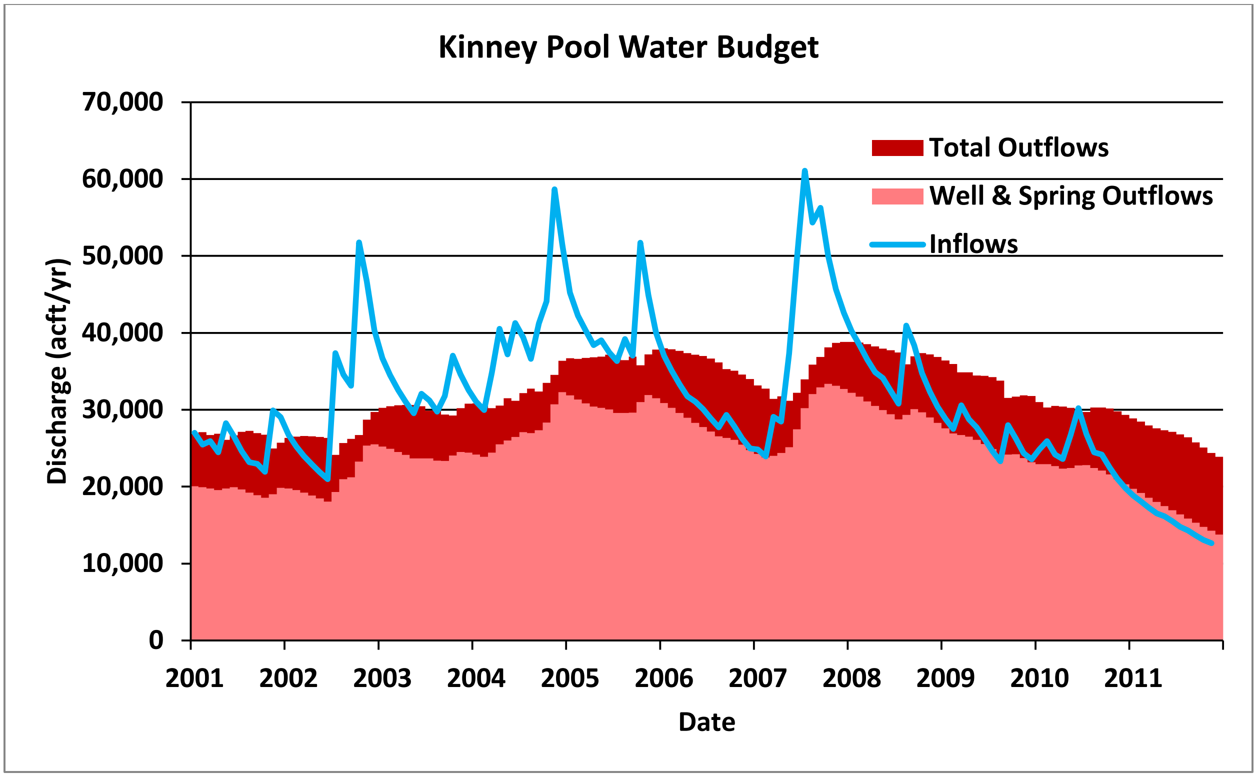


Figure 4.4.1.1-1. Water budget of the Kinney Pool. Recharge is indicated by the blue line. Discharge by pumping and via Pinto and Las Moras Springs is in pink. Total outflow is in dark red.

4.4.1.2 Uvalde Pool Water Budget

The area that recharges the Uvalde Pool was constrained by several fundamental precepts in the conceptual model (Sections 2.4.2.3 and 2.4.2.4). (i) The recharge zone to the Kinney Pool was removed from the Uvalde Pool recharge zone; (ii) The Dry Frio River groundwater basin discharges into the Knippa Gap, which in turn discharges to the San Antonio Pool, and not into the Uvalde Pool; (iii) The Frio River groundwater basin discharges directly to the San Antonio Pool; ;and. (iv) Discharge from the Uvalde Pool to the Nueces River via Soldiers Camp Springs and other un-named springs on the Nueces River and to the Leona Springs and Leona Gravel in the Leona River channel is conceptually sound although specific discharge values are variable and highly dependent on stage.

The minimum flow rate through the Knippa Gap is estimated to be 50,000 acre-ft/yr. It last occurred during the drought of record in the 1950s during which the minimum groundwater elevation at J-27 (i.e., 811 ft, msl) was recorded (Sections 2.4.2.3 and 2.4.2.4). This minimum flow estimate is predicated on the conceptualization that recharge to the Uvalde pool is solely from the Nueces River channel and that it averaged 34,080 acre-ft/yr as surface water and 4,620 acre-ft/yr as groundwater. This estimate of discharge via the Knippa Gap reflects the observation that no water was discharged through the springs on the Nueces River and that a minimum of 18,700 acre-ft/yr was discharged via the Leona Formation in the Leona River floodplain. The last component to the water budget was the 38,400 acre-ft/yr that was lost from Uvalde Pool storage during this period.

Discharge via Knippa Gap is estimated for high stage in the Uvalde Pool which defined to be when J-27 is at least 880 ft, msl. The maximum recharge to the Uvalde Pool was measured by the U.S. Geological Survey at 481,900 acre-ft/yr in 2004. Again, this measurement did not include recharge as groundwater. Discharge from the Uvalde Pool via the springs on the Nueces River is accounted for in the U.S. Geological Survey Nueces River recharge calculations. Discharge via the Leona River channel during high stage is calculated to be as high as 81,500 acre-ft/yr (Green et al., 2008a). Pumping in Uvalde County during 2004 was 91,300 acre-ft (Tremallo et al., 2014), of which 51,100 acre-ft was in the Uvalde Pool. This calculation indicates that 329,300 acre-ft (plus whatever amount was recharged via the Nueces River as groundwater), was discharged from the Uvalde Pool via the Knippa Gap in 2004.

Values for simulated recharge of and discharge from the Uvalde Pool are illustrated in Figure 4.4.1.2-1. The blue line is simulated recharge. Light red is the simulated discharge by Nueces River springs, the Leona Springs and underflow, and pumping. Total discharge is indicated by dark red. The additional discharge is via the Knippa Gap. As illustrated, discharge via the Knippa Gap remains relatively constant and ranges from 40,000–60,000 acre-ft/yr. This constancy in discharge via the Knippa Gap is consistent with the analysis in Sections 2.4.2.3 and 2.4.2.4 in which a 50-ft increase in the water level of the 2½-mile wide Knippa Gap would not be capable of accommodating increase flow of 280,000 acre-ft/yr during high stage. This suggests that Nueces River springs and the paleo-stream channel in the Leona River channel must be capable of higher rates of discharge than previously thought or that the manner in which Knippa Gap is incorporated in the alternative model needs to be refined to allow greater passage of water during high stage.

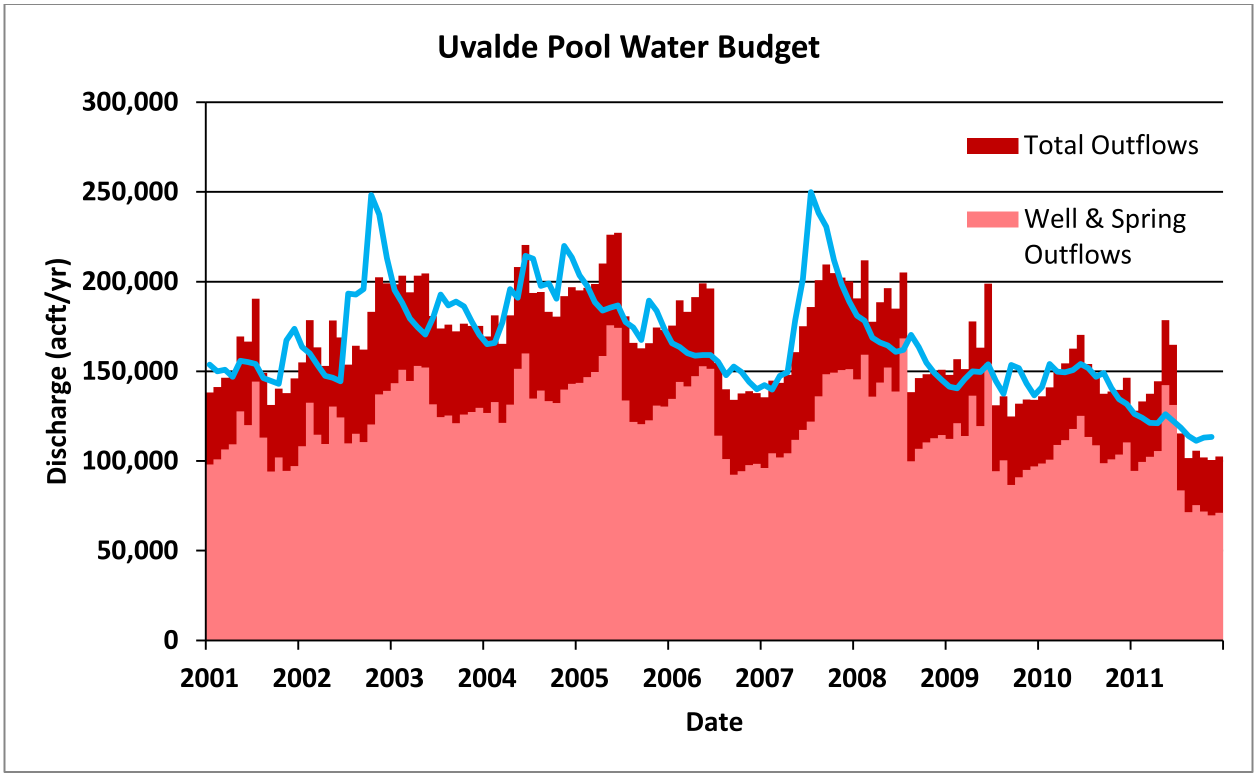


Figure 4.4.1.2-1. Water budget of the Uvalde Pool. The blue line is simulated recharge of the Uvalde Pool from the surface flow and underflow from the Nueces River. Light red is simulated discharge from the Uvalde Pool by Nueces River springs, the Leona Springs and underflow, and pumping. Dark red is discharge from the Uvalde Pool via the Knippa Gap.

4.4.2 Central Hydrogeology

4.4.2.1 Western San Antonio Pool

The western San Antonio Ppool is recharged by the Dry Frio, Frio, and Sabinal River watersheds. To the east of the Sabinal River watershed and west of the Medina River watershed, water that is conveyed as either surface water or groundwater south out of the model domain was discharged from the Austin Chalk and other shallow formations that are not in hydraulic connection with the Edwards Aquifer. The conceptual model of this portion of the model domain is described in Section 2.4.3.1. Based on this conceptualization, there is minimal recharge to the Edwards Aquifer in the western San Antonio Pool to the east of Sabinal River watershed, with the exception of minor recharge that may occur near the headwaters of the interbasin area between the Dry Frio/Frio /Sabinal River watershed on the west and the Medina River watershed on the east. The numerical model is consistent with this conceptualization.

The HSPF calculation for recharge for the Dry Frio /Frio /Sabinal River watershed is 198,436 acre-ft/yr (Table 4.4-1). The U.S. Geological Survey calculated the median and mean recharge for the Dry Frio River/Frio River/Sabinal River watershed for the period 2001–2011 to be 143,900 acre-ft/yr and 203,100 acre-ft/yr, respectively. A mean recharge of 143,900 acre-ft equates to 2.91 inch/yr of recharge when averaged over the 594,176 acres in the Contributing and Recharge Zones of the Dry Frio/Frio/Sabinal River watersheds. This recharge value is somewhat less than the 3.34 inch/yr recharge estimate for the Frio River Basin derived using baseflow separation. Given that the U.S. Geological Survey calculation does not account for recharge that occurs in the Contributing Zone upstream of the river gauges, values of recharge for the Dry Frio/Frio/Sabinal River watersheds in excess of the U.S. Geological Survey calculations appear to be justified. If 3.34 inch/yr of recharge is representative of average recharge over the Dry Frio/Frio/Sabinal River watersheds, then the average recharge by these watersheds would be 165,400 acre-ft/yr. Mean recharge for the Dry Frio/Frio/Sabinal River watersheds simulated by the alternative model was 168,000 acre-ft/yr. The conceptual model, HSPF, U.S. Geological Survey, and alternative model simulation values for recharge of the western San Antonio Pool are approximately consistent and similar.

4.4.2.2 Medina River Watershed Water Budget

Like the other major watersheds in the model domain, the Medina River Basin is an internally contained watershed with little or no hydraulic communication with the adjoining groundwater basins. The conceptual model of the Medina River Basin described in Sections 2.4.3.2 and 2.4.3.3 explains how significant water that is recharged to the basin is discharged as both surface flow and underflow to the Medina River channel and does not recharge the Edwards Aquifer.

The average annual discharge in Medina River at Bandera is representative for Medina River flow upgradient from the hydrologic effect of the dam at Medina River. The baseflow fraction of flow in the headwaters of the Medina River indicates that 4.60 inch/year is attributed to recharge (Green and Bertetti, 2010a). 453,696 acres of the Medina River watershed are in the Contributing and Recharge zones of the Edwards Aquifer. This suggests that 173,900 acre-ft/yr is recharged in the Medina River watershed. Discharge via the Medina River paleo-stream channel is significant which indicates that the net recharge in the watershed is considerably less, probably closer to 100,000 acre-ft/yr. The conceptual model was valuable in recognizing that the water budget of the Medina and Diversion Lakes needed to account for discharge via the Medina River paleo-stream channel, however, the conceptual model does not constrain how much is recharged to the Edwards Aquifer by the Medina River watershed.

The alternative model simulated that recharge from the Medina River watershed had a mean of 61,500 acre-ft/yr. This value is slightly less, but consistent with the 71,000 acre-ft/yr calculated by the U.S Geological Survey, and the 75,677 acre-ft/yr modeled using HSPF (Table 4.4-1).

4.4.3 Eastern Hydrogeology

4.4.3.1 Interbasin Area Between Medina River and Cibolo Creek Basins

The Upper Glen Rose in the interbasin area between Medina River and Cibolo Creek Basins is observed to be relatively highly permeable. This high permeability in the creek beds in the Contributing Zones explains why baseflow in San Geronimo, Helotes, and Leon Creeks does not reach the Recharge Zone. Consequently, river flow measurements at gauges located at the Contributing and Recharge Zone boundaries are not reflective of recharge that occurs upstream of the gauges. Conversely, the interbasin area between Medina River and Cibolo Creek Basins does not extend far into the Contributing Zone (Figure 2.1-3). Much of the flow in San Pedro

Creek and San Antonio River where they exit the model domain is due to distributed recharge that is accumulated downstream of the Recharge Zone.

The alternative model simulated that recharge in the interbasin area between Medina River and Cibolo Creek Basins has a mean of 50,900 acre-ft/yr which is less than the 87,800 acre-ft/yr calculated mean by the U.S Geological Survey and the 78,740 acre-ft/yr modeled using HSPF (Table 4.4-1). The lower recharge value simulated by the alternative model is in line with the conceptual model that recognizes the limited size of the Contributing and Recharge Zones located within the San Antonio River watershed.

4.4.3.2 Cibolo Creek Watershed Water Budget

Calculated values for recharge from Cibolo Creek watershed vary considerably. The conceptual model of the Cibolo Creek groundwater basin described in Sections 2.4.4.2 and 2.4.4.3 explains how essentially all of the water recharged to the basin is recharged to the Edwards Aquifer. The conceptual model of the Cibolo Creek watershed is that most water recharged to the Cibolo Creek Basin is recharged in the Contributing Zone of the Edwards Aquifer, well before the creek enters the Recharge Zone. The Upper Glen Rose, which is exposed in the bed of Cibolo Creek (Clark et al., 2009) is obviously highly permeable, similar to the interbasin area between Medina River and Cibolo Creek Basins. The correlation between precipitation and recharge that was developed for the Edwards-Trinity Aquifer (Green and Bertetti, 2010a; Green et al., 2012a) was used to estimate recharge by the Cibolo Creek Basin (Eq. 2.4.2.2-1). This conceptual estimate is based on flow data gathered in the headwater portion of the watershed. For the 175,360-acre watershed upstream from Selma, recharge from Cibolo Creek watershed should average approximately 37,800 acre-ft/yr if this evaluation is valid.

Model results using HSPF suggests the Cibolo Creek watershed recharges an average of 95,543 acre-ft/yr. The U.S. Geological Survey calculated that the mean annual recharge is 155,600 acre-ft/yr. The alternative model simulated mean recharge at 69,000 acre-ft/yr. Over the 253,365 acres of Contributing and Recharge Zone in the Cibolo Creek watershed, these three estimates for recharge equate to 4.52, 7.23, and 3.20 inch/yr as determined by HSPF, U.S. Geological Survey, and the alternative model, respectively. With annual precipitation of 33.74 inch/yr in the Cibolo Creek watershed, reasonable recharge should be less than 7.23 inch/yr, marginally greater than 3.20 inch/yr, and consistent with the HSPF estimate of 4.52 inch/yr. Given the ephemeral nature of Cibolo Creek, virtually all recharge to the Cibolo Creek watershed should recharge the Edwards Aquifer, however the elevated calculation of recharge by the U.S. Geological Survey is not possible unless significant groundwater is pirated from adjoining watersheds. There is no evidence that this degree of piracy occurs.

4.4.3.3 Guadalupe River Watershed Water Budget

The conceptual model of the Guadalupe River groundwater basin described in Sections 2.4.4.4 and 2.4.4.5 explains how a significant portion of the water recharged to the basin is discharged as surface flow to the Guadalupe River channel and does not recharge the Edwards Aquifer. The conceptual model of the Guadalupe River watershed is that most water recharged to the Guadalupe River basin is conveyed out of the Contributing Zone, past the Recharge Zone, and beyond the Confining Zone without recharging the Edwards Aquifer. Nonetheless, it appears that a minor component of recharge from the Guadalupe River does recharge the Edwards Aquifer. This is estimated to be 36,000 acre-ft/yr, or about 9 percent of the annual average flow of 417,852 acre-ft/yr measured in the Guadalupe River, although this estimate is not well constrained and retains a high level of uncertainty.

Similar to the Medina River Basin, the quantity of recharge to the Guadalupe River basin that does not enter the Edwards Aquifer is subtracted from the recharge that is specified as input to the alternative model to maintain numerical stability in the model. The recharge coefficients described in Section 3.2.3 and assigned to the Guadalupe River watershed were determined by calibration so that the quantity of water that recharged the Edwards Aquifer was consistent with the quantity needed to match well and spring hydrographs. Values for monthly and annual recharge for the Guadalupe River watershed are graphically illustrated in Figures 4.4-1 and 4.4-2.

Values for recharge from Guadalupe River watershed also vary considerably. Model results using HSPF suggests Cibolo Creek watershed recharges an average 10,566 acre-ft/yr. The U.S. Geological Survey assumes the Guadalupe River watershed provides absolutely no recharge to the Edwards Aquifer. The alternative model simulated mean recharge at 137,600 acre-ft/yr, but with a median value of 43,800 acre-ft/yr. As illustrated in Figures 4.4-1 and 4.4-2, recharge is highly variable, both by basin and temporally. Median recharge was calculated using simulated monthly recharge values. The large variance between the mean value of 137,600 acre-ft/yr and the median of 43,800 acre-ft/yr attests to the significant influence that a few months of excessive precipitation has on the Guadalupe River watershed simulation.

The relatively large amounts of recharge that were determined to be from the Guadalupe River watershed that were derived during calibration of the alternative model was motivated by the need to transmit flashy discharge to San Marcos Springs. As discussed in Sections 2.4.4.4 and 2.4.4.5, the local contribution to San Marcos Springs discharge is believed to be modest, and that most discharge is derived from regional flow. Sensitivity analyses with the model indicated that the local component to San Marcos Springs discharge is heavily influenced by the Guadalupe River discharge. Recharge rates from the Guadalupe River watershed with a median of 43,800 acre-ft/yr were required to achieve flashy discharge at San Marcos Springs.

4.4.3.4 Blanco River Watershed Water Budget

The conceptual model of the Blanco River groundwater basin described in Sections 2.4.4.6 and 2.4.4.7 explains how a significant portion of the water recharged to the basin is discharged as surface flow to the Blanco River channel and does not recharge the Edwards Aquifer. Recharge of the Edwards Aquifer from the Blanco River Basin remains uncertain, however, the consensus is that the Blanco River does provide meaningful recharge to the Edwards Aquifer and that this recharge is of the order of 15 cfs or 10,900 acre-ft/yr, however, this estimate is highly uncertain. There is limited information to constrain this estimate.

Similar to the Medina and Guadalupe River Basins, the quantity of recharge to the Blanco River Basin that does not enter the Edwards Aquifer is subtracted from the recharge that is specified as input to the model to maintain numerical stability in the model. The recharge coefficients described in Section 3.2.3 assigned to the Blanco River watershed were determined by calibration so that the quantity of water that recharged the Edwards Aquifer was consistent with the quantity needed to match well and spring hydrographs. Simulated recharge in the Blanco River watershed that recharged the Edwards Aquifer had a mean of 85,600 acre-ft/yr. These values are comparable with the U.S. Geological Survey calculation of 72,400 acre-ft/yr and the HSPF model mean of 80,679 acre-ft/yr.

5. Model Limitations

The alternative model is a distributed finite-element numerical model developed to simulate groundwater flow in the San Antonio segment of the Edwards Aquifer (hereafter known as Edwards Aquifer). Element size is variable with higher resolution in areas with high hydraulic gradients or abrupt property value changes. The model is developed to be a tool to evaluate regional water-resource management scenarios. The range of uses in the evaluations can be broad from assessing well-field management to supporting the Habitat Conservation Plan. The similarity in these applications is that the model provides a means to evaluate the impact of various recharge and pumping scenarios on the state of the aquifer and spring discharge.

The model is predicated on simplifying assumptions and approximations of the physical system. The Edwards Aquifer is karstic carbonate aquifer with a complex geometry that spans the Contributing, Recharge, and Confined Zones. The alternative model is not expected to capture all or even most of the complexity of the aquifer. The model is expected to capture the general input/response of the aquifer at a regional scale. For example, tracer-test results clearly demonstrate the presence of conduit flow, however the morphology, location, and extent of the conduit system are poorly known. The alternative model was developed with a level of detail and resolution commensurate with the resolution of data on which the model was predicated. An effort was made to avoid over-parameterization for the purpose of achieving localized agreement between observations and model output. Accommodation of high transmissivity zones assigned to river channels and the inclusion of conduits as discrete features should not be construed as a claim that these hydraulic features are precisely located where they appear in the model. Placement and characterization of these hydraulic features can only be as detailed as the resolution of data on which the conceptual and numerical models are predicated.

The model has a specified stress period of a month. This stress period was designed to match the frequency of pumping data, which are typically available only on an annual or monthly basis. Pumping data reported on an annual basis were converted to monthly using pumping curves developed to reflect seasonal variations in pumping. The desire to provide daily stress-period simulations is motivated by the availability of daily well and spring hydrographs, however, daily stress-period simulations will not be meaningful until realistic daily pumping data are available.

FEFLOW offers a number of solvers when performing simulations. Some are predicated on laminar flow (i.e., Darcy's Law) and others represent turbulent flow (i.e., Manning-Strickler equation). Given that the stress period is monthly and that hydraulic head and spring discharge hydrographs represent monthly-averaged data, accommodation of turbulent flow was determined to not be required.

As with all models, there is interest to apply the model to evaluate as many scenarios as possible. Given that the Edwards Aquifer is a karstic carbonate aquifer that exhibits a complex blend of diffuse and conduit flow, there is a desire to use this alternative model to capture the hydraulics of the karst system to the greatest degree possible. The most important caveat with this model is that it is not an appropriate tool to simulate groundwater travel time and contaminant transport. Attempts to use this model for these purposes will provide misleading and likely erroneous results.

6. Data Needs and Future Work

The data needs and future development of the alternative model are motivated by those areas that provided the greatest uncertainty during model development and in the model simulation results. The importance of uncertainty is classified as high, medium, and low. Uncertainty may result from a shortfall in the conceptual model (either as a mis-conceptualization or due to a lack of understanding of the physical system) or it may be directly attributable to inaccurate, misleading, or scarcity of data. Following is a discussion of the three levels of uncertainty identified during development of the alternative model.

Sources of high uncertainty in the alternative model are attributed to: (i) the recharge model, (ii) how rivers are incorporated in the model, and (iii) the hydraulics of the confined zone in the eastern San Antonio pool and near the springs. The fundamental difference between the alternative model and the 2004 MODFLOW model (Lindgren et al., 2004) is the inclusion of the Contributing Zone and manner in which recharge is input. Significant effort was expended to conceptualize recharge during the development of the alternative model, however there remains a high level of uncertainty in the generation of the recharge-model component. As currently incorporated, the coefficients in the recharge model for each basin are calibrated separately. Incorporation of additional data from the Contributing Zone and improved understanding of the hydraulic relationship between the Trinity and Edwards Aquifers will reduce this uncertainty. As part of this effort, improved characterization of the Upper Glen Rose, particularly in the western half of the model domain where most recharge is derived, should substantively reduce this uncertainty.

Recharge to the Medina, Guadalupe, and Blanco River watersheds was reduced by an amount equal to the quantity of water that was discharged from the basins downstream from the Recharge Zone. This adjustment was made to maintain numerical stability at the river channels. Numerical instability was encountered when actual recharge was added to the Contributing Zone, allowed to enter the river system, and removed from the model downstream. As understood and conceptualized, this water never enters the Edwards Aquifer. Thus, by not recharging this quantity of water to the Contributing Zone, the water budget as it affects the Edwards Aquifer should not be affected. Nonetheless, one refinement to the model would be to revise the manner in which rivers are incorporated in the model so that full precipitation and recharge can be applied throughout the entire Contributing Zone, including the Medina, Guadalupe, and Blanco River Basins.

Related to recharge is the interformational flow from the Trinity Aquifer. This relationship is not well defined and needs additional study to be assessed. There is an absence of data to ascertain whether interformational flow from the Trinity Aquifer to the Edwards Aquifer is constant or varies along the 180-mile interface of the San Antonio segment of the Edwards Aquifer. The Edward Aquifer Authority (EAA) is engaged in a multiple-year effort to reduce this uncertainty.

The hydraulic response at Comal Springs during periods of high flow was not adequately captured in the alternative model. The source of this uncertainty is not well constrained. This may be a result of the limitations of the recharge approach in this area of the model to effectively compute recharge in all circumstances. In the 2004 MODFLOW model as well as in the recent update to that model, significant adjustments to U.S. Geological Survey-estimated recharge were necessary to achieve a suitable match to observed springflows. These adjustments included a global reduction of flow to the Cibolo River Basin for all stress periods and substantial reductions to recharge for certain individual stress periods during exceptionally wet periods. In the alternative model, the hydraulic impact of recharge from Cibolo Creek and Guadalupe River watersheds has a clear impact on spring discharge, but a consistent approach was used to compute recharge input in the same manner for all stress periods. Significant improvement in the calibration to observed spring flows may be achieved by further adjustment to the computed recharge at specific stress periods as was done for the MODFLOW model.

Sources of medium uncertainty in the model include: (i) delineation of the recharge zone of the Kinney pool and (ii) delineation of the hydraulics of the Knippa Gap. Detailed water chemistry analysis of discharge from Las Moras Springs and Pinto springs should help to resolve the sources of water for the springs. This classification would provide insight on the demarcation between the Recharge Zone for Las Moras and Pinto Springs and the groundwater basin of the Nueces River. Characterization of the underflow of Las Moras and Pinto Creeks by geophysical imaging of the floodplain sediments and possible measurement of the sediments hydraulic properties using aquifer testing would provide the basis to discern the discharge from the Kinney Pool. This information would help constrain the size of the Kinney Pool recharge zone.

The hydraulics of Knippa Gap play an important role on the hydrographs of the Uvalde Pool index well, J-27, and discharge from Leona Springs and underflow and the springs on the Nueces River. Although conceptualization of the Uvalde Pool has been significantly refined in recent years, uncertainty remains in effectively capturing the hydraulics of the Knippa Gap in the model. Resolving this uncertainty may be more achievable once the boundaries of the Nueces and West Nueces River Basins are resolved, which will help refine the recharge model and clarify the hydraulic relationship between the Trinity and Edwards Aquifers in the western portion of the model domain. An integral component to this uncertainty is the role that the Upper Glen Rose plays on recharge particularly in Uvalde and western Medina Counties.

Sources of low uncertainty in the model include: (i) hydraulics of the Kinney Pool and (ii) hydraulics of San Pedro and San Antonio Springs. The performance of Las Moras and Pinto Springs is of secondary importance in the model given that Kinney Pool is essentially hydraulically separated from Uvalde Pool in the model. As discussed in the report, this hydraulic separation is justified as part of the conceptual model developed as part of this project. Uncertainty reduction in characterizing the extent of the Kinney Pool Recharge Zone will help constrain the hydraulics of the Kinney Pool. The structure associated with San Pedro and San Antonio Springs needs to be refined to enable matching both springs.

7. Summary

An alternative groundwater flow model of the San Antonio segment of the Edwards Aquifer was developed to provide an independent numerical tool against which to compare with the current Edwards Aquifer groundwater availability model (Lindgren et al., 2004). The alternative model was developed to be conceptually independent from existing models. The fundamental difference between the alternative model and past models (Klemt et al., 1979; Maclay and Land. 1988; Lindgren et al., 2004) is the method used to input recharge. Previous groundwater models of the Edwards Aquifer included only the Recharge and Confined Zones. Recharge as surface flow from the Contributing Zone was calculated by the U.S. Geological Survey or using the HSPF model and input as a boundary condition at the upgradient boundary of the Recharge Zone. The principal limitation of this approach was that recharge from river underflow and interformational flow in the subsurface was omitted from the water budget unless these components were explicitly included as recharge. This poses a dilemma because river underflow and especially interformational flow in the subsurface are difficult to measure. Because the recharge input into these models is likely less that what actually occurs, discharge from the model has to be modified to account for this deficiency. The result is that discharge calculations are under-predicted when all sources of recharge are not included.

In contrast, the alternative model includes the Contributing Zone and calculates recharge directly from precipitation. This approach obviates the problem of accommodating river underflow and interformational flow in the subsurface by including a three-layer model in the Contributing and Recharge Zones. Inclusion of the Upper and Lower Glen Rose Formations allows for subsurface recharge to be conveyed from the Contributing Zone to the Recharge Zone. This is accomplished as both river underflow by including high transmissivity zones along rivers that enter the Recharge Zone and as diffuse flow via interformational flow through the Upper and Lower Glen Rose Formations in the inter-river zones.

The major river basins in the Contributing Zone were characterized as hydraulically independent. By doing this, surface water and groundwater flow from each basin to adjoining basin was minimized. This characterization honored the conceptual model developed for the Contributing Zone in which surface water and groundwater flow in each basin was mostly restricted to each basin. This conceptualization allowed the precipitation/recharge model to be calibrated for each basin (i.e., the recharge model for each basin had its own coefficients).

The water budget for each basin was separately analyzed when independent or complementary data were available. The basis for the analysis is described in this model report. These water-budget analyses and the associated descriptions form the basis for the conceptual model on which the alternative numerical model was based. The salient fundamental concepts on which the conceptual model was based are summarized as follows.

- The Edwards Aquifer in Kinney County was characterized as a separate pool. The extent of the pool spans Grass Valley and Pinto Valley and receives limited recharge from the West Nueces River watershed.

- The demarcation between the groundwater basin aligned with the West Nueces River watershed and the Nueces River watershed is not well defined. It appears that a portion of the West Nueces River watershed is pirated by the Nueces River watershed.
- The groundwater basin of the Nueces River groundwater basin extends farther north than the Nueces River watershed and pirates groundwater from the Llano River watershed.
- The Uvalde Pool is recharged solely by surface and underflow associated with the Nueces River and possibly some interformational flow in the subsurface. Natural discharge from the Uvalde Pool is via Nueces River Springs, Leona Springs and underflow, and the Knippa Gap.
- Although the Uvalde Pool area is designated as Confined Zone in the Edwards Aquifer, it responds as an unconfined aquifer due to its hydraulic communication with the overlying Buda Formation and Austin Chalk and the absence of an effective overlying confining layer.
- The capacity of the Knippa Gap does not appear sufficient for the large quantities of recharge that occurred in 1990, 2004, and 2007. The capacity for discharge via the Nueces River Springs and Leona Springs and underflow is likely greater than previously estimated.
- The Dry Frio River and underflow discharges to the Knippa Gap, which in turn discharges to the San Antonio Pool.
- The Frio River and underflow discharges directly to the San Antonio Pool.
- The streams in Medina County from Seco Creek on the west to Quihi Creek on the east are recharged by the Austin Chalk, not the Edwards Aquifer, at locations where the hydraulic head in the Austin Chalk is significantly higher than the Austin Chalk. Only if this water is recharged to the Austin Chalk from the Edwards Aquifer at locations where the two aquifers are in hydraulic communication, should this discharge be considered in the water budget of the Edwards Aquifer. This quantity of water is conceptualized as minimal.
- Water lost from Medina and Diversion lakes does not recharge the Edwards Aquifer. Water lost from these two rivers is discharged to the paleo-stream channel in the Medina River floodplain.
- Recharge calculations in the headwaters of the Medina River watershed indicate that the watershed may pirate groundwater from an adjoining watershed or that recharge in this watershed is elevated due to localized high rates of precipitation possibly due to orographic effects. As a consequence, recharge from the Medina River watershed may be greater than previously thought.
- The Cibolo Creek watershed is recognized as highly permeable as evidenced by the ephemeral nature of the river channel. Water recharged in this watershed likely recharges the Edwards Aquifer, however, the magnitude of this recharge is conceptualized as less than previous estimates based on the limited extent of the watershed.
- Recharge of the Edwards Aquifer from the Guadalupe River watershed has been previously characterized as negligible. Calibration of the alternative model indicates that the Guadalupe River watershed does recharge the Edwards Aquifer.
- The Blanco River watershed contributes a limited, yet important portion of the recharge to San Marcos Springs.

- Recharge from the Guadalupe River and Blanco River watersheds is required to provide the local component of recharge to San Marcos Springs. San Marcos Springs cannot exhibit flashy discharge without sufficient local recharge.

These attributes establish the alternative model as fundamentally independent from the 2004 MODFLOW model (Lindgren et al., 2004) which is current used as the official groundwater availability model.

Simulated discharge at nine springs and hydraulic head at 102 monitoring wells were compared with observations and measurements. Index wells J-17 (Bexar County), J-27 (Uvalde County), Comal Springs, and San Marcos Springs were the most prominent of the calibration goals. The calibration period was eleven years, from 2001 to 2011. This calibration period was chosen because it includes two very wet years, 2004 and 2007, and four very dry years, 2006, 2008, 2009, and 2011. Additional justification for this period was that pumping data and NEXRAD precipitation are available, compared with the drought of the 1950s during which pumping and precipitation data would need to be estimated. In addition, water-budget assessments derived from simulations performed with the alternative model were compared with similar assessments based on the conceptual model, U.S. Geological Survey calculations, and model results using HSPF.

Seven of 14 of the target goals were met by the alternative model. In comparison, the 2004 MODFLOW model met 3 of the 14 target goals. The inability of the alternative model to match high discharge at Comal Springs and San Marcos Springs led to the greatest discrepancy between simulation results and the target goals. The alternative model was more successful in matching low discharge at the two springs. Matching low discharge is recognized to be more important than matching high discharge in model performance. Aside from this discrepancy, simulated heads and spring discharge are in general agreement with observations as attested by model performance statistics. Agreement between simulations and observations is encouraging when compared with existing models given that the alternative model has the additional constraint imposed by the recharge model and a decreased degree of freedom due to the fact that recharge is calculated solely on precipitation and is not a specified, calibrated input variable. This feature in the alternative model clearly sets it apart from the 2004 MODFLOW model and substantiates its status as a conceptually independent model. These attributes of the alternative model qualify it for future use to provide the EAA with an independent numerical tool to evaluate aquifer responses to different spatial and temporal patterns of precipitation, recharge and pumping.

8. References

Abbott, P. L., and C. M. Woodruff Jr. 1986. The Balcones escarpment-geology, hydrology, ecology and social development in Central Texas. Field Trip Guidebook for the 1986 Geological Society of America Annual Meeting in San Antonio.

Adkins, J. 2013. Assessing Karst Groundwater Resources in a Complex Region of Structural Confinement. Abstract. National Groundwater Association Summit.

Adkins, J. 2014. Assessment of groundwater flow in the Edwards Aquifer through the Knippa Gap in Uvalde County, Texas. M.S. Thesis. University of Arkansas.

Anaya, R. and I. Jones. 2004. Groundwater availability model of the Edwards-Trinity (Plateau) and the Cenozoic alluvium aquifer systems, Texas. GAM Report. Texas Water Development Board. 124 p.

Anaya, R. and I. Jones. 2009. Groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers of Texas. Texas Water Development Board. Austin, TX. Report 373. 103 p.

Arnold, J.G., P.M. Allen, R. Muttiah, and G. Bernhardt. 1995. Automated base flow separation and recession analysis techniques. Ground Water 33(6), 1010-1018.

Arnold, J.G. and P.M. Allen. 1999. Automated methods for estimating baseflow and ground water recharge from streamflow records. Journal of the American Water Resources Association 35(2), 411-424.

Asquith, W.H. and R.M. Slade, Jr. 1995. Flood Frequency in Texas—Calculation of Peak-Streamflow Frequency at Gaging Stations. U.S. Geological Survey. Fact Sheet 181–95.

Asquith, W.H. and R.M. Slade, Jr. 1997. Regional equations for estimation of peak-streamflow frequency for natural basins in Texas. Water-Resources Investigations Report. 96-4307

Bader, R.W, S.D. Walthour, and J.R. Waugh. 1993. Edwards aquifer hydrogeologic status report for 1992: San Antonio, Tex., Edwards Underground Water District Report 93-05,71 p.

Barnes, V.E. 1977. Geologic atlas of Texas, Del Rio sheet: Austin, University of Texas, Bureau of Economic Geology, scale 1:250,000, 1 sheet.

Barnes, V.E. 1983. Geologic atlas of Texas, San Antonio sheet: Austin, University of Texas, Bureau of Economic Geology, 8 p., scale 1:250,000, 1 sheet.

Başağaoğlu , H., L. Gergen, and R.T. Green. 2015. Assessing the effects of the epikarst on groundwater recharge and regional fast -flow pathways in a karstic aquifer via impulse-response functions. Accepted by the Journal of Hydrologic Engineering.

Bear, J. 1979. *Hydraulics of Groundwater*. McGraw-Hill. New York, NY. 569 p.

Bennett, R.R. and A.N. Sayre. 1962. Geology and Ground Water Resources of Kinney County, Texas. Texas Water Commission, Bulletin 6216, 163 p.

Blome, C.D., J.R. Faith, E.W. Collins, D.E. Pedraza, and K.E. Murray. 2004. Geologic map compilation of the upper Seco Creek area, Medina and Uvalde counties, south-central Texas. U.S. Geological Survey. Open-File Report 2004–1430. Reston, Virginia. 20 p + attachments.

Blome, C.D., J.R. Faith, D.E. Pedraza, G.B. Ozuna, J.C. Cole, A.K. Clark,. T.A. Small, and R.R. Morris. 2005a. Geologic map of the Edwards Aquifer recharge zone south-central Texas. U.S. Geological Survey. 1:200,000 sheet.

Blome, C.D., J.R. Faith, D.E. Pedraza, G.B. Ozuna, J.C. Cole, A.K. Clark, T.A. Small, and R.R. Morris. 2005b. Geologic Map of the Edwards Aquifer Recharge Zone, South-Central Texas U.S. Geological Survey Scientific Investigations Map 2873.

Blome, C.D., J.R. Faith, and G.B. Ozuna. 2007. Geohydrologic framework of the Edwards and Trinity aquifers, south-central Texas. U.S. Geological Survey. Fact Sheet 2006–3145. Reston, Virginia. 1 p + attachments.

Brune, G. 1981. *Springs of Texas*. Volume 1. Texas A&M University Agricultural Series, No. 5. College Station, TX.

Bush, P.W., A.F. Ardis, and K.H. Wynn. 1992. Historical piezometric surface of the Edwards-Trinity aquifer system and contiguous hydraulically connected units, west-central Texas. US Geological Survey Water-Resources Investigations Report 92-4055. 3 sheets.

Clark, A.K. 2003. Geologic framework and hydrogeologic characteristics of the Edwards Aquifer, Uvalde County, Texas: U.S. Geological Survey Water-Resource Investigations Report 03-4010. 17 p.

Clark, A.K., and T.A. Small. 1997. Geologic framework of the Edwards Aquifer and upper confining unit, and hydrogeologic characteristics of the Edwards Aquifer, south central Uvalde County, Texas: U.S. Geological Survey Water-Resource Investigations Report 97-4094. 11 p.

Clark, A.K. and C.A. Journey. 2006. Flow Paths in the Edwards Aquifer, Northern Medina and Northeastern Uvalde Counties, Texas, Based on Hydrologic Identification and Geochemical Characterization and Simulation. Scientific Investigations Report 2006-5200, vi, 48 p.

Clark, A.K., J.R. Faith, C.D. Blome, and D.E. Pedraza. 2006. Geologic Map of the Edwards Aquifer in Northern Medina and Northeastern Uvalde Counties, South-central Texas. Open-File Report 2006-1372, 22 p.; plate.

Clark, A.K., C.D. Blome, and J.R. Faith. 2009. Map showing geology and hydrostratigraphy of the Edwards Aquifer catchment area, northern Bexar County, south-central Texas. U.S. Geological Survey Open-File Report 2009-1008. Reston, Virginia. 24 p + attachments.

Clark, A.K. D.E. Pedraza, and R.R. Morris. 2013. Geologic framework, structure, and hydrogeologic characteristics of the Knippa Gap area in eastern Uvalde and western Medina Counties, Texas. USGS Scientific Investigations Report: 2013-5149.

Clark, A.K., D.E. Pedraza, and R.R. Morris. 2013. Geologic framework, structure, and hydrogeologic characteristics of the Knippa Gap area in eastern Uvalde and western Medina Counties, Texas. Scientific Investigations Report 2013-5149.

Clear Creek Solutions. 2009. The Medina Lake HSPF Model Refinements Report. Prepared for U.S. Army Corps of Engineers, Fort Worth, TX.

Clear Creek Solutions. 2012. Edwards Aquifer Recharge HSPF Subbasins Models Modifications for Nueces River and Tributaries Calibration and Recharge Report. Prepared for U.S. Army Corps of Engineers, Fort Worth, TX. 473 pp.

Clear Creek Solutions. 2013. HSPF Model Updates to Nueces and Blanco Sub-Basins of the Edwards Aquifer for Nueces River and Tributaries, Texas Feasibility Study. Prepared for U.S. Army Corps of Engineers, Fort Worth, TX. 191 pp.

Clement, T.J. and J.M. Sharp, Jr. 1988. Hydrochemical facies of the badwater zone of the Edwards Aquifer, Central Texas. In Proceedings of the Ground Water Geochemistry Conference. Dublin, Ohio: National Water Well Association. pp. 127-149.

Collins, E.W. 1993. Fracture zones between overlapping *en echelon* fault strands: outcrop analogs within the Balcones fault zone, central Texas: Gulf Coast Association of Geological Societies Transactions, v. 43, p. 77–85.

Collins, E.W. 2000. Geologic map of the New Braunfels, Texas, 30° 60 minute quadrangle: geologic framework of an urban-growth corridor along the Edwards Aquifer, south-central Texas: The University of Texas at Austin Bureau of Economic Geology Miscellaneous Map No. 39, 28 p., scale 1:100,000, 1 sheet.

Collins, E.W., and S.D. Hovorka. 1997. Structure map of the San Antonio segment of the Edwards Aquifer and Balcones fault zone, south-central Texas: Structural framework of a major limestone aquifer: Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties: The University of Texas at Austin, Bureau of Economic Geology, Miscellaneous Map No. 38, scale 1:250,000, 2 sheets.

DeCook, K.J. 1963. Geology and Ground-Water Resources of Hays County, Texas: U.S. Geological Survey Water- Supply Paper 1612, 72 p. [Also published as Texas Board of Water Engineers Bulletin 6004, 167 p., 1960.]

Diersch, H-J. G. 2014. *FEFLOW – Finite Element Modeling of flow, Mass and Heat Transport in Porous and Fractured Media*. Springer. New York. 996 p.

Donnelly, A.C.A. 2007. GAM Run 07-03. Texas Water Development Board. 20 p + attachments.

Doyle, F.L. 2003. Ancestral Medina River and alluvial surfaces adjacent to the Balcones Escarpment: Bexar and Medina Counties, Texas. South Texas Geological Society Bulletin. 63(7). pp. 25-32.

Edwards Aquifer Authority. 2007. Edwards Aquifer Authority report to the Kinney County Groundwater Conservation District summarizing the Edwards Aquifer Authority 2007 Kinney County tracer tests.

Edwards Aquifer Authority. 2009. The March 2009 EAA status report to the Kinney County Groundwater Conservation District on Kinney County tracer test results.

Espey, Huston & Associates, Inc. 1989. Medina Lake Hydrogeology Study. Contract report for the Edwards Underground Water District prepared by Espey, Huston & Associates, Inc. 26 p + attachments.

Ewing, T.E. 2004. Volcanoes, asphalt, tectonics, and groundwater in the Uvalde area, southwest Texas. Field Trip Guidebook. Gulf Coast Association of Geological Socieities. 54th Annual Convention. San Antonio, Texas. October 9-12, 2004. South Texas Geological Society Guidebook 2004-1.

Ewing, T.E. 2005. Report on seismic and well interpretation. Contract report to the Edwards Aquifer Authority.

Ferrill, D.A., Morris, A.P., 2003. Dilational normal faults. Journal of Structural Geology 25, 183–196.

Ferrill, D.A., and A.P. Morris. 2008. Fault zone deformation controlled by carbonate mechanical stratigraphy, Balcones fault system, Texas. American Association of Petroleum Geologists Bulletin 92, 359-380.

Ferrill, D.A., D.W. Sims, A.P. Morris, D.J. Waiting, and N. Franklin. 2003. Structural Controls on the Edwards Aquifer/Trinity Aquifer Interface in the Camp Bullis Quadrangle, Texas Final report prepared for the Edwards Aquifer Authority and the US Army Corps of Engineers.

Ferrill, D.A., D.W. Sims, D.J. Waiting, A.P. Morris, N. Franklin, and A.L. Schultz. 2004. Structural Framework of the Edwards Aquifer recharge zone in south-central Texas. Geological Society of America Bulletin 116, 407-418.

Ferrill, D.A., D.W. Sims, N. Franklin, A.P. Morris, and D.J. Waiting. 2005. Structural Controls on the Edward Aquifer/Trinity Aquifer Interface in the Helotes Quadrangle, Texas. Final report prepared for the Edwards Aquifer Authority and the US Army Corps of Engineers.

Ferrill, D.A., A.P. Morris, D.W. Sims, R. Green, F.N., and D.J. Waiting. 2008. Geologic Controls on Interaction Between the Edwards and Trinity Aquifers, Balcones Fault System, Texas. South Texas Geological Society Bulletin, April 2008, 21-45.

Ferrill, D.A., A.P. Morris, R.N. McGinnis, K.J. Smart, and W.C. Ward. 2011. Fault zone deformation and displacement partitioning in mechanically layered carbonates: The Hidden Valley fault, central Texas. American Association of Petroleum Geologists Bulletin, 95, no. 8, 1383-1397.

Flawn, P.T., A. Goldstein Jr., P.B. King, and C.E. Weaver. 1961. The Ouachita System. Bureau of Economic Geology, The University of Texas at Austin. Publication No. 6120.

Fisher, W.L. 1983. Geologic Atlas of Texas: San Antonio Sheet. Bureau of Economic Geology: University of Texas at Austin, Texas.

Foley, L.L. 1926. Mechanics of the Balcones and Mexia faulting: Bulletin of the American Association of Petroleum Geologists. V. 10. no. 12. pp. 1261–1269.

Ford, D. and P. Williams. 1989. *Karst Geomorphology and Hydrology*. Chapman and Hall. 601 p.

Freeze, R.A., and J.A. Cherry. 1979. *Groundwater*. Englewood Cliffs, New Jersey: Prentice Hall.

Gary, M., G. Veni, B. Shade, and R. Gary. 2011. Spatial and temporal recharge variability related to groundwater interconnection of the Edwards and Trinity aquifers, Camp Bullis, Bexar and Comal Counties, Texas. *In Interconnection of the Trinity (Glen Rose) and Edwards Aquifers along the Balcones Fault Zone and Related Topics, Proceedings from Karst Conservation Initiative Meeting*. p. 6–10.

Garza, S. 1962. Recharge, discharge, and changes in ground-water storage in the Edwards and associated limestones, San Antonio area, Texas, A progress report on studies, 1955-59: Texas Water Engineers Bull. 6201. 51 p.

Garza, S. 1966. Ground-water resources of the Edwards and associated limestones, San Antonio area, Texas, A progress report on studies, 1960-64: Texas Water Engineers Report 34. 36 p.

George, W.O., S.D. Breeding, and W.W. Hastings. 1952. Geology and Ground-Water Resources of Comal County, Texas, with Sections on Surface-Water Supplies and Chemical Character of the Water: Water Supply Paper Report Number 1138, 126 p.

Green, R.T. 2003. Geophysical survey to determine the depth and lateral extent of the Leona Aquifer in the Leona River Floodplain, south of Uvalde, Texas. Southwest Research Institute. Contract report for the Edwards Aquifer Authority.

Green, R.T., and F.P. Bertetti. 2010a. Investigating the Water Resources of the Western Edwards-Trinity Aquifer. Contract Report Prepared by Southwest Research Institute for the Sutton County Groundwater Conservation District.

Green, R.T. and F.P. Bertetti. 2010b. Development of a Candidate Drought Contingency Plan for Uvalde County, Texas. Contract Report Prepared for the Uvalde County Underground Water Conservation District. 24 p.

Green, R.T., F. P. Bertetti, N.M. Franklin, A.P. Morris, D.A. Ferrill, and R.V. Klar. 2006. Evaluation of the Edwards Aquifer in Kinney and Uvalde Counties, Texas. Southwest Research Institute. Contract report for the Edwards Aquifer Authority.

Green, R.T., J.R. Winterle, and J.D. Prikryl. 2008a. Discharge from the Edwards Aquifer through the Leona River Floodplain, Uvalde, Texas. *J of American Water Resources Association.* 44(4):887-901. DOI: 10.1111/j.1752-1688.2008.00187.x.

Green, R.T., F. P. Bertetti, B.P. Wilcox, and R.N. McGinnis. 2008b. Investigation of the Groundwater Systems in the Wintergarden Groundwater Conservation District—Phase II. Southwest Research Institute. Contract Report to the Wintergarden Groundwater Conservation District.

Green, R.T., F. P. Bertetti, and R.N. McGinnis. 2009a. Investigation of the Secondary Aquifers in Uvalde County. Southwest Research Institute. Contract project conducted for the Uvalde County Underground Water Conservation District. 74 p.

Green, R.T., F.P. Bertetti, and R.N. McGinnis. 2009b. Measureing floodplain hydraulics of the Frio River where it overlies the Edwards Aquifer. Contract project conducted for the Edwards Aquifer Authority. 40 p.

Green, R.T., F.P. Bertetti, and M.O. Candelario. 2011. Edwards Aquifer–Upper Glen Rose aquifer hydraulic interaction. In Interconnection of the Trinity (Glen Rose) and Edwards Aquifers along the Balcones Fault Zone and Related Topics, Proceedings from Karst Conservation Initiative Meeting, February 17, pp. 30–35.

Green, R., F. Bertetti, and M. Hernandez. 2012a. Recharge Variability In Semi-Arid Climates. Nature Education Knowledge 3(10):34.

Green, R.T., F.P. Bertetti, R.N. McGinnis, and J. Prikryl. 2012b. Measureing floodplain hydraulics of Seco Creek and the Medina River where they overly the Edwards Aquifer. Contract project conducted for the Edwards Aquifer Authority. 36 p. + attachments.

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

Groschen, G.E. 1996. Hydrogeologic factors that affect the flowpath of water in selected zones of the Edwards Aquifer in the San Antonio region, Texas. U.S. Geological Survey Water-Resources Investigations Report 96–4046. 73 p.

Guyton, W.F. 1979. Geohydrology of Comal, San Marcos, and Hueco Springs: Texas Department of Water Resources [present Texas Water Development Board] Report 234, 85 p.

Halihan, T., R.E. Mace, and J.M. Sharp. 2000. Flow in the San Antonio segment of the Edwards aquifer; matrix, fractures, or conduits? in I.D. Sasowsky and C.M. Wicks. Groundwater flow and contaminant transport in carbonate aquifers: Brookfield, Vermont, A. A. Balkema. pp. 129-146.

Hamilton, J.M., R. Esquilin, and G.M. Schindel. 2006. Edwards Aquifer Authority Synoptic Water Level Program 1999—2004 Report. Report No. 06-02. Edwards Aquifer Authority. San Antonio. Texas.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald. 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00–92, 121 p.

Harbaugh, A.W., and M.G. McDonald., 1996. User's documentation for MODFLOW–96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96–485, 56 p.

Harden, R.W. 1968. File Memorandum on review of water quality changes in Edwards reservoir – Especially near the bad water line. William F. Guyton and Associates. 23 p.

Hauwert, N. 2011. Could much of Edwards aquifer "matrix storage" actually be Trinity aquifer contributions from the Blanco River? In *Interconnection of the Trinity (Glen Rose) and Edwards Aquifers along the Balcones Fault Zone and Related Topics, Proceedings from Karst Conservation Initiative Meeting*. p. 15–24.

Hauwert, N.M, D.A. Johns, J.W. Sansom, and T.J. Aley. 2002. Groundwater tracking of the Barton Springs Edwards Aquifer, Travis and Hays Counties, Texas. Gulf Coast Association of Geological Societies Transactions 52. pp. 377—384.

Hauwert, N., D. Johns, B. Hunt, J. Beery, B. Smith J.M. Sharp, Jr. 2004. Flow Systems of the Edwards Aquifer Barton Springs Segment Interpreted from Tracing and Associated Field Studies. Edwards Symposium.

HDR Engineering. 2002. Pilot Recharge Models of the Nueces and Blanco River Basins: June, 73 p.

Holt, C.L.R. 1956. Geology and water-resources of Medina County, Texas. Texas Board of Water Engineers Bulletin 5601. 97p.

Holt, C.L.R., Jr. 1959. Geology and ground-water resources of Kinney County, Texas. U.S. Geological Survey Water-Supply Paper1422. 213p.

Hovorka, S.D., S.C., Ruppel, A.R. Dutton, and J. Yeh. 1993. Edwards Aquifer storage assessment, Kinney County to Hays County, Texas. The University of Texas at Austin, Bureau of Economic Geology, contract report to the Edwards Underground Water District under Contract No. 93-04-FO, 101 p.

Hovorka, S.D., R.E. Mace, and E.W. Collins. 1995. Regional distribution of permeability in the Edwards Aquifer. Edwards Underground Water District Report 95-02. 128 p.

Hovorka, S.D., A.R. Dutton, S.C. Ruppel, and J. Yeh. 1996. Edwards Aquifer ground-water resources: geologic controls on porosity development in platform carbonates, South Texas. Report of Investigations No. 238. Bureau of Economic Geology, University of Texas, Austin, Texas.

Hovorka, S.D., R.E. Mace, and E.W. Collins. 1998. Permeability Structure of the Edwards Aquifer, South Texas-Implications for Aquifer Management. Bureau of Economic Geology. The University of Texas at Austin. Report of Investigations No. 250. Austin, Texas: The University of Texas.

Hovorka, S.D., T. Phu, J.P. Nicot, and A. Lindley. 2004. Refining the conceptual model for flow in the Edwards Aquifer – Characterizing the role of fractures and conduits in the Balcones Fault Zone segment. The University of Texas at Austin, Bureau of Economic Geology, contract report to the Edwards Aquifer Authority. 58 p.

Hutchison, W.R., J. Shi, and M. Jigmond. 2011a. Groundwater flow model of the Kinney County area. Texas Water Development Board.

Hutchison, W.R., I.C. Jones, and R. Anaya. 2011b. Update of the Groundwater Availability Model for the Edwards-Trinity (Plateau) and Pecos Valley Aquifers of Texas. Texas Water Development Board. 61 p.

Jiang, Y., A.D. Woodbury, and S. Painter. 2004. Full-Bayesian inversion of the Edwards Aquifer. Ground water 2004;42(5):724-33.

Johnson, S.B. and G.M. Schindel. 2008. Evaluation of the option to designate a separate San Marcos pool for critical period management. Report No. 08-01. Edwards Aquifer Authority. 109 pp.

Johnson, S., G. M. Schindel, and G. Veni. 2009. Tracing groundwater flowpaths in the Edwards Aquifer Recharge Zone, Panther Springs Creek Basin, northern Bexar County, Texas. Proceedings of the 15th International Congress of Speleology. p. 1538.

Johnson, S., G. Schindel, and G Veni. 2010. Dye tracer tests in the Edwards Aquifer, Balcones Fault Zone, San Antonio Segment, Bexar County, Panther Springs Creek. Edwards Aquifer Authority. Report 10-01. 112 pp.

Johnson, S., G. Schindel, G. Veni, N. Hauwert, B. Hunt, B. Smith, and M. Gary. 2012. Tracing groundwater flowpaths in the vicinity of San Marcos Springs, Texas. Edwards Aquifer Authority. Report No. 12-01. 99 pp + attachments.

Jones, I., R. Anaya, and S. Wade. 2011. Groundwater availability model: Hill Country portion of the Trinity aquifer of Texas. Texas Water Development Board, Report 377, 160. http://www.twdb.state.tx.us/publications/reports/numbered_reports/doc/R377_HillCountryGAM.pdf.

Kier, R.S. 1998. Edwards-Trinity Aquifer ground water availability, preliminary assessment for central Kinney County, Texas: Revision. Consulting Report. 9 p. + attachments.

Khorzad, K. 2002. Kinney County groundwater availability evaluation. Kinney County, Texas. Contract report prepared for the Edwards Aquifer Authority. 28 p + attachments.

Khorzad, K. 2003. Edwards aquifer evaluation: Kinney County, Texas: Journal of the American Water Resources Association. October. pp. 1093-1107.

Klemt, W.B., T. R. Knowles, G.R. Edler, and T.W. Sieh. 1979. Ground-water resources and model applications for the Edwards (Balcones fault zone) aquifer in the San Antonio region: Texas Water Development Board Report 239, 88 p.

Krejca, J. K. 2005. Stygobite phylogenetics as a tool for determining aquifer evolution. Dissertation, University of Texas at Austin. 115 pp.

Kresic, N. and Z. Stevanovic. 2010. Groundwater Hydrology of Springs: Engineering, Theory, Management, and Sustainability. Elsevier, New York, NY.

Kuniansky, E.L. 1994. Multi-layer finite element model of the Edwards and Trinity aquifers central Texas, *in* Dutton, A.R., ed., Toxic substances and the hydrologic sciences: Minneapolis, American Institute of Hydrology, p. 234–249.

Kuniansky, E.L., and K.Q. Holligan. 1994. Simulations of flow in the Edwards-Trinity aquifer system and contiguous hydraulically connected units, west-central Texas. U.S. Geological Survey Water-Resources Investigations Report 93–4039, 40 p.

Kuniasky, E.L. and A.F. Ardis. 2004. Hydrogeology and ground-water flow in the Edwards-Trinity Aquifer system, west-central Texas. U.S. Geological Survey Water-Professional Paper 1421-C, 78 p.

Lambert, R.B. K.C. Grimm, and R.W. Lee. 2000. Hydrogeology, hydrologic budget, and water chemistry of the Medina Lake area, Texas. USGS Water-Resources Investigations Report: 2000-4148. 54 p + appendices.

Land, L.F., C.W. Boning, L. Harmsen, and R.D. Reeves. 1983. Streamflow losses along the Balcones Fault Zone, Nueces River Basin, Texas. U.S. Geological Survey Water-Resources Investigations Report 83-4372. 68 p.

LBG-Guyton Associates. 1995. Edwards/Glen Rose Hydrologic Communication, San Antonio region, Texas. Edwards Underground Water District Report 95-03. 38 p + attachments.

LBG-Guyton Associates. 2004. Evaluation of Augmentation Methodologies in Support of In-Situ Refugia at Comal and San Marcos Springs, Texas: Report prepared for the Edwards Aquifer Authority, June, [variously paginated].

LBG-Guyton Associates and Aqua Terra Consultants. 2005. HSPF recharge models for the San Antonio Segment of the Balcones Fault Zone Edwards Aquifer. Prepared for the Edwards Aquifer Authority.

LBG-Guyton Associates. 2010. Groundwater data acquisition in Edwards, Kinney, and Val Verde counties, Texas. Prepared for the Plateau Region Water Planning Group and the Texas Water Development Board.

Lee, T.M., and A. Swancar. 1997. Influence of evaporation, ground water, and uncertainty in the hydrologic budget of Lake Lucerne, a seepage lake in Polk County, Florida. U.S. Geological Survey Water-Supply Paper 2439. 61 p.

Lindgren, R.J., A.R. Dutton, S.D. Hovorka, S.R.H. Worthington, and S. Painter. 2004 Conceptualization and simulation of the Edwards Aquifer, San Antonio region, Texas. Scientific Investigation Report 2004-5277. U.S. Geological Survey.143 p.

Lindgren, R.J. 2006. Diffuse-flow conceptualization and simulation of the Edwards aquifer, San Antonio region, Texas: U.S. Geological Survey Scientific Investigations Report 2006–5319. 47 p.

Lindgren, R.J., C.J. Taylor, and N.A. Houston. 2009. Description and evaluation of numerical groundwater flow models for the Edwards aquifer, south-central Texas: U.S. Geological Survey Scientific Investigations Report 2009–5183. 25 p.

Livingston, P. 1947. Relationship of ground water to the discharge of the Leona River in Uvalde and Zavala Counties, Texas. Texas Board of Water Engineers. 52 p + attachments.

Long, A. T. 1958. Ground-water geology of Real County, Texas. Texas Board Water Engineers Bulletin 5803. 46 p.

Long, A.T. 1962. Ground-water geology of Edwards County, Texas. Texas Water Commission. Bulletin 6208. 113 p.

Long, A. T. 1963. Ground-water geology of Edwards County, Texas. U.S. Geological Survey Water-Supply Paper 1619-J. 29 p.

Lowry, R.L. 1955. Recharge to the Edwards ground-water reservoir. Consulting Report to the San Antonio City Water Board Report.

Lozo, F. E., and F. L. Stricklin, Jr. 1956. Stratigraphic notes on the outcrop basal Cretaceous, central Texas: Transactions of the Gulf Coast Association Geological Societies, v. 6, p. 67–78.

Mace, R.E. 2000. Determination of Transmissivity from Specific Capacity Tests in a Karst Aquifer. *Ground Water*. Vol. 35, No. 5. 738–742 p.

Mace, R.E. and S.E. Hovorka. 2000. Estimating porosity and permeability in a karstic Aquifer using core plugs, well tests, and outcrop measurements. *Groundwater Flow and Contaminant Transport in Carbonate Aquifers*. I.D. Sasowsky and C.M. Wicks, eds. Rotterdam, Netherlands: A.A. Balkema Publishers.

Mace, R.E. and R. Anaya. 2004. Estimate of recharge to the Edwards (Balcones Fault Zone) and Edwards-Trinity (Plateau) aquifers in Kinney County, Texas. Proceedings of Aquifers of the Edwards Plateau Conference. 345-366 p.

Mace, R.E., A.H. Chowdhury, R. Anaya, and S.-C. Way. 2000. Groundwater Availability of the Trinity Aquifer, Hill Country Area, Texas: Numerical Simulations through 2050. Texas Water Development Board. Report 353. 174 p.

Maclay, R.W. 1989. Edwards Aquifer in San Antonio: Its hydrogeology and management: South Texas Geological Society Bulletin, V. 30, no. 4, 11–28 p.

Maclay, R.W. 1995. Geology and hydrogeology of the Edwards Aquifer in the San Antonio area, Texas. U.S. Geological Survey Water-Resources Investigations Report 95-4186. 64p+ attachments.

Maclay, R.W., P.L. Rettman, and T.A. Small. 1980. Hydrochemical data for the Edwards Aquifer in the San Antonio area, Texas. Texas Department of Water Resources. LP-131. 38 p.

Maclay, R.W., T.A. Small, and P.L. Rettman. 1981. Location and analysis of borehole data for the Edwards Aquifer in the San Antonio area, Texas. Texas Department of Water Resources. LP-139. 88p.

Maclay, R.W., and T.A. Small. 1983. Hydrostratigraphic subdivisions and fault barriers of the Edwards Aquifer, south-central Texas. U.S.A.: Journal of Hydrology. v. 61. p. 127–146.

Maclay, R.W., and T.A. Small. 1984. Carbonate geology and hydrology of the Edwards Aquifer in the San Antonio area, Texas: U.S. Geological Survey Open-File Report OFR 83-537, 72 p. 14 sheets.

Maclay, R.W. and T.A. Small. 1986. Carbonate geology and hydrology of the Edwards Aquifer in the San Antonio area, Texas. Texas Water Development Board Report 296. 90p.

Maclay, R.W. and L.F. Land. 1988. Simulation of flow in the Edwards Aquifer, San Antonio Region, Texas, and refinement of storage flow concepts. U.S. Geological Survey Water-Supply Paper2336, 48 pp.

McDaniels, L.L. 1962. Consumptive use of water by major crops in Texas. Texas Board of Water Engineers. Bulletin 6019. 21 p. + attachments.

McKinney, D.C. and J.M. Sharp. 1995. Springflow and augmentation of Comal Springs and San Marcos Springs, Texas: Phase 1–Feasibility Study, Austin Texas: Center for Research in Water Resources, Technical Report CRWR 247. 416 p.

Medina, A. and J. Carrera. 1996. Coupled estimation of flow and solute transport parameters. Water Resources Research, 32(10): 3063-3076.

Medina, A. and J. Carrera. 2003. Geostatistical inversion of coupled problems: dealing with computational burden and different types of data. Journal of Hydrology, 281(4): 251-264.

Miggins, D.P., C.D. Blome, and D.V. Smith. 2004. Preliminary 40Ar/39Ar geochronology of igneous intrusions from Uvalde County, Texas—Defining a more precise eruption history for the southern Balcones Volcanic Province: U.S. Geological Survey Open-File Report 2004–1031. Reston, Virginia. 33 p.

Muller, D.A. and R.D. Price. 1979. Ground-water Availability in Texas, Estimates and Projections Through 2030: Texas Department of Water Resources Report 238. 77 p.

Musgrove, M., and C.L. Crow. 2012, Origin and characteristics of discharge at San Marcos Springs based on hydrologic and geochemical data (2008–10), Bexar, Comal, and Hays Counties, Texas: U.S. Geological Survey Scientific Investigations Report 2012–5126, 94 p.

Murray, G. E. 1961. Geology of the Atlantic and Gulf Coastal Province of North America: New York. Harper and Brothers. 692 p.

Nance, H.S. 2004. Hydrochemical variability in the Edwards-Trinity Aquifer system, Edwards Plateau, Texas. Proceedings of Aquifers of the Edwards Plateau Conference. 63-89 p.

National Weather Service, 2005. http://www.srh.noaa.gov.

Oetting, G.C., J.L. Banner, and J.M. Sharp, Jr. 1996. Regional Controls on the Geochemical Evolution of Saline Groundwaters in the Edwards Aquifer, Central Texas. Journal of Hydrology. Vol. 181. pp. 251–283.

Okerman, D.J. 2005. Simulation of streamflow and estimation of recharge to the Edwards Aquifer in the Hondo Creek, Verde Creek, and San Geronimo Creek watersheds, south-central Texas. U.S. Geological Survey Scientific Investigations Report 2005-5252. Reston, Virginia. 37 p.

Otero, C.L. 2007. Geologic, Hydrologic, and Geochemical Identification of Flow Paths in the Edwards Aquifer, Northeastern Bexar and Southern Comal Counties, Texas. Geological Survey (U.S.) Scientific Investigations Report 2007-5285, vi, 49 p.

Painter, S., J. Yefang, and A. Woodbury. 2002. Edwards Aquifer parameter estimation project final report. Consultants Report to the Edwards Aquifer Authority. Southwest Research Institute. San Antonio, TX.

Painter, S.L., A.D. Woodbury, and Y. Jiang. 2007. Transmissivity Estimation for Highly Heterogeneous Aquifers: Comparison of Three Methods Applied to the Edwards Aquifer, Texas, USA. Hydrogeology Journal, 15(2):315-331.

Palmer, A.N. 2003. Patterns of dissolution porosity in carbonate rocks. Karst Modeling: Special Publication 5, (A.N. Palmer, M.V. Palmer, and I.D. Sasowsky, eds.). Charles Town, West Virginia: The Karst Waters Institute. 71–78 p.

Pantea, M.P., J.C. Cole, B.D. Smith, J.R. Faith, C.D. Blome, and D.V. Smith. 2008. Three-dimensional geologic model in the upper Seco Creek area, Medina and Uvalde counties, south-central Texas. U.S. Geological Survey Scientific Investigations Report 2008-5153. Reston, Virginia. 9 p + attachments.

Pearson, D.K. 2007. Geologic Database of Texas: Project Summary, Database Contents, and User's Guide. Texas Water Development Board, U.S. Geological Survey, Bureau of Economic Geology. Located at: http://tnris.org/data-catalog/geology/geologic-database-of-texas/

Pearson, F.J. and P.L. Rettman. 1976. Geochemical and isotopic analyses of waters associated with the Edwards Limestone aquifer, Central Texas. Edwards Underground Water District Report. Reston, VA: U.S. Geological Survey. 35 p.

Pedraza, D.E. and D.J. Okerman. 2012. Watershed modeling applications in south Texas. U.S. Geological Survey Fact Sheet 2012-3005. Reston, Virginia.

Petitt, Jr., B.M. and W.O. George. 1956. Ground-water resources of the San Antonio area, Texas – A progress report on current studies. Bulletin 5608, Volume I, Texas Board of Water Engineers. 80 p.

Prickett, T.A. and C.G. Lonnquist. 1971. Selected digital computer techniques for ground water resource evaluation. Illinois Water Survey Bill. 55. 62 p.

Puente, C. 1975. Relation of precipitation to annual ground-water recharge in the Edwards Aquifer, San Antonio area, Texas. U.S. Geological Survey Open-File Report 75-298. 31 p.

Puente, C. 1976. Statistical analysis of water-level, springflow, and streamflow data for the Edwards Aquifer in south-central Texas. U.S. Geological Survey Report. 58 p.

Puente, C. 1978. Method of estimating natural recharge to the Edwards Aquifer in the San Antonio area, Texas. U.S. Geological Survey Water Resources Investigations 78-10. 34 p.

Rives, J.S. 1967. Structural and Stratigraphic Traps Related to Extrusive Rocks in South-Central Texas: AAPG Bulletin. Volume 51. DOI: 10.1306/5D25C241-16C1-11D7-8645000102C1865D.

Rose, P.R. 1972. Edwards Group, surface and subsurface, Central Texas. Report of Investigations No. 74. Bureau of Economic Geology, University of Texas, Austin, Texas. 198 p.

Sayre, A.N. 1936. Geology and ground-water resources of Uvalde and Medina Counties, Texas. US. Geological Survey Water Supply Paper 678.

Sayre, A.N. and R.R. Bennett. 1942. Recharge, movement, and discharge in the Edwards limestone reservoir, Texas.

Schindel, G.M., J.F. Quinlan, and J.A. Ray. 1994. Determination of the recharge area for the Rio Springs groundwater basin, near Munfordville, Kentucky: An application of dye tracing and potentiometric mapping for determination of springhead and wellhead protection areas in carbonate aquifers and karst terranes: Project completion report, U.S. Environmental Protection Agency, Groundwater Branch, Atlanta, Ga., 25 p. 33.

Schindel, G. and S. Johnson. 2011. Using tracer testing data for resource management planning. In Interconnection of the Trinity (Glen Rose) and Edwards Aquifers along the Balcones Fault Zone and Related Topics, Proceedings from Karst Conservation Initiative Meeting, February 17, 38. http://www.speleogenesis.info/directory/karstbase/pdf/seka _pdf9869.pdf.

Schultz, A.L. 1994. 1994 Review and Update of the Position of the Edwards Aquifer Freshwater/Saline-Water Interface from Uvalde to Kyle, -Texas. Edwards Underground Water District report 94-05. 31 p.

Sharp, J.M., Jr., and J.L. Banner. 1997. The Edwards Aquifer: A resource in conflict: GSA Today, v. 7, 1–9 p.

Slade, R.M., Jr. 1986. The Balcones Escarpment: Large Rainstorms along the Balcones Escarpment in Central Texas, p.15-19 by. *in* Abbott, Patrick L. and Woodruff, C.M., Jr. eds., The Balcones Escarpment, Central Texas: Geological Society of America, p. 15-20.

Slade, R.M., J.T. Bentley, and D. Michaud. 2002. Results of streamflow gain-loss studies in Texas, with emphasis on gains from and losses to major and minor aquifers. U.S. Geological Survey Open-File Report 02–068. 136 p.

Slattery, R.N. and L.D. Miller. 2004. A water-budget analysis of Medina and Diversion Lakes and the Medina/Diversion lake system, with estimated recharge to Edwards aquifer, San Antonio area, Texas. USGS Scientific Investigations Report: 2004-5209. 17 p.

Small, T.A. 1986. Hydrogeologic sections of the Edwards aquifer and its confining units in the San Antonio area, Texas: U.S. Geological Survey water-Resources Investigations report 85-4259. 52 p.

Small, T.A. and Maclay, R.W. 1982. Test-hole data for the Edwards aquifer in the San Antonio area, Texas. Texas Department of Water Resources. LP-171. 153 p.

Small, T.A. and A.K. Clark. 2000. Geologic framework and hydrogeologic characteristics of the Edwards Aquifer outcrop, Medina County, Texas. Water-Resources Investigations Report 2000-4195.

Smith, B.A., and B.B. Hunt. 2009. Potential hydraulic connections between the Edwards and Trinity Aquifers in the Balcones Fault Zone of central Texas. Bulletin of the South Texas Geological Society, L, 2:15–34.

Smith, B.A., and B.B. Hunt. 2010. Flow potential between stacked Karst Aquifers in Central Texas, USA. In Advances in Research in Karst Media Environmental Earth Sciences, eds. B. Andreo, F. Carrasco, J.J. Duran, and J.W. LaMoreaux. p. 43–48.

Smith, B.A., and B.B, Hunt. 2011. Potential for vertical flow between the Edwards and Trinity Aquifer, Barton Springs Segment of the Edwards Aquifer. In *Interconnection of the Trinity (Glen Rose) and Edwards Aquifers along the Balcones Fault Zone and Related Topics, Proceedings from Karst Conservation Initiative Meeting*. p.11–14.

Smith, C.I., J.B. Brown, and E.E. Lozo. 2000. Regional stratigraphic cross sections, Comanche Cretaceous (Fredericksburg-Washita Division), Edwards and Stockton Plaeaus, West Texas: Interpretation of Sedimentary facies, Depositional Cycles, and Tectonics. Bureau of Economic Geology, The University of Texas, Austin, Texas.

Smith, D.V., B.D. Smith, and P.L. Hill. 2002. Aeromagnetic survey of Medina and Uvalde counties, Texas: A Website for Distribution of Data: U.S. Geological Survey. Open File Report 02-0049. http://greenwood.cr.usgs.gov/pub/open-file -reports/ofr-02-0049/EA_Texas.html.

Smith, D.V., R.R. McDougal, B.D. Smith, and C.D. Blome. 2008. Distribution of Igneous Rocks in Medina and Uvalde Counties, Texas, as Inferred from Aeromagnetic Data. U.S. Geological Survey Scientific Investigations Report 2007–5191. U.S. Geological Survey. Reston, Virginia.

Snyder, G.L. 2004. Boundary condition between Edwards (BFZ) Aquifer and Edwards-Trinity (plateau) Aquifer in Kinney County, Texas Area. Letter to R.E. Mace, Texas Water Development Board with associated fact sheet.

Stein, W.G., and G.B. Ozuna. 1996. Geological framework and hydrogeologic characteristics of the Edwards Aquifer recharge zone, Bexar County, Texas. U.S. Geological Survey Water-Resources Investigations Report 95-4030. 1:75,000 scale. Reston, Virginia. 8 p. 1 plate.

Stricklin Jr., F. I., C. I. Smith, and F. E. Lozo. 1971. Stratigraphy of Lower Cretaceous Trinity deposits of central Texas: University of Texas at Austin, Bureau of Economic Geology, Report of Investigations 71, 63 p.

Szilagy, J., F.E. Harvey, and J.F. Ayers. 2003. Regional estimation of base recharge to groundwater using water balance and a base-flow index. Ground Water. 41(4), 504-514.

Texas Board of Water Engineers. 1960. Channel Gain and Loss investigations, Texas Streams, 1918–1958: Texas Board of Water Engineers Bulletin 5807-D, 270 p.

Texas Water Development Board. 2005. Well Information/Groundwater Data. http://www.twdb.state.tx.us/GwRD/waterwell/well_info.asp.

Thorkildsen, D. and P.D. McElhaney. 1992. Model refinement and applications for the Edwards (Balcones Fault Zone) Aquifer in the San Antonio Region, Texas. Texas Water Development Board. Report 340, 33 p.

Todd Engineers. 2004. Analysis of Recharge and Recirculation, Edwards Aquifer, Phase I. Contract report for the Edwards Aquifer Authority by Todd Engineers.

Todd Engineers. 2005. Analysis of Recharge and Recirculation, Edwards Aquifer, Phase II. Contract report for the Edwards Aquifer Authority by Todd Engineers.

Todd Engineers. 2008. Analysis of Recharge and Recirculation, Edwards Aquifer, Phases III/IV. Contract report for the Edwards Aquifer Authority by Todd Engineers.

Tremallo, R.L, J.M. Hamilton, S. Johnson, R. Esquilin, C. Burgoon, D. Gregory, G. Luevano, M. Schwarz, T. Marsalia, J. Mireles, R. Gloyd, and G. Schindel. 2014. Edwards Aquifer Authority Hydrologic Data Report for 2013. 86 p.

Trescott, P.C., G.F. Finder, and S.P. Larson. 1976. Finite difference model for aquifer simulation in two dimensions with numerical experiments: U.S. Geological Survey Techniques of Water Resources Investigation., chap. C1, *in* book 7, 116 p.

Uliana, M.M., S, N. Johnson, and J. Trungale. 2006. Stream-groundwater interactions in the upper reaches of Pinto Creek; Kinney Count, Texas. National Ground Water Association Summit. San Antonio, TX.

Veni, G. 1988. The caves of Bexar County, second edition. Speleological Monographs, 2, Texas Memorial Museum, Austin, 300 p.

Waiting, D.J., D.A. Ferrill, D.A., and D.W. Sims. 2003. Development of a high-resolution geological framework model for the Edwards Aquifer Recharge Zone: Data, assumptions, procedures, and workflow, South Texas Geological Society Bulletin, v. XLIII, no. 7, p. 13-24.

Watson, J.A. 1985. Recharge investigation, Blanco River into the Edwards Aquifer, Hays County: Texas Department of Water Resources, Interoffice Memorandum, 17 p., 1 plate.

Weeks, A.W. 1945. Balcones, Luling, and Mexica fault zones in Texas: Bulletin of the American Association of Petroleum Geologists. V. 29. 1733–1737 p.

Welder, F.A. and R.D. Reeves. 1962. Geology and ground-water resources of Uvalde County, Texas. Texas Water Commission Bulletin 6212. 246 p.

White, W.B. 2006. Fifty years of karst hydrology and hydrogeology: 1953–2003. In: Harmon RS, Wicks C (eds) Perspectives on karst geomorphology, hydrology, and geochemistry: a tribute volume to Derek C. Ford and William B. White. Geol Soc Am Spec Pap 404:139–152.

White, W.B. and E.L. White. 2001. Conduit fragmentation, cave patterns, and localization of karst ground water basins: The Appalachians as a test case: Theoretical and Applied Karstology, v. 13-14, p. 9-23.

Wong, C.I., J.S. Kromann, B.B. Hunt, B.A. Smith, and J.L. Banner. 2013. Investigation of flow between Trinity and Edwards aquifers (central Texas) using physical and geochemical monitoring in multiport wells, Groundwater (published online Aug 2013). DOI: 10.1111/gwat.12106.

Woodruff, C.M., Jr. 1974. Evidence for stream piracy along the Balcones escarpment, central Texas. Geological Society of America, Abstracts with Programs. 6(7). p. 1010.

Woodruff, C.M., Jr. 1977. Stream piracy near the Balcones fault zone, Central Texas. Journal of Geology. 85(4). pp. 483-490.

Woodruff, C.M., Jr. and P.L. Abbott. 1979. Drainage-basin evolution and aquifer development in a karstic limestone terrain, South-Central Texas, USA. Earth Surface Processes. 4. pp. 319-334.

Woodruff, C. M., Jr. and P.L. Abbott. 1986. Stream piracy and evolution of the Edwards Aquifer along the Balcones Escarpment, Central Texas. In Abbott, P.L. and Woodruff, C.M. Jr. eds., The Balcones Escarpment, Central Texas: Geological Society of America. pp. 77-90.

Worthington, S.R.H. 1999. A comprehensive strategy for understanding flow in carbonate aquifers. In *Karst Modeling*, edited by A.N. Palmer, M.V. Palmer & I.D. Sasowsky, Charles Town, West Virginia: Karst Waters Institute (KWI Special Publication 5).

Worthington, S.R.H. 2004. Conduits and turbulent flow in the Edwards aquifer. Contract report for the Edwards Aquifer Authority. San Antonio, TX.

Young, K. 1972. Mesozoic history, Llano region, *in* V.E., Barnes, W.C. Bell, S.E. Clabaugh, P.E. Cloud, Jr., R.V. McGehee, P.U. Rodda, and K. Young, eds. Geology of the Llano Region and Austin Area, Field Excursion: The University of Texas at Austin Bureau of Economic Geology Guidebook 13. 154 p.