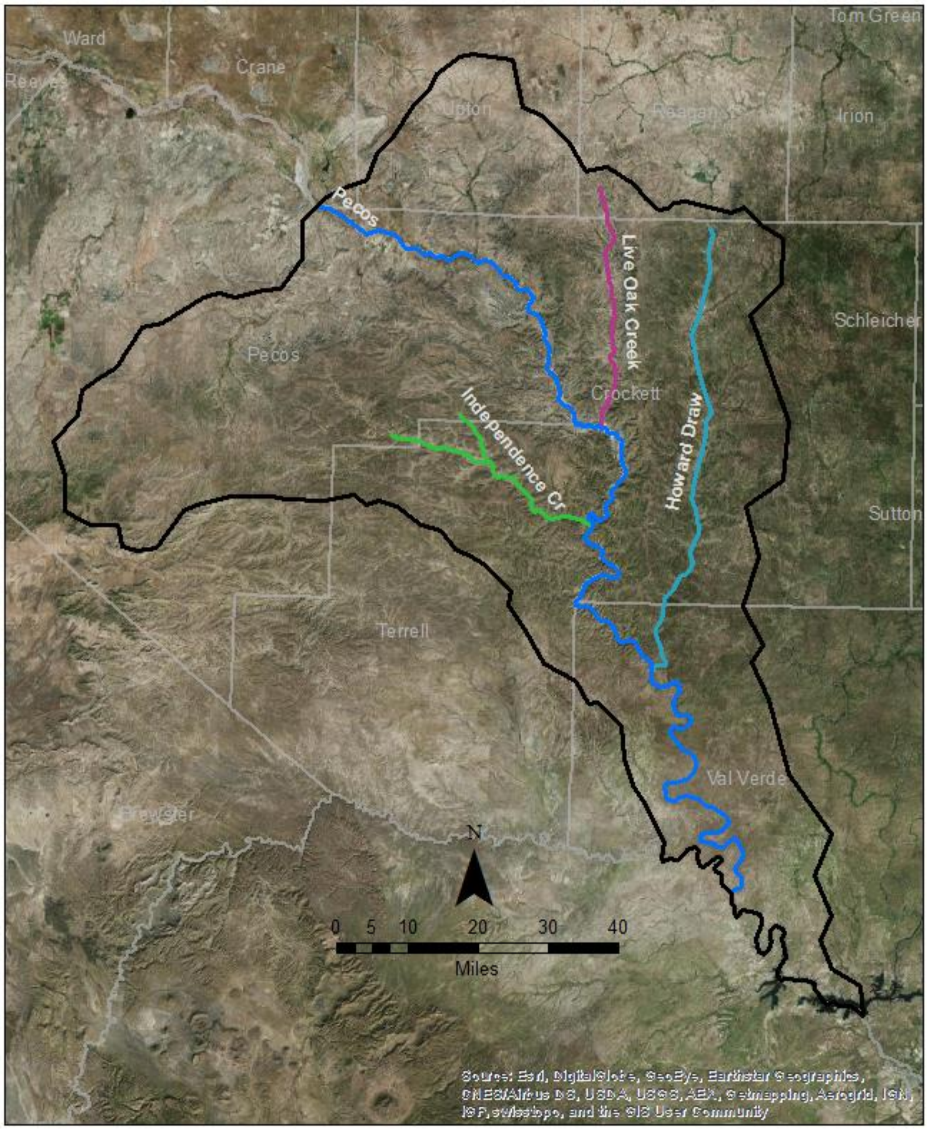
Modeling Groundwater Flow to Understand the Water Resources of the Lower Pecos River Watershed



Final Report

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Introduction

The groundwater resources of many arid and semi-arid regions of the United States and elsewhere are increasingly stressed due to already limited recharge being further reduced by prolonged and more frequent drought cycles as well as increased pumping to supply growing populations. Climate change that results in altered precipitation patterns can exacerbate these stresses, particularly if changes in precipitation result in reduced recharge. While characterization of water resources is desirable wherever water is used, accurate assessment of water availability is especially critical in areas where resources are limited and stressed. In addition, environments where carbonate aquifers are relied on to provide meaningful water supply warrant special considerations when characterizing and managing the water resources. Effective management of the water resources in such environments requires that the groundwater and surface-water regimes be sufficiently characterized and modeled to provide the proper tools to simulate not only groundwater and surface-water flow, but also the hydraulic interactions between the two regimes. A critical factor for effective management is specification of the sustainability of the water resources.

Compounding this challenge is determining what constitutes the sustainable or safe yield of groundwater from a specified domain. This concept has been actively discussed and debated for decades (Lee, 1915; Theis, 1940; Bredehoeft et al. 1982; Sophocleous, 1997; Alley and Leake, 2004; Watson et al., 2014). On one end of the debate, development of groundwater is considered safe if the rate of groundwater extraction does not exceed the rate of recharge. The term "safe yield," when defined as the attainment and maintenance of a long-term balance between the amount of groundwater withdrawn annually and the annual amount of recharge, reflects this perspective, but has been discredited as an indicator of sustainability (Sophocleous, 1997). Conversely, sustainable yield can be defined as a function of increased recharge and decreased discharge induced by pumping. A critical aspect to sustainable yield is the effect of pumping on surface water flow, which highlights the need to effectively characterize both surface water and groundwater in addition to their hydraulic interaction. A general quantitative method to define "sustainability" has been elusive; thus, sustainable yield is typically formulated with respect to specific water-management objectives and the constraints associated with the targeted resources.

The Rio Grande is sourced by water from Colorado, New Mexico, Texas, and Mexico. Approximately 1,600,000 acre-ft/yr flows into the Amistad Reservoir. The Amistad Reservoir receives 600,000 acre-ft/yr of its average annual input from within Val Verde County, Texas (Green and Bertetti, 2010; Green et al., 2012, 2014). The water demand of the lower Rio Grande region is estimated at approximately 1,500,000 acre-ft/yr (Reclamation and the Rio Grande Regional Water Authority, 2013), of which approximately 1,000,000 acre-ft/yr is from surface water provided by the Rio Grande. The majority of the 1,000,000 acre-ft/yr of surface water used in the lower Rio Grande is taken from the 1,600,000 acre-ft/yr of water discharged from the Amistad Reservoir. The Rio Grande is recharged downstream of Amistad Dam from San Felipe (65,000 acre-ft/yr) and Cienegas (8,700 acre-ft/yr) springs, both located in Del Rio, Texas

(Ashworth and Stein, 2005). Contributions to flow in the Rio Grande from watersheds in Mexico downstream of Amistad Reservoir are not well characterized or quantified.

The principal sources of inflow to the Rio Grande within Val Verde County are the Devils River (263,000 acre-ft/yr), Pecos River (195,000 acre-ft/yr), and Goodenough Spring (103,000 acre-ft/yr) (Heitmuller and Reece, 2003; Kamps et al., 2009; Green and Bertetti, 2010; Green et al., 2014). Although the Pecos River contributes 9.5 percent of the recharge to the Amistad Reservoir, it contributes 26 percent of the total salt loading (Miyamoto et al., 2006). High salinity of the Pecos River is attributed to saline intrusion from both surface water and groundwater coupled with a reduction in flow since the 1930s due to increased groundwater extraction (Miyamoto et al., 2008). Based on these observations, it is clear that water-resource management actions that affect flow to the Amistad Reservoir would have a direct impact on the quantity and quality of water available to the lower Rio Grande region.

The objective of the study is to develop a groundwater flow model for the lower Pecos River watershed (Figure 1). Stewards assigned to oversee the water resources of the Pecos River watershed would be better positioned and prepared to make decisions regarding management of its water resources if its water resources were assessed using refined conceptual and numerical surface water and groundwater flow models. Thus, a groundwater flow model that is capable of representing the lower Pecos River watershed is needed to be able to accurately evaluate proposed or potential groundwater management scenarios.

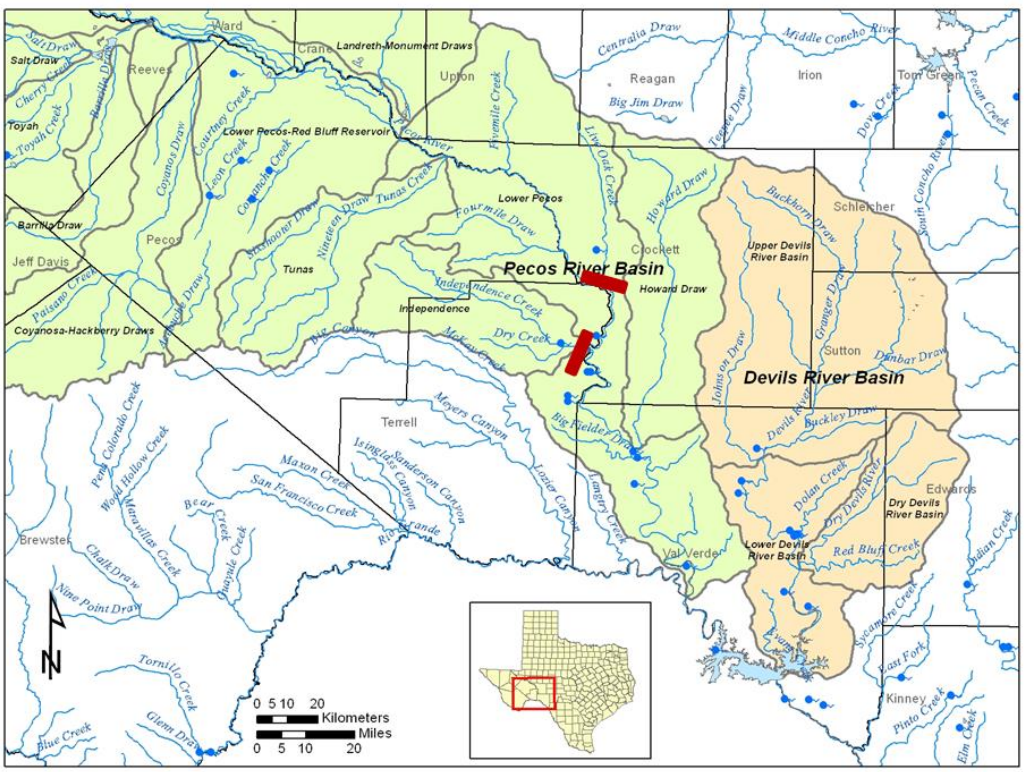


Figure 1. Map of the lower Pecos River watershed. Resistivity survey locations are denoted by a red bar.

Background

Regional studies of the lower Pecos River watershed include Davis and Leggat (1965), Bush (1986), Richey et al. (1985), Kuniansky (1989, 1990), Lurry and Pavlicek (1991), Barker and Ardis (1992, 1996), Ardis and Barker (1993), Bush et al. (1993, 1994), Barker et al. (1994), Boghici (2004), and Beach et al. (2006). Local investigations of the lower Pecos River watershed include Reeves and Small (1973), McKee et al. (1990), Brown Engineering Company (2003), Ashworth and Stein (2005), and Thornhill Group, Inc. (2008). Water quantity and quality studies include Grozier et al. (1966), Walker (1979), Rees and Buckner (1980), Armstrong (1995), Hopkins (1995), Nance (2002, 2003, 2010), and Pearson et al. (2012). Supporting documentation of the water resources of the study area has been prepared for Regional Water Planning Groups (LBG-Guyton and Associates, 2001, 2010; Plateau Water Planning Group 2006; Plateau Underground Water Conservation & Supply District, 2009; Region F Water Planning Group, 2009; Freese and Nichols and LBG-Guyton and Associates, 2009a,b; LBG-Guyton and Associates and Freese and Nichols, 2010; Stein, 2010).

Previous Groundwater Flow Models

Previous groundwater flow models developed for the study area were regional in scale and focused on the Edwards-Trinity Aquifer. These models include: (i) the Regional Aquifer-Studies Area (RASA) model developed by the U.S. Geological Survey (USGS) (Kuniansky and Holligan, 1994) and (ii) the Groundwater Availability Model (GAM) developed by and for the Texas Water Development Board (Anaya and Jones, 2004; 2009; Young et al., 2009; Hutchison et al., 2011). Because these models are regional in scale, they included multiple watersheds, and did not provide sufficient local detail to support watershed scale or water resource management assessments. Recently, the USGS developed a local-scale groundwater model of the southwestern side of Pecos River in Pecos County (Bumgarner et al., 2012; Clark et al., 2014). The down-gradient portion of the USGS model extends into part of the up-gradient portion of the lower Pecos River watershed groundwater model developed for this study.

River Description

The Pecos River is an iconic water body that traverses 926 miles of arid and semi-arid landscapes from its headwaters at an elevation of over 12,000 feet on the western slope of the Sangre de Cristo Mountains in northern New Mexico to its discharge into the Rio Grande in west-central Texas. The extent of the watershed is about 44,300 square miles. Pecos River flow is regulated by the installation and operation of five dams in New Mexico: Santa Rosa Dam, Sumner Dam, Avalon Dam, Brantley Dam, and Red Bluff Dam. Although the Pecos River has no dams in Texas, river flow measurements taken over time show that river flow in Texas has been significantly impacted by anthropogenic activities. The most downstream dam on the Pecos River, the Red Bluff Dam, forms the Red Bluff Reservoir at the New Mexico/Texas state border (Figure 1). Pecos River discharge into Texas is strongly affected by release from Red Bluff Dam. Except during floods, Pecos River flow for a considerable distance downstream from the Red Bluff Reservoir consists principally of releases from the reservoir and some reservoir seepage. Nonetheless, the Pecos River can still be dangerous during heavy thunderstorms due to flooding.

Discharge from New Mexico to Texas via the Pecos River is regulated by the Pecos River Compact, a binding, yet somewhat disputed, agreement between the states of New Mexico and Texas. The purpose of the Compact is to guarantee that certain minimum flows are released to Texas. The 1948 Compact was amended by decree in 1988 and again in 2003 to provide for better accounting during periods of low flow (US Supreme Court, 1988 and Chaves County Fifth Judicial District). Although this assessment targets the lower Pecos River and focuses on flow downstream of Fort Stockton, Texas, it is necessary to evaluate river flow as it is affected by dams and other anthropogenic activities in the upstream reach to be able to understand flow in the lower reach.

The earliest known flow measurements of the Pecos River were taken in 1918, during which surface flow in the lower Pecos River increased from an average of 8.28 cubic feet per second (cfs) at Grandfalls, Texas to 218 cfs at Comstock, Texas (Grover et al., 1922) (Figure 2**Error! Reference source not found.**). Two reports from 1966 and 1968 publish results of flow measurements made along the 188-mile reach between Red Bluff Dam and Girvin, Texas (Grozier et al., 1966, 1968) (Figure 3). A flow study of the reach from Girvin, Texas to the confluence of the Pecos River with the Rio Grande was also published in 1970 (Spiers and Hejl, 1970), with measured flow increasing from 25.9 cfs to 134 cfs along this reach. The dramatic increases in Pecos River flow at Live Oak Creek and Independence Creek (291 and 326 miles downstream of Red Bluff Dam, respectively) is illustrated in Figure 3 (Spiers and Hejl, 1970). As illustrated in Figure 3, the river is gaining in the lower Pecos River, beginning approximately midway between Galvin and the confluence with Live Oak Creek, with only limited flow entering the Pecos River upstream of the confluence with Live Oak Creek.

As illustrated in Figure 3, there is a dramatic decrease in flow by the time the Pecos River enters Pecos County (i.e., approximately 120 miles from Red Bluff Dam). River flow remains low until the contributions from Live Oak Creek, Independence Creek, and Howard Draw increase flow approximately 270 miles downstream from Red Bluff Dam. As also illustrated in Figure 3, the river is gaining in the reach containing the confluence with Live Oak Creek, Independence Creek, and Howard Draw and only limited flow in the Pecos River enters the upstream boundary of the model domain. Discharge from the Pecos River to the Amistad Reservoir is measured at the International Boundary and Water Commission river gauge near Langtry (http://www.ibwc.state.gov/Water_Data/rio_grande_WF.html#Stream).

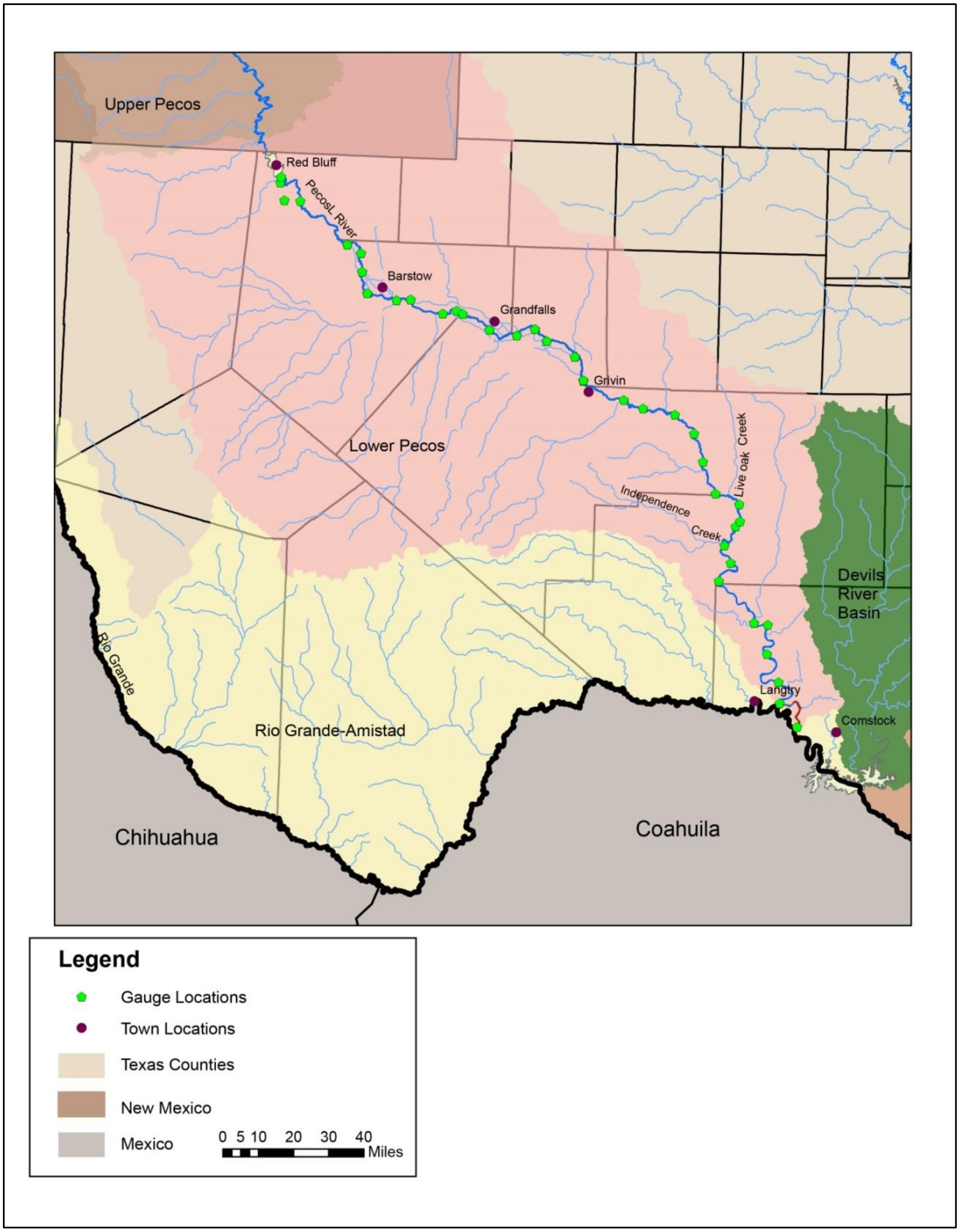


Figure 2. Locations of flow measurements taken on the Pecos River

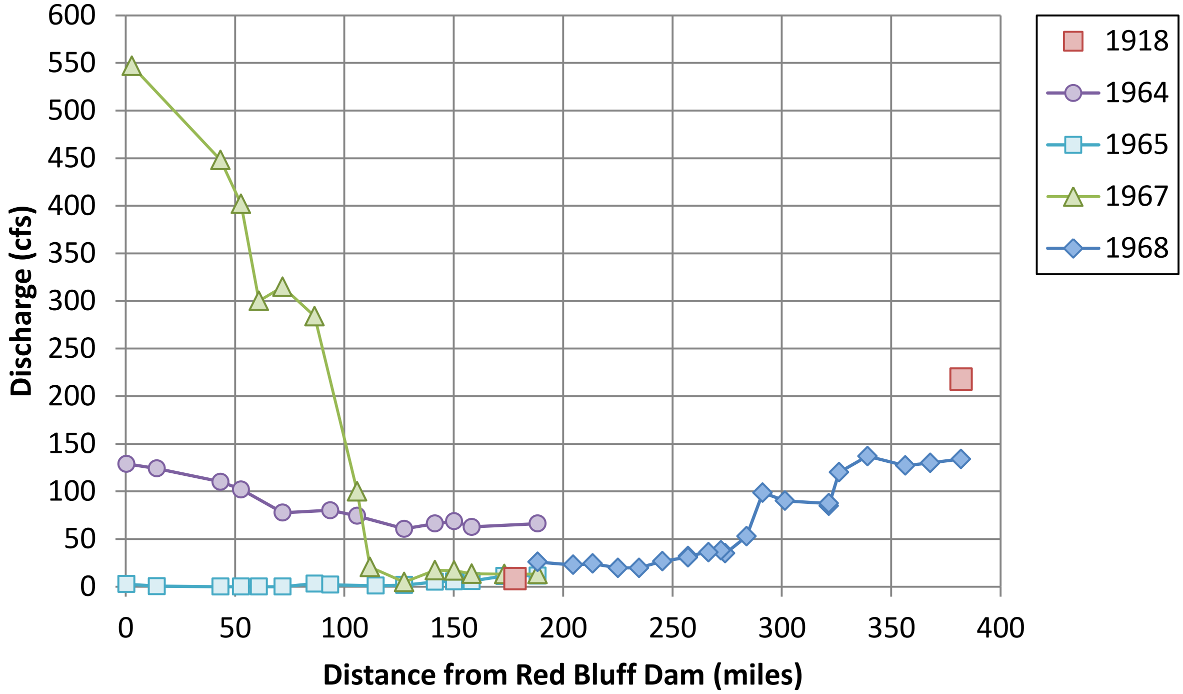


Figure 3. Discharge in the Pecos River intermittently measured between 1918 and 1968 (Spiers and Hejl, 1968)

Study Domain

The domain of the study encompasses the lower Pecos River watershed (Figure 4**Error! Reference source not found.**). The downstream boundary is the confluence of the Pecos River watershed with the Rio Grande. Discharge from the Pecos River watershed to the Rio Grande is believed to occur mostly as surface water although limited subsurface discharge is possible (Green and Bertetti, 2010; Green et al., 2012, 2014). This assumption is based on the observation that the lower reach of the Pecos River is a gaining river and that most of the water flowing through the Pecos River watershed occurs as surface-water flow. The lateral boundaries of the model domain are designated as coincident with the topographic boundaries of the Pecos River watershed. Although, in general, surface-watershed boundaries are not necessarily coincident with the boundaries of the groundwater basin, particularly in carbonate aquifers, there is insufficient information on the lower Pecos River watershed to specify if and where the surface watershed and groundwater basin area boundaries diverge (Ford and Williams, 1989; White and White, 2001; White, 2006). The lateral boundaries of the model domain were specified at the perceived groundwater catchment boundaries so that they could be designated as no-flow boundaries in the numerical model.

The upstream boundary of the model domain was located so that the model domain includes the preponderance of the Pecos River watershed that contributes to the volume of river flow that discharges to Amistad Reservoir (Grover et al., 1922; Grozier et al., 1966, 1968; Spiers and Hejl, 1970). Delineating the lower reach of the Pecos River watershed as a separate model domain from the entire Pecos River watershed is made feasible by virtue of the fact that groundwater extraction near Roswell and Carlsbad, New Mexico (Thomas, 1963) and in the vicinity of Fort Stockton, Texas (Grozier et al., 1966, 1968) intercepts a significant portion of water that flows from the upper reaches of the Pecos River watershed as either surface water or groundwater. As a consequence, discharge of the Pecos River to the Amistad Reservoir is derived mostly from the main tributary watersheds in the lower Pecos River watershed, namely Live Oak Creek, Independence Creek, and Howard Draw watersheds (Brune, 1975; Brown Engineering, 2003). The contribution from the upper Pecos River watershed to the lower Pecos River watershed is small compared with the contributions from these three watersheds (Spiers and Hejl, 1970). Nonetheless, the amount of groundwater flow into the upgradient boundary of the model domain is not accurately known and is estimated during model calibration. Verification of the lower Pecos River watershed groundwater model will help determine the validity of the premise that most water discharged from the Pecos River watershed to the Amistad Reservoir is from Live Oak Creek, Independence Creek, and Howard Draw watersheds.

Hydrostratigraphy

A description of the stratigraphy and structural geology of the Edwards Plateau is taken from the USGS Regional Aquifer Study Analysis of the Edwards-Trinity Aquifer (Bush, 1986; Kuniansky, 1989, 1990; Barker and Ardis, 1992, 1996; Ardis and Barker, 1993; Bush et al., 1993, 1994; Barker et al., 1994) and the USGS study of the water resources of the Pecos County area (Pearson et al. 2012; Bumgarner et al., 2012; Clark et al., 2014). Figure 5 summarizes stratigraphy representative of the lower Pecos River watershed**Error! Reference source not found.**. The Cretaceous-age stratigraphy in the Edwards Plateau consists of the Comanche

Series, which is divided into, from oldest to youngest, the Trinity, Fredericksburg, and Washita Groups. The Trinity Group consists of Hosston, Sligo, Pearsall, and Glen Rose Formations and the Paluxy Sand. The Antlers Formation lies at the base of the Trinity Group. The Fredericksburg Group consists of the Walnut, Comanche Peak, Edwards, and Kiamichi Formations. The Washita Group consists of the Georgetown, Del Rio, Buda, and Eagle Ford Formations. There is a range of thicknesses and occurrences of these stratigraphic units throughout the Edwards Plateau; however, the altitude of the top of the Trinity Group decreases from a high of over 3,000 ft mean sea level (msl) in Ector County to a low of 0 ft msl in southern Val Verde County.

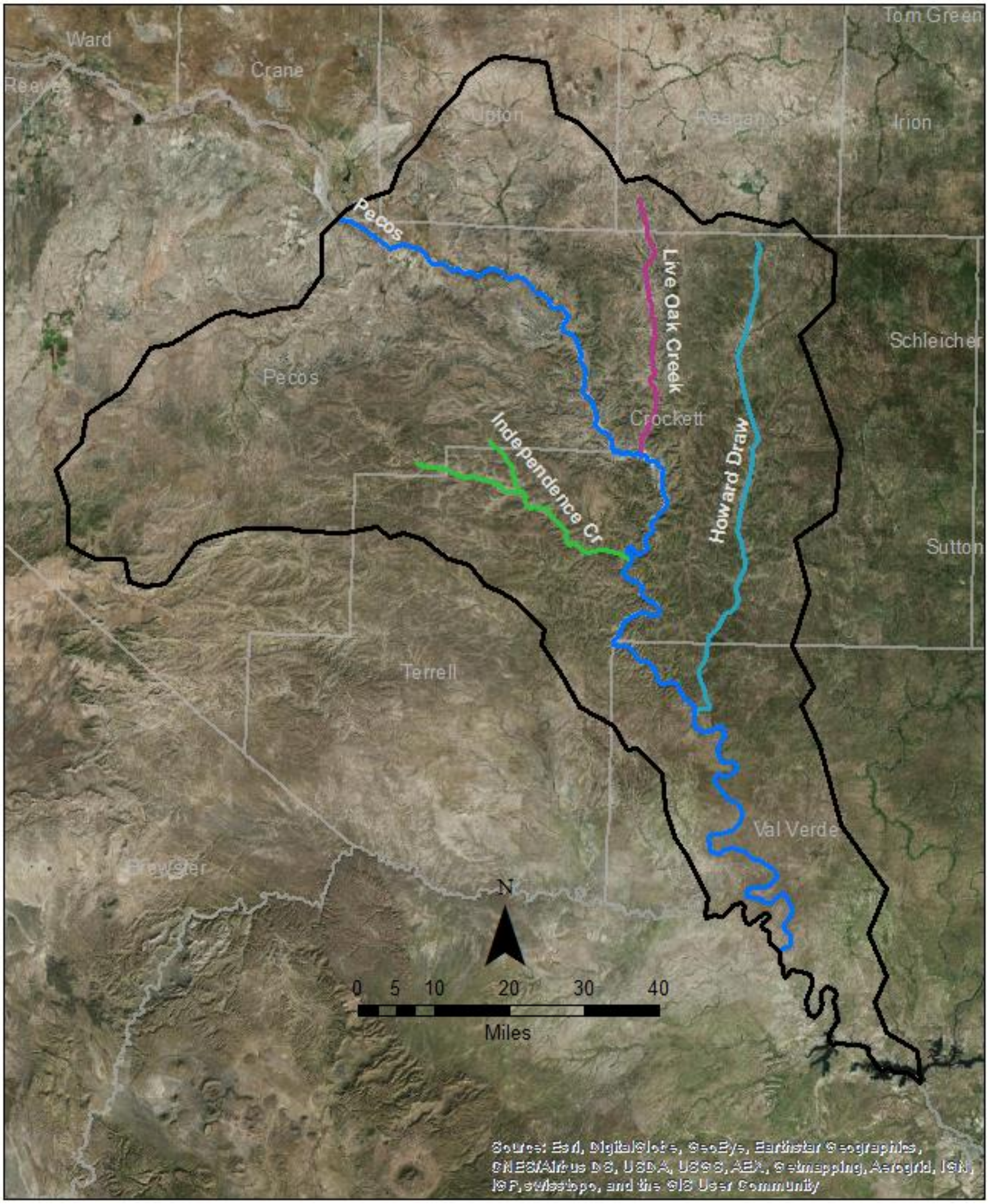


Figure 4. Map of the lower Pecos River watershed. Major tributaries are illustrated by color.

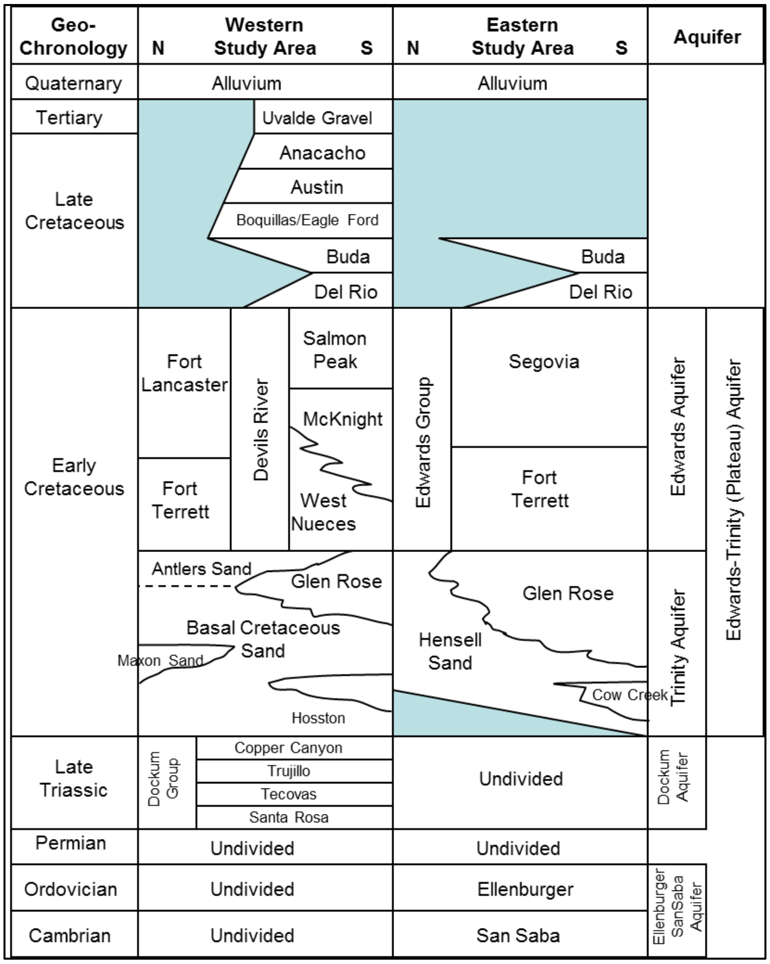


Figure 5. Stratigraphy of the study area

The Edwards-Trinity Aquifer is the major aquifer in the model domain. The Pecos Valley Aquifer, which is designated as a major aquifer northwest of the study domain, is only present in the model domain in a zone adjacent to the Pecos River that extends from the upgradient boundary for 18 miles along the Pecos River. The Edwards-Trinity Aquifer includes all rocks of the Fredericksburg Group from the base of the Antlers Formation to the top of the Georgetown Formation. The Edwards portion of the Edwards-Trinity Aquifer is the principal water-bearing unit in the model domain. Regional flow of groundwater in both the Pecos Valley and the Edwards-Trinity aquifers in the model domain is southerly, although local flow is toward river and stream beds. The base of the Cretaceous rocks dips to the south and southeast.

Groundwater Elevation Data

Groundwater elevation data for the lower Pecos Basin were assembled from the Texas Water Development Board database, and were analyzed to construct a map that represents groundwater elevations. **Error! Reference source not found.**Figure 6 shows the lower Pecos River watershed groundwater elevations for average conditions. These data are consistent with previous water elevation data (Muse, 1965). In addition to creating water elevation maps, wells with water level datasets that have long periods of record were identified for use in transient calibration.

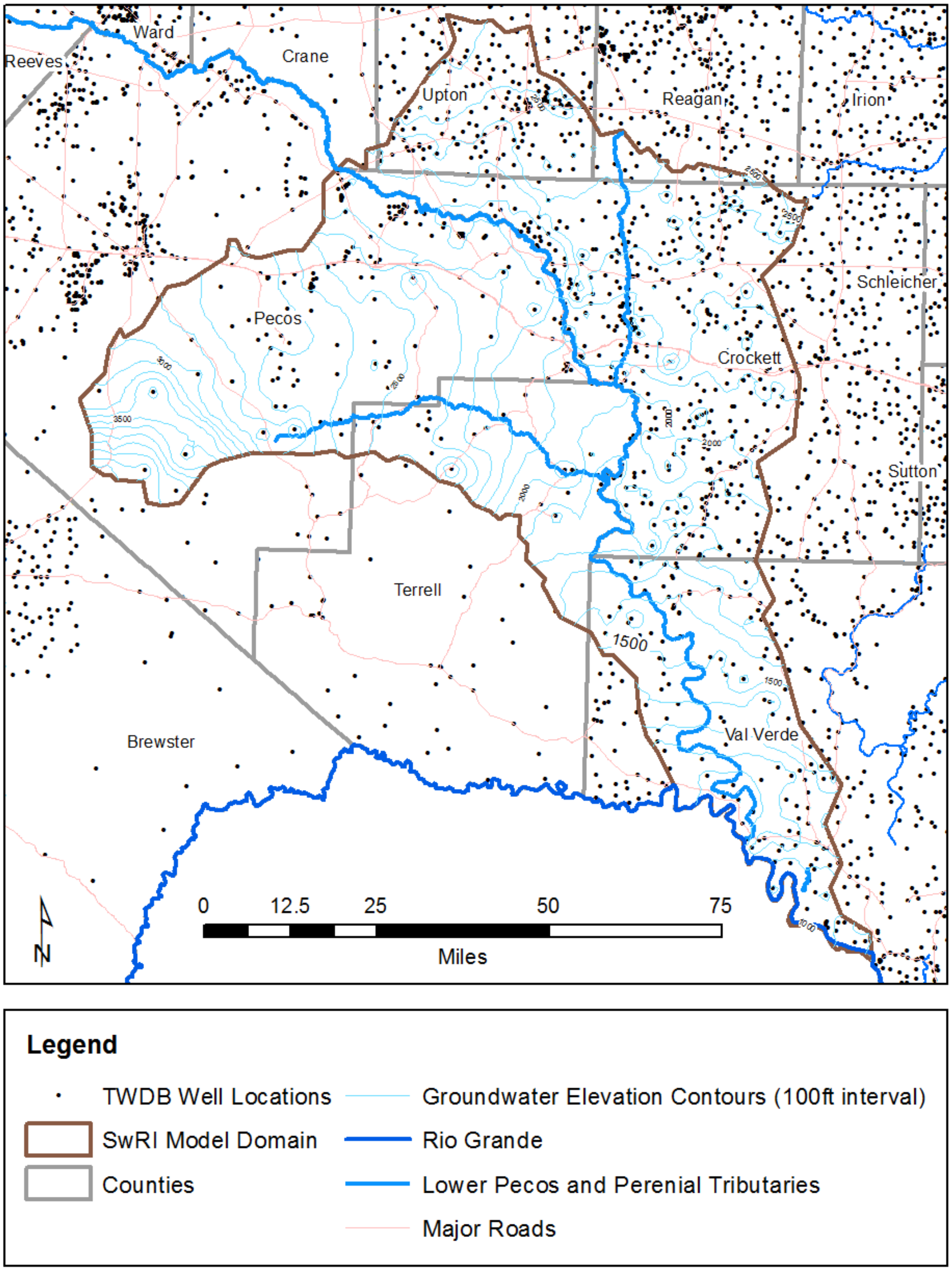


Figure 6. Location of the lower Pecos River and the selected model domain with interpolated groundwater elevation contours (ft, above mean sea level amsl).

Streamflow Data

Flow data for the gauge on the Pecos River near Langtry, Texas (Gauge 8447410) were acquired from the International Boundary and Water Commission. The gauge location is shown in Figure 7**Error! Reference source not found.**. Pecos River flow at Langtry is assumed to represent the downgradient discharge from the Pecos River watershed to the Amistad Reservoir. These data were used in calibration of the groundwater numerical model.

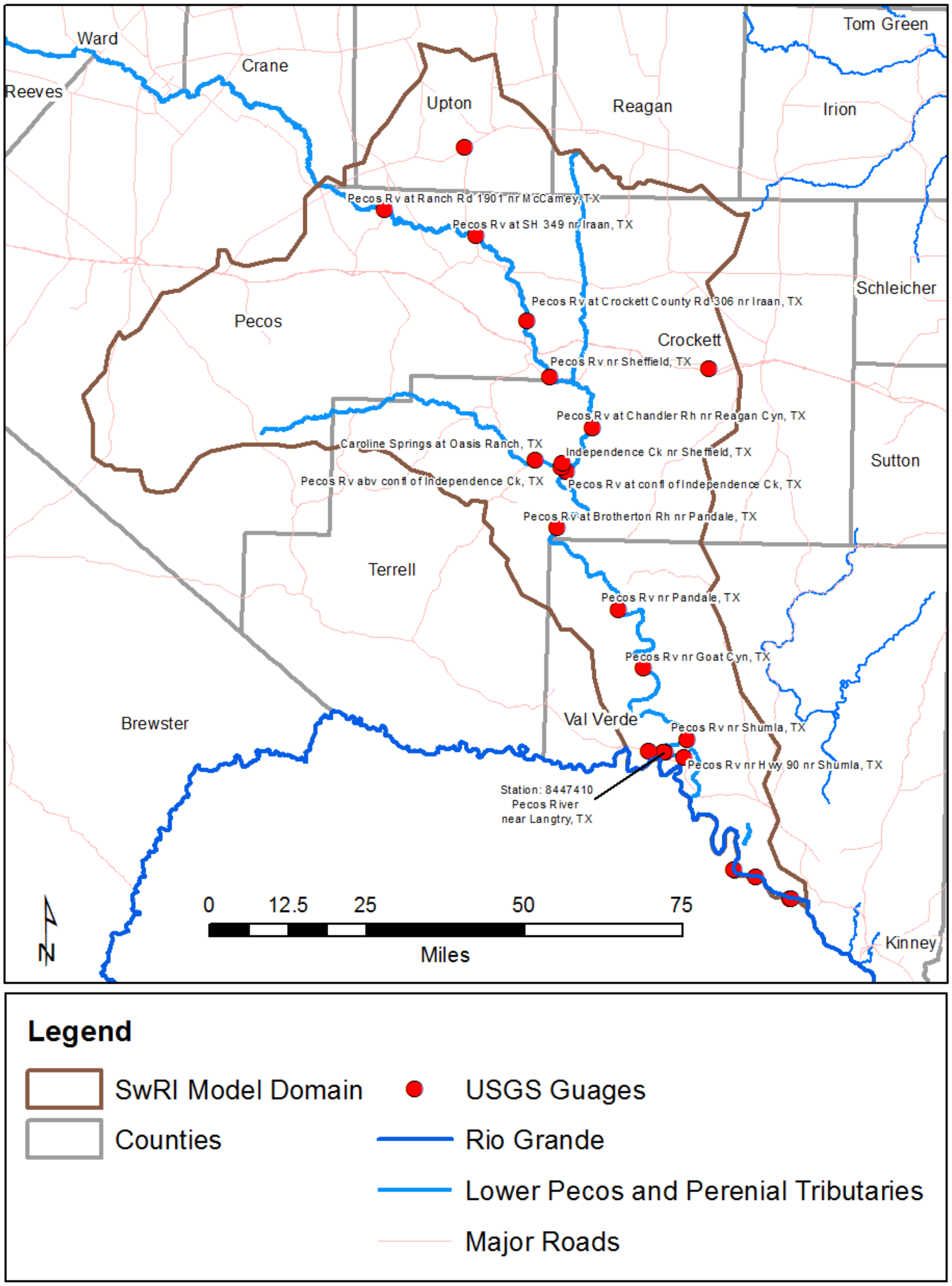


Figure 7. Location of USGS river gauging stations relative to the study domain

Electrical Resistivity Survey

An electrical resistivity survey was conducted at two locations in the Pecos River watershed (see Figure 1) to provide insight on the permeability structure of the subsurface proximal to river channels incised in the Edwards-Trinity Aquifer. Bedrock within the major river channels in the Devils River watershed has been hypothesized to have preferential flow paths aligned with major river channels (Green et al., 2014). The survey locations targeted Live Oak Creek and Independence Creek, the two most prominent tributaries discharging to the lower Pecos River. Both surveys were located immediately upstream from the confluence of the creeks with the Pecos River.

The electrical resistivity survey was conducted using a 96-electrode, 10-channel Syscal Pro electrical resistivity system (IRIS Instruments, Orleans, France). The measured resistivity data were inverted to provide a geo-electrical image of the subsurface using EarthImager 3D, Version 1.5.4 (Advanced Geosciences Inc., 2008). A pole-dipole array was employed in all transects. The dipole separation was 16 ft. The depth of investigation was approximately 200 ft.

The first survey was conducted along River Road where it crosses Live Oak Creek (denoted as DR-7) (Figure 8). The survey transect is located less than one-half mile to the east of the confluence of Live Oak Creek and the Pecos River. The second survey was conducted at the Oasis Ranch and crossed Independence Creek (Figure 9 and 11), less than two miles west of the confluence of Independence Creek and the Pecos River. This survey consisted of two transects (DR-8 and DR-9).

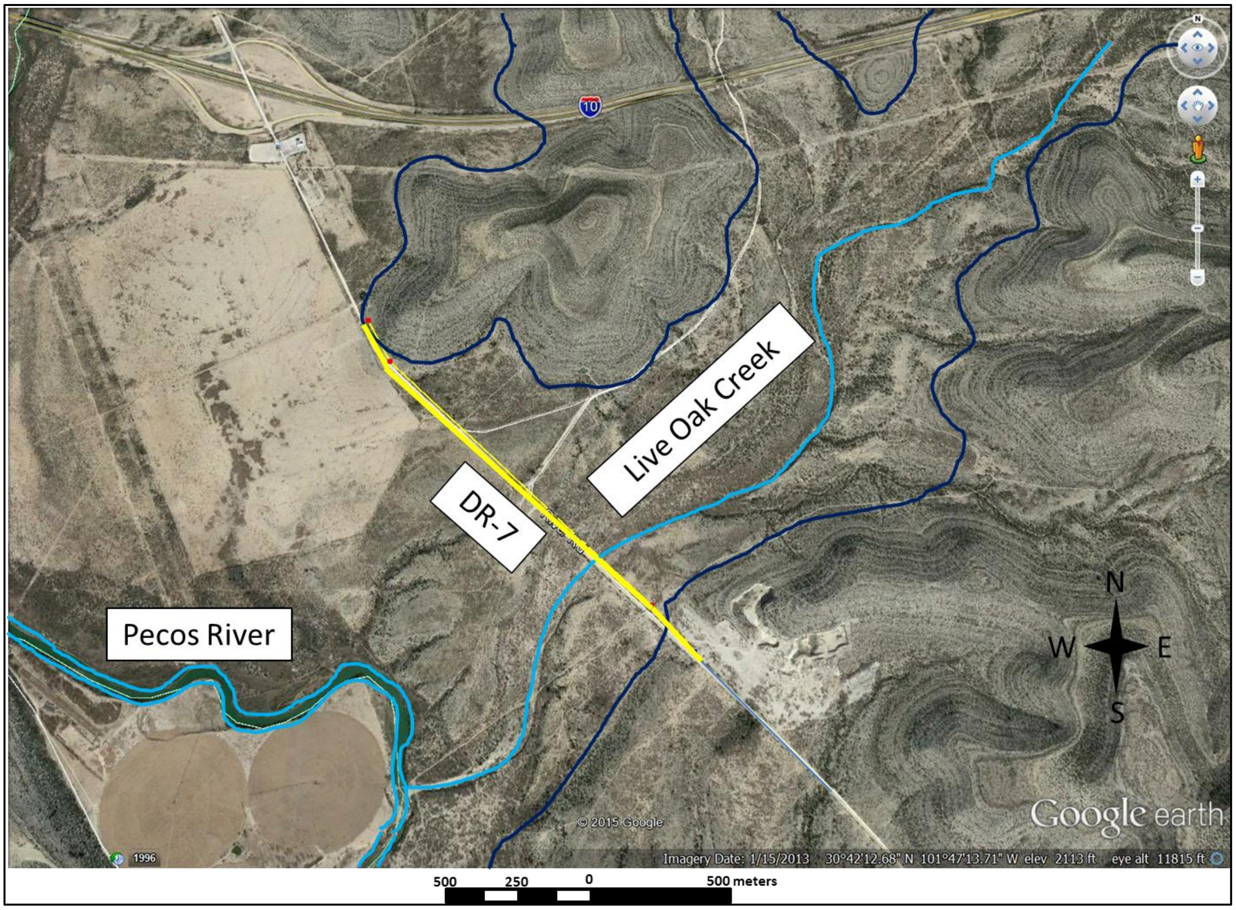


Figure 8. Location of the electrical resistivity geophysical survey transect that crosses Live Oak Creek (denoted with a yellow line and red boxes). The main active channels of Live Oak Creek and the Pecos River are denoted in light blue. The extents of the rivers' flood plains are interpreted to coincide with limestone bedrock outcrops (dark blue line).

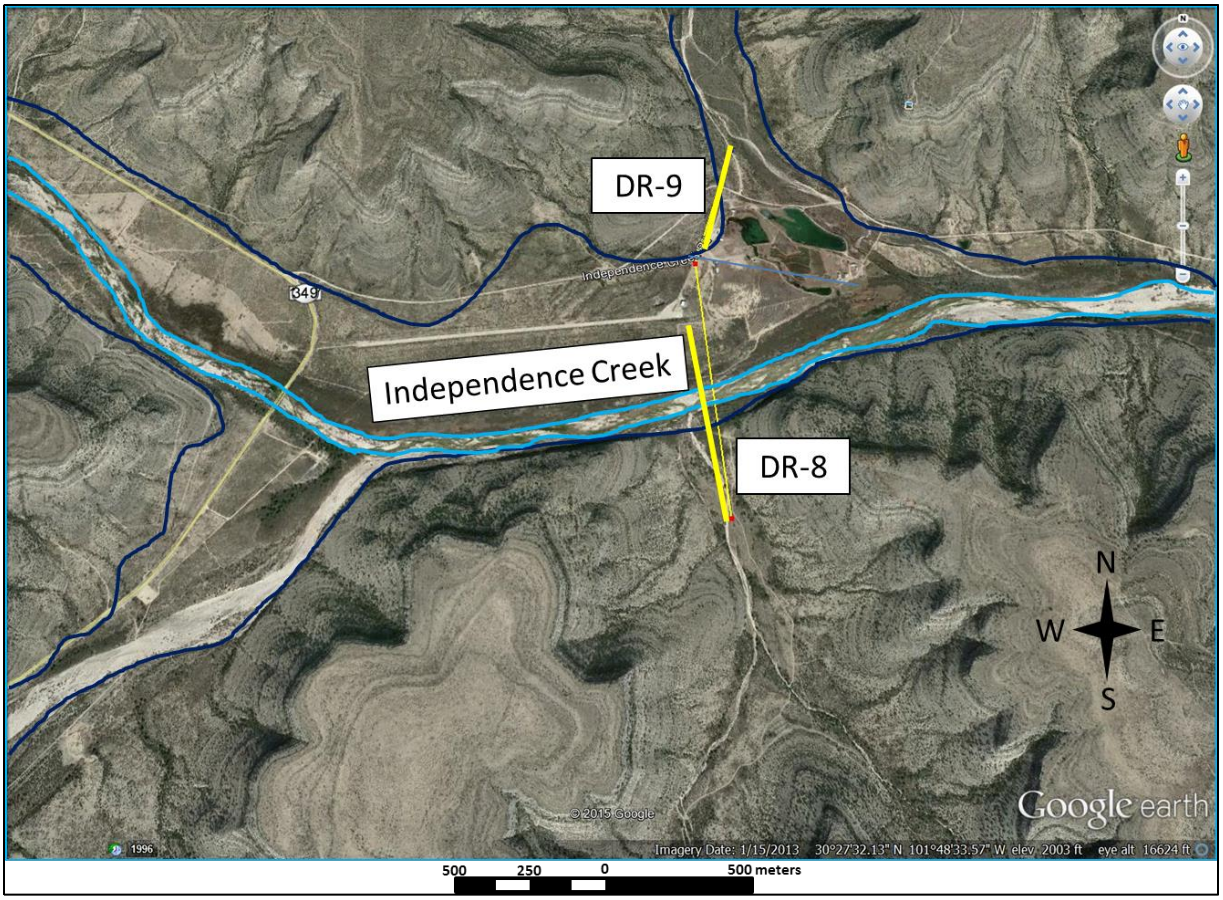
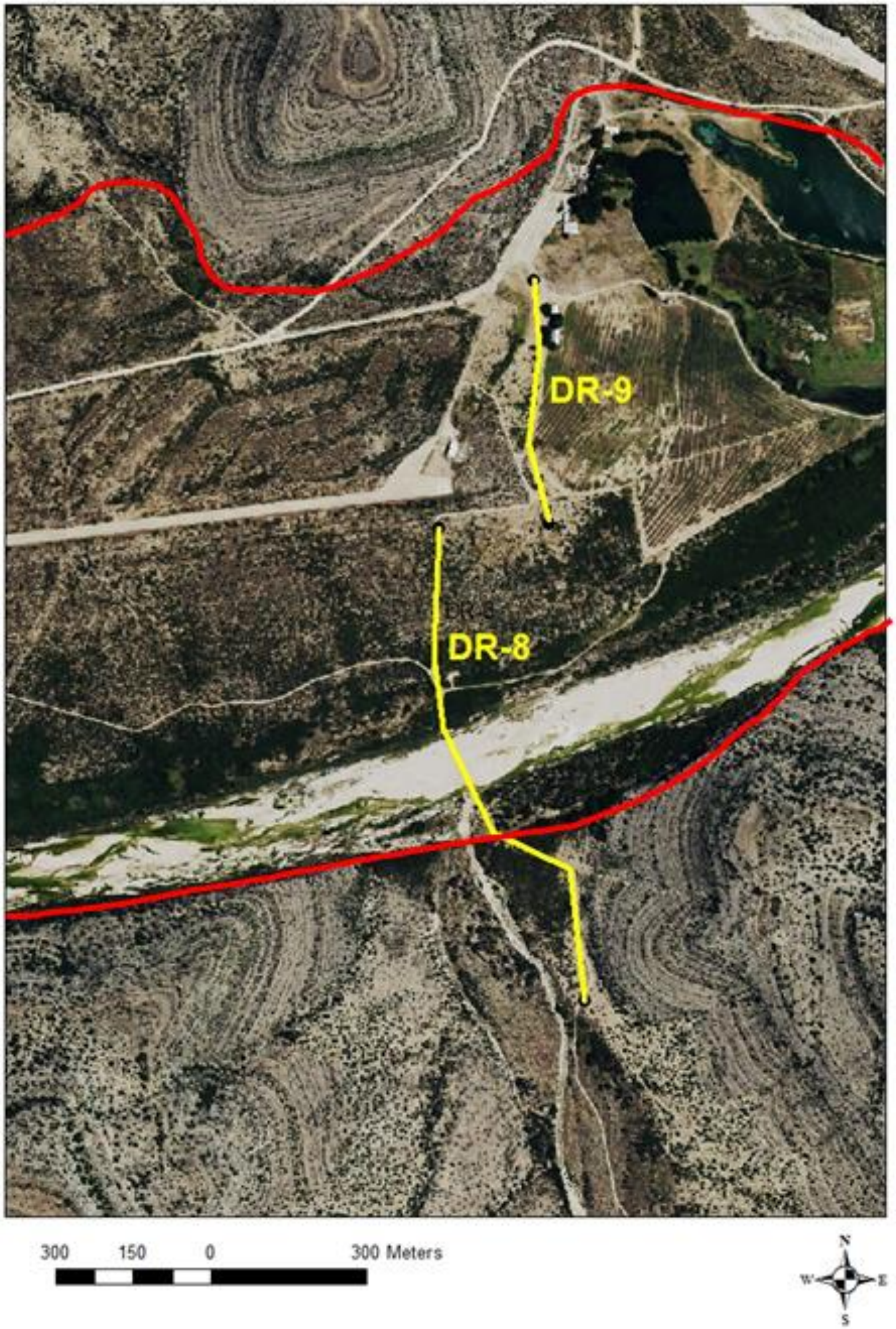


Figure 9. Location of the electrical resistivity geophysical survey transect that crosses Independence Creek (denoted with a yellow line). The main active channel of Independence Creek is denoted in light blue. The extents of the flood plains are interpreted as where limestone bedrock crops (dark blue line).

Figure 10. Close in view of the location of the electrical resistivity geophysical survey transect that crosses Independence Creek (denoted with yellow). The flood plain of Independence Creek is denoted in red.



Results of the Live Oak Creek electrical resistivity surveys are presented in Figure 11. Transect DR-7 indicates that a more electrically resistive layer at the surface overlies more electrically conductive material at depth. The electrically resistive layer is approximately 40-80 ft thick. There appears to be a layer of more electrically conductive material that overlies the electrically resistive layer on the southeast side of Live Oak Creek. The exact nature of the subsurface geology at transect DR-7 is not clear; however, it is apparent that the transect is not underlain with competent limestone, which would have large electrical resistivity. If the subsurface geology is limestone, then the limestone is either significantly weathered or contains significant clay, which would explain the electrically conductive (i.e., small electrical resistivity) signature. A more likely interpretation is that the underlying electrically conductive material is floodplain sediments, implying that the overlying electrically resistive material is coarser sands and gravels.

The second electrical survey was conducted at the Oasis Ranch, located on Independence Creek approximately two miles west of the confluence of Independence Creek and the Pecos River (Figure 9 and 11). Electrical resistivity cross sections at this location are presented in Figure 12. There is some similarity with the electrical resistivity transect on Live Oak Creek (Figure 11) in that there is underlying material with a signature of low electrical resistivity. There are some electrically resistive materials at the surface on the north end of DR-8 and the south end of DR-9. There is additional electrically resistive material at depth in the north portion of DR-9 and the south portion of DR-8. These complex profiles are difficult to interpret in the absence of borehole data or other corroborating information; however, the broad expanse of low electrically conductive material in the north half of DR-8 is likely floodplain sediments. The high electrically resistive material at depth in the south half of DR-8 is possibly competent limestone.

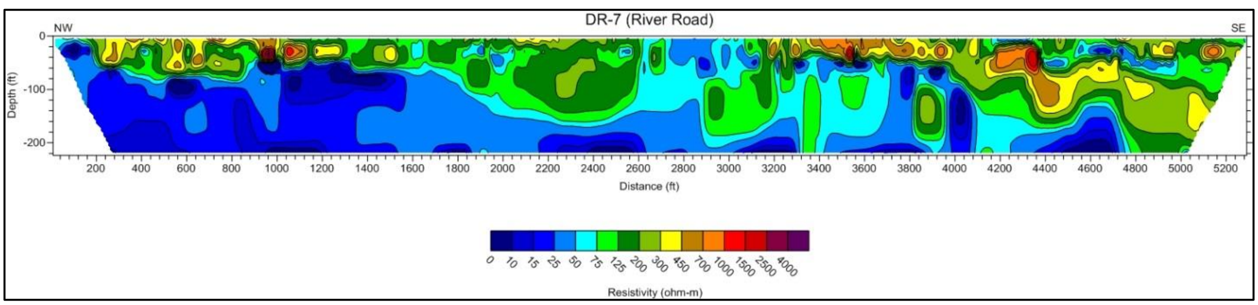


Figure 11. Electrical resistivity transect DR-7, located along River Road where it crosses Live Oak Creek. Resistivity is in ohm-m.

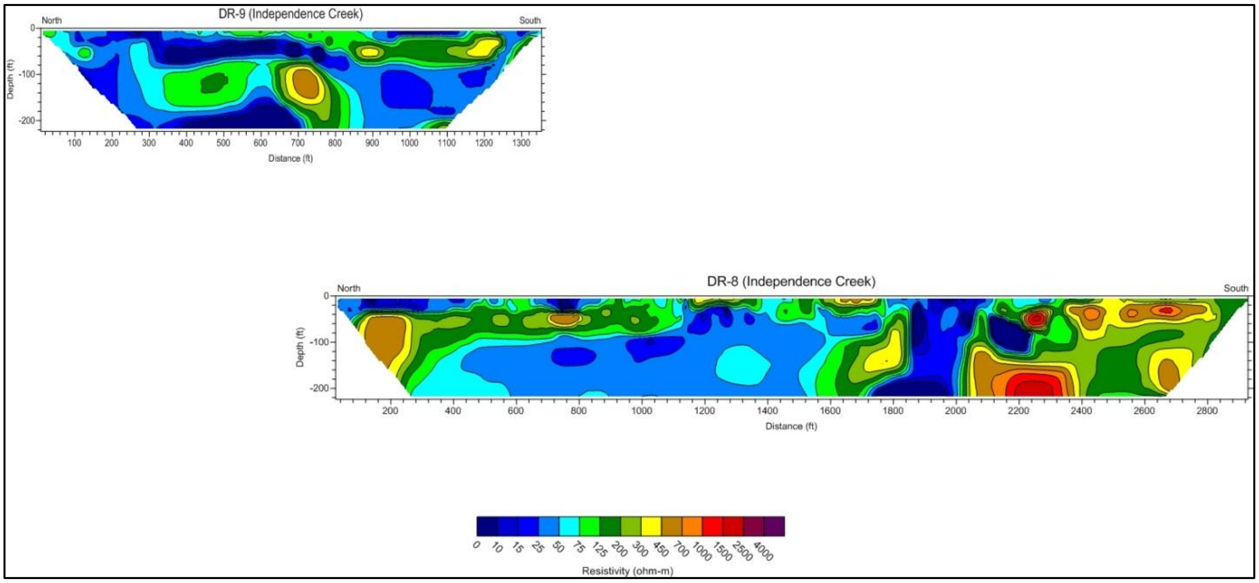


Figure 12. Electrical resistivity transects DR-8 and DR-9, located at the Oasis Ranch on Independence Creek and approximately two miles west of the confluence of Independence Creek within the Pecos River. Resistivity is in ohm-m.

Model Construction

The FEFLOW modeling package (Diersch, 2014) was selected as the model code and pre/post-processor for this modelling effort. The approach to model construction was to create a realistic reproduction of the physical environment with simplifications required for numerical efficiency. To accommodate the deep incisions of the Pecos River in the southern portion of the domain and the potential for steep gradients, the mesh has been refined along streambed alignments. The model mesh is shown in Figure 13. An oblique view of the model mesh is shown in Figure 14. Cross-sections through the model domain and mesh are shown in Figure 15 and Figure 16. Figures 15 and 16 also indicate the calibrated steady-state heads to generally indicate flow, which is from high head to low head.

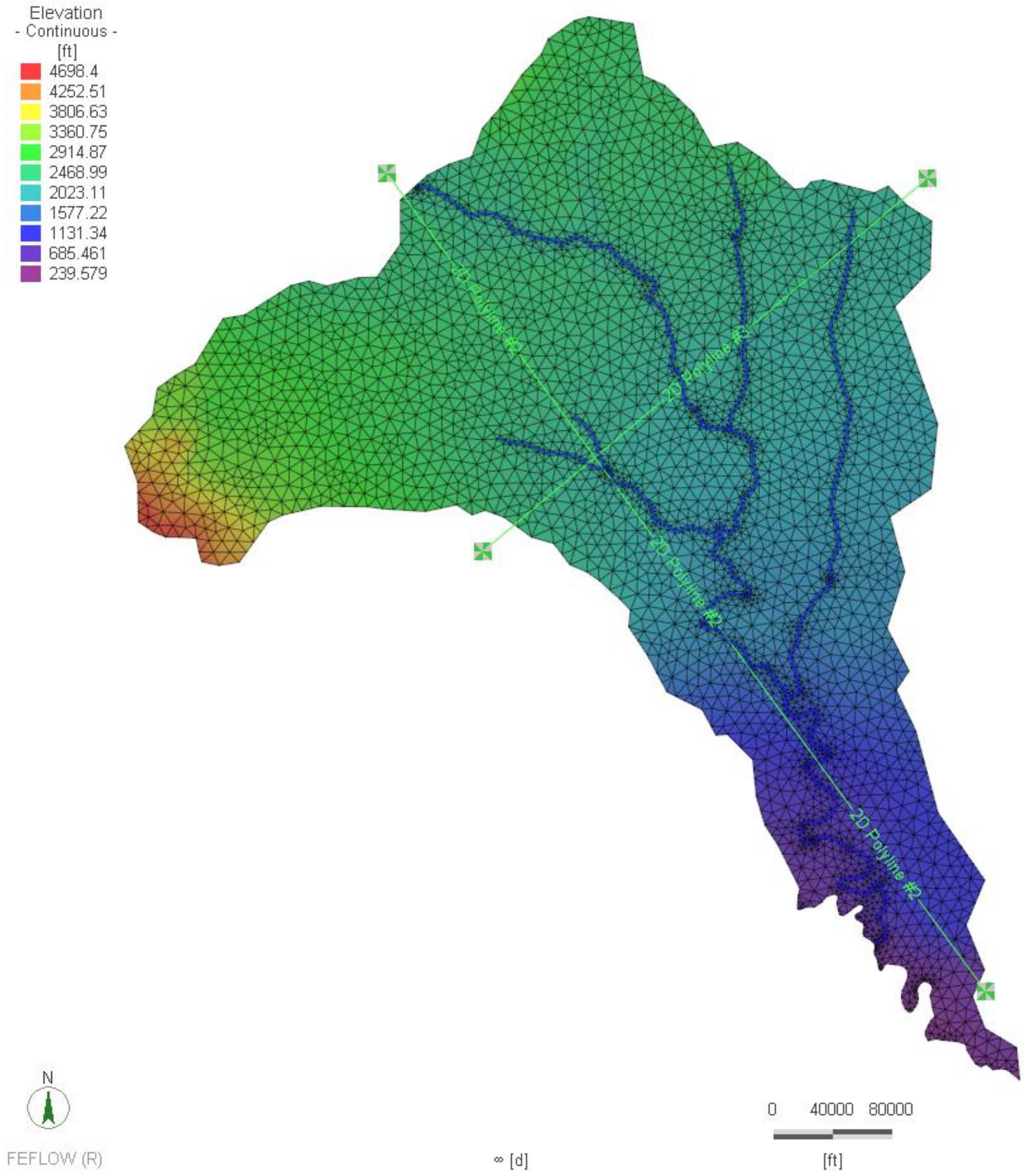


Figure 13. Top slice of the lower Pecos model mesh. The model mesh is comprised of approximately 4,500 elements per layer.

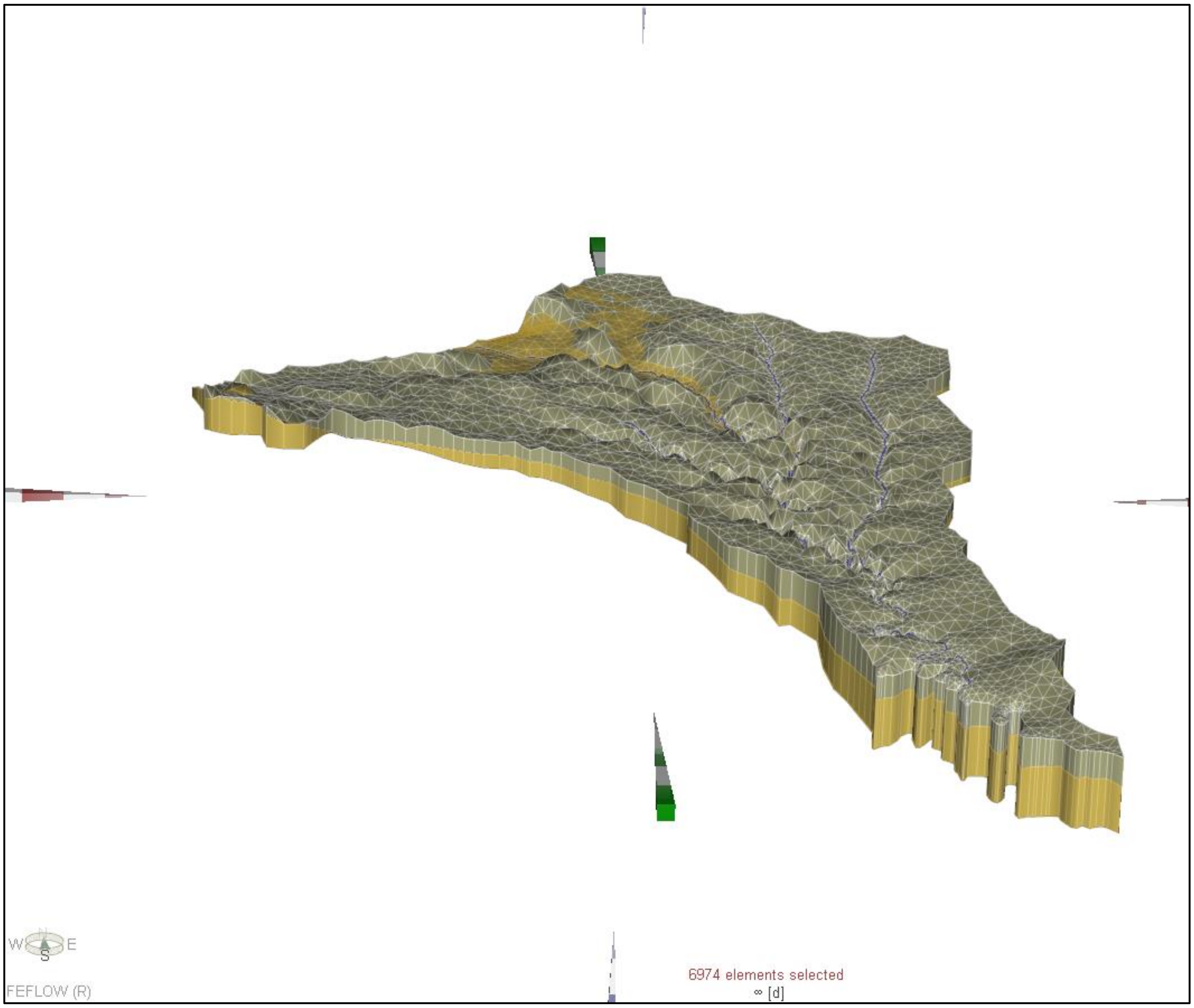


Figure 14. Oblique view of the model mesh looking from the south to the north. The current model consists of two layers, one each for the Edwards and Trinity rock units.

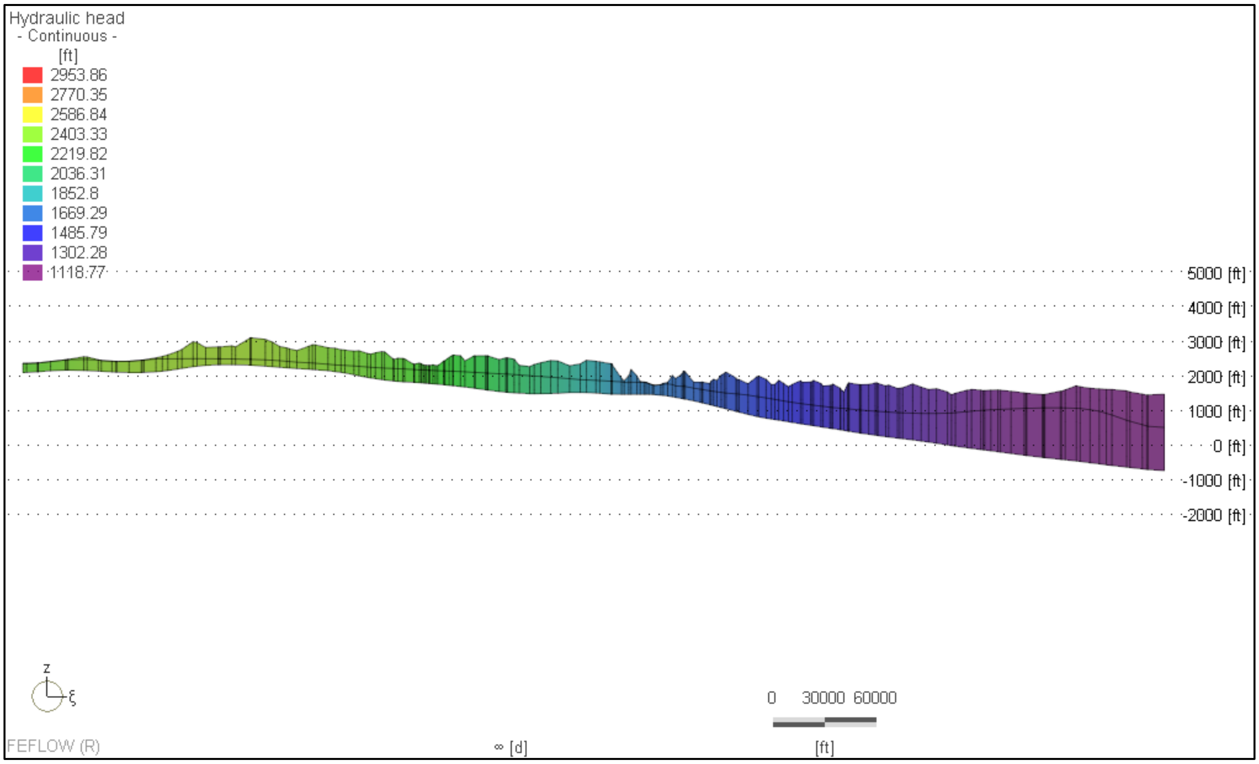


Figure 15. Model cross-section along two-dimensional Polyline #2 (shown in Figure 14). In the model domain, the Edwards-Trinity Aquifer thickens from <200 ft in the north to >2,000 ft in the south. Cross-section is colored according to the scale for hydraulic head.

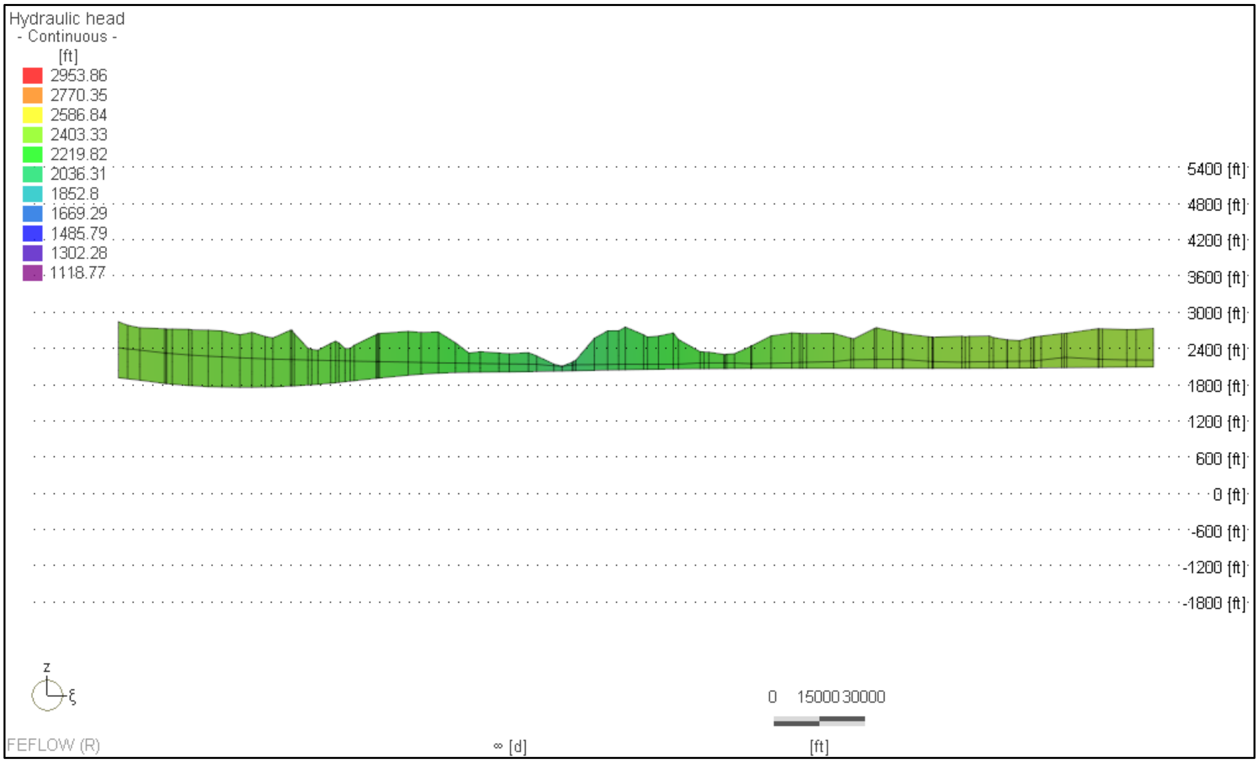


Figure 16. Model cross-section along two-dimensional Polyline #3 (shown in Figure 14). The Edwards-Trinity aquifer is incised by the Pecos River, with the Edwards sequence completely eroded in many sections of the Pecos River.

Significant effort was devoted to accurately representing the hydrostratigraphy for the lower Pecos River watershed. Stratigraphic cross-sections from the Bureau of Economic Geology (Rose, 1972; Bureau of Economic Geology, 1994; Smith et al., 2000), USGS (Barker and Ardis, 1992, 1996; Barker et al., 1994), and the Texas Water Development Board (Armstrong and McMillion, 1961; Ashworth 1983, 1990; Anaya and Jones, 2004, 2009; Hutchison et al., 2011) were reviewed to determine the discretization required to provide sufficient resolution in areas of interest. Given the complexity of the stream network and topography, a two-layer model is used to represent the model domain. Two layers were the minimum vertical discretization required to adequately represent the Edwards-Trinity aquifer as conceptualized in this report. The top layer of the model represents the Edwards rock units while the bottom layer represents the Trinity rock units.

The lateral boundaries of the model were chosen to coincide with the Pecos River watershed boundaries, and were designated as no-flow boundaries. The southeast (i.e., downgradient) boundary was specified as a time variant constant head and was set to historical water levels in the Amistad Reservoir. The northwest (i.e., upgradient) boundary was specified to approximate a groundwater divide between the Edwards-Trinity/Pecos Valley Aquifer in Pecos County and the mostly Edwards-Trinity Aquifer that spans from the southeast portion of Pecos County and extends downgradient to the Amistad Reservoir. The quasi-hydraulic boundary is formed by the high level of groundwater extraction that occurs in the Fort Stockton area, which has interrupted groundwater flow that would otherwise flow to the Amistad Reservoir via the Pecos River watershed (Bumgarner et al., 2012). The northwest boundary of the model domain specified as a no-flow boundary with constant flux from the upper Pecos alluvium aquifer is intended to take advantage of this reduced flow via the Pecos River watershed. It is recognized that flow of groundwater in the watershed is not halted, it is only reduced. As a consequence, much of the flow in the lower Pecos River watershed is believed to be sourced from Live Oak Creek, Independence Creek, and Howard Draw watersheds. The groundwater basin for Goodenough Spring, which discharges into the base of the Amistad Reservoir, is assumed to extend west into Mexico and is not considered to be in the domain of this model (Kamps et al., 2009).

Numerical Model Development

The model domain is represented by two hydrostratigraphic units: (i) the Edwards Group rocks and (ii) the Trinity Group rocks (Figure 14 through 16). This designation was guided by insights gained in the development of the finite-element models of the Edwards Aquifer (Fratesi et al., 2015) and the Devils River (Green et al., 2015) watersheds. Hydraulic properties assigned to the matrix of the carbonate units are denoted in Table 1 and graphically illustrated in Figure 17 and Figure 18.

Table 1. Hydraulic parameters for the lower Pecos River watershed model

Parameter	Layer	Value
Edwards Aquifer Hydraulic Conductivity	1	15-25 ft/day
Eastern Trinity Aquifer Hydraulic Conductivity	2	15 ft/day
Western Trinity Aquifer Hydraulic Conductivity	2	6 ft/day
Preferential Path Hydraulic Conductivity – Perennial Pecos Alluvial Aquifer	1,2	400 ft/day
Aquifer Specific Storage Coefficient	1,2	1×10^{-6} (1/m)
Preferential Path Hydraulic Storage Coefficient	1,2	1×10^{-3} (1/m)
Edwards Aquifer Effective Porosity	1	5%
Trinity Aquifer Effective Porosity	2	3%

Boundaries on the east and west sides of the model that align with the Pecos River watershed were specified as no-flow boundaries. The upgradient boundary that traverses the watershed approximately perpendicular to the Pecos River was also specified as a no-flow boundary with the exception of the location where the Pecos River and Pecos Alluvium Aquifer enter the model domain. At this location, flow into the model was specified as time-varying flow. The quantity of flow was specified as the flow measured at the Girvin gauge on the Pecos River. Discharge from the model where the Pecos River exits the model domain was a model output and was adjusted during model calibration.

The Pecos River and its tributaries were designated as a fluid-transfer boundary. The base elevation of the boundary was set as the river- or creek-bed elevation. By using this boundary assignment, groundwater is discharged into Pecos River only when the groundwater elevation exceeds the river-bed elevation. This boundary condition is appropriate for the hydraulic conditions exhibited by the lower Pecos River.

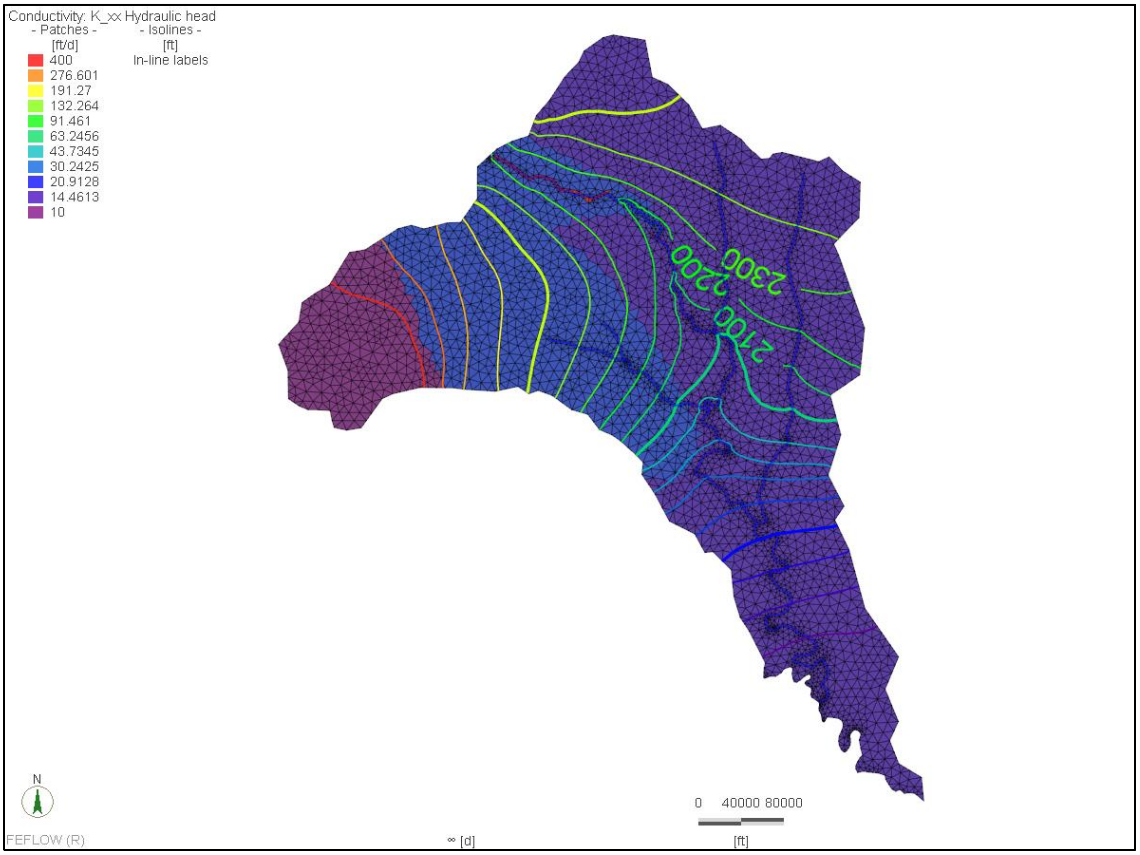


Figure 17. Groundwater elevation contours at steady state (ft). Hydraulic properties assigned to the matrix of the Edwards layer are illustrated by color (ft/d).

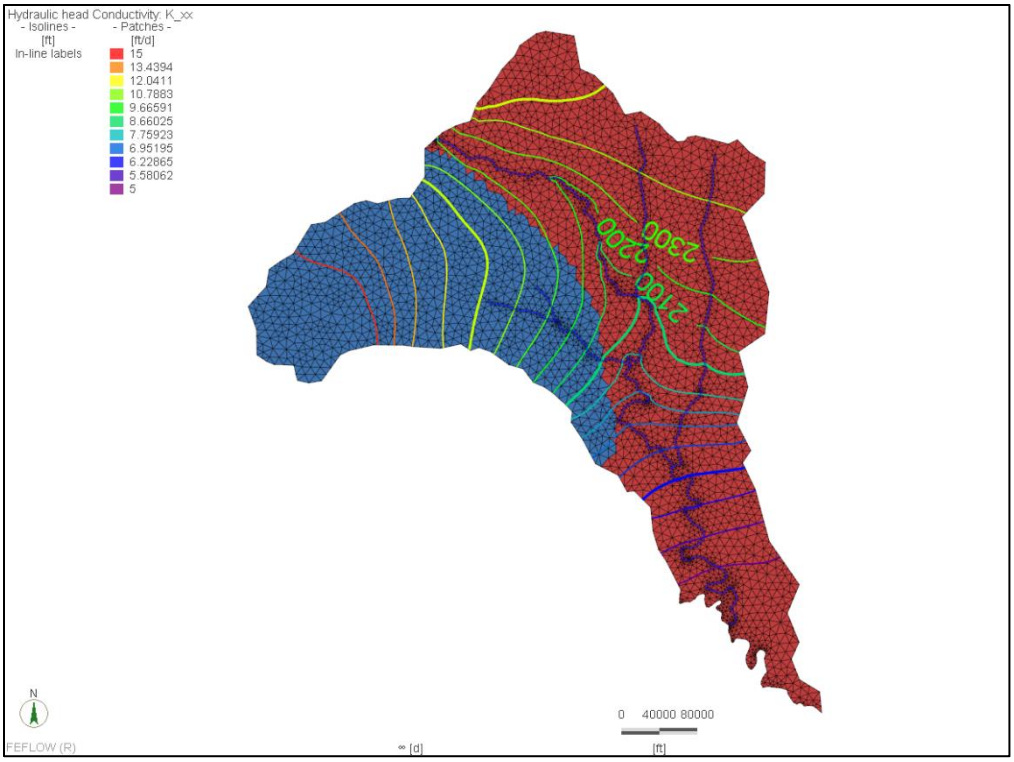


Figure 18 Groundwater elevation contours at steady state (ft). Hydraulic properties assigned to the matrix of the Trinity layer are illustrated by color (ft/d).

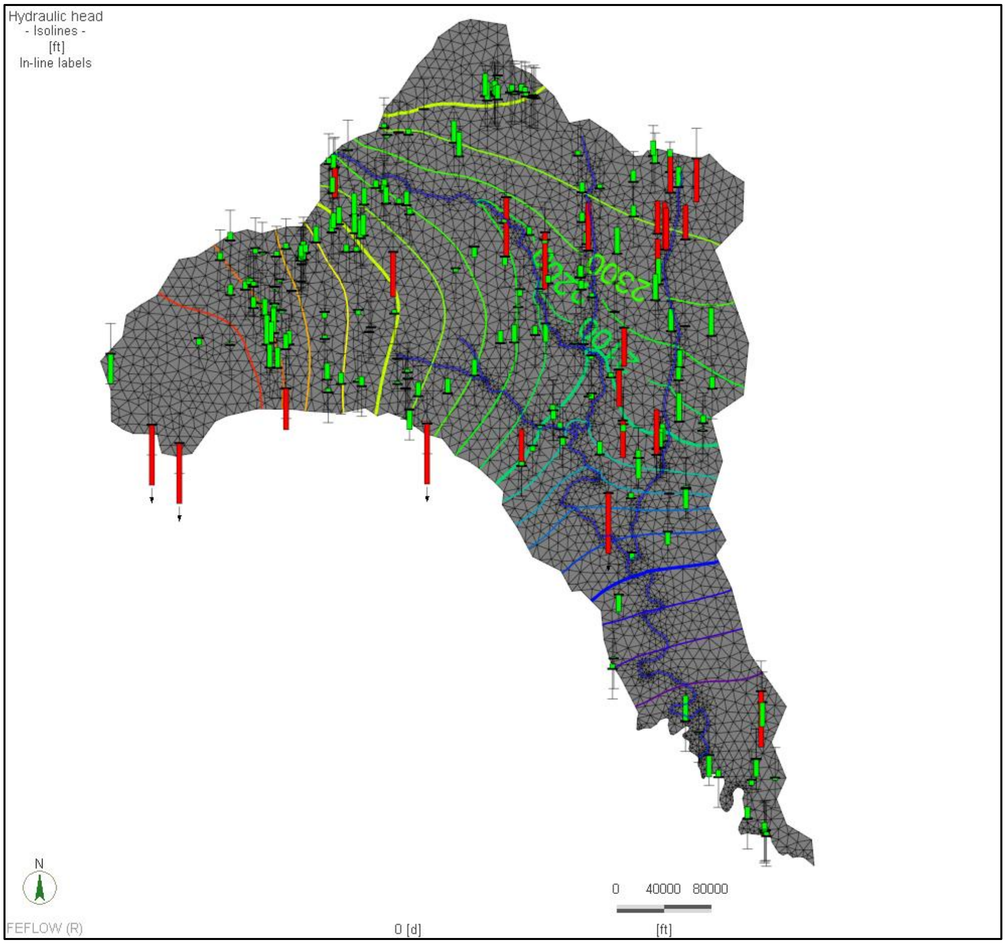


Figure 19. Groundwater elevation contours at steady state (ft). Absolute differences between the observed hydraulic heads and the simulated heads are shown as bars, with lengths proportional to absolute difference. Green bars represent calculated heads that are within +/-98ft of the observed heads. Red bars represent calculated heads that are more than 98ft above or below observed heads.

Conduit or preferential flow was incorporated into the model by including discrete features aligned with the primary river channels in the model domain. These channels included the Pecos River, Live Oak Creek, Independence Creek, and Howard Draw. In addition, a high transmissivity zone was assigned to the reach of the Pecos River that was also occupied by the Pecos Alluvium Aquifer at the upstream boundary of the model domain (the red zone along the river in Figure 17).

Recharge

Recharge estimates remain uncertain in the study region (Jennings, et al., 2001; Scanlon et al, 2003; Green and Bertetti, 2010; Green et al., 2012, 2014). Recharge was calculated directly from precipitation data and applied as a spatially varying areal source across the model domain. Gridded precipitation data with a 4-km by 4-km pixel size was obtained from the Prism Climate Group as monthly precipitation values (Prism Climate Group, 2015). Monthly recharge was calculated for each 4-km by 4-km PRISM pixel overlying the lower Pecos River model domain, and each model cell was assigned recharge by area-weighting the recharge in its overlying pixels. Recharge was calculated with assigned seasonal and antecedent moisture weighting factors, using the following equation (Fratesi et al., 2015):

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

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
m = number of months included in antecedent moisture calculation
MaxP=maximum monthly precipitation allowed to recharge the aquifer

Equation 1 provides several degrees of freedom that were used to calibrate recharge. The number of months included in Equation 1, m, can be increased or decreased to reflect the duration over which antecedent moisture has measurable impact. The amplitude of each of the m antecedent moisture weighting factors, Φ_i, can be adjusted to match the magnitude of recharge to the targeted discharge and the lag between the time of the recharge event and the time at which the recharge impulse is observed in the aquifer. The maximum monthly precipitation threshold value, $MaxP$, can be changed to control the impact of very large precipitation events, limiting the size of the monthly precipitation allowed to recharge the aquifer. The maximum threshold of monthly precipitation was eight inches. Finally, the evapotranspiration scaling factor, a, can adjust the measured pan evaporation to control the effect of evaporation.

Losses due to evapotranspiration were calculated from the average of monthly gross-lake evaporation rates from Texas Water Development Board for Texas Quadrangle 807 (TWDB, 2016). Average lake evaporation by month varies from a high of 9.09 inches in July to a low of 2.56 inches in January for the period 1954–2014 (Table 2). The precipitation-to-recharge algorithm predicts that the fraction of precipitation that becomes recharge is greater in the winter than in the summer due to decreased evapotranspiration during the winter.

Table 2. Average lake evaporation, E_i, by month for Texas Quadrangle 807

J	F	M	A	M	J	J	A	S	O	N	D
2.56	3.03	4.89	6.02	6.24	8.05	9.09	8.77	6.59	5.19	3.49	2.59

The calibration procedure considered antecedent moisture factors, Φ, for the month for which recharge is calculated and the preceding five months. Prior monthly precipitation is weighted by assigning successively less weight to months farther in the past. The antecedent moisture weighting factors were adjusted during calibration. The amplitudes of the weighting factors were adjusted at the same time that the evapotranspiration scaling factor, a, was adjusted, so that the volume of recharge equated to the downstream discharge. The relative weightings among the six weighting factors were adjusted to provide the appropriate degree of flashiness in the observed hydraulic response.

The estimated weighting factors, Φ, varied from 0.00 to 0.20. Weighting factors for the 6-month averaging period (e.g., five previous months plus the current month) are listed in Table 3. Weighting factors Φ_{i-4} and Φ_{i-5} had values of 0.00 after calibration. The calibration process set aE_i to zero whenever Φ_i was zero. The calibration indicated that antecedent moisture was only significant if the precipitation leading to the antecedent moisture occurred within the 3 months prior to month of recharge calculation.

Table 3. Weighting factors, Φ_i, to account for antecedent moisture

Φ_{i-5}	Φ_{i-4}	Φ_{i-3}	Φ_{i-2}	Φ_{i-1}	Φ_i
0.00	0.00	0.001	0.005	0.03	0.20

The temporal duration represented by the algorithm (in this case the duration was set at 4 months) was adjusted so that the length of time that a precipitation event continues to contribute to recharge was consistent with the "hydraulic memory" of the karstic Edwards-Trinity Aquifer. The memory of this hydraulic system is clearly also a function of the conduit/matrix hydraulic responsiveness of the entire Edwards-Trinity Aquifer system; however, a 4-month length in the weighting algorithm implies that the Edwards-Trinity Aquifer, which includes the epikarst surface source of moisture, has a "hydraulic memory" no longer than 4 months. This estimate for the "hydraulic memory" is consistent with precipitation/hydraulic response correlation calculations of the Edwards Aquifer by Başağaoğlu et al. (2015), in which the preponderance of hydraulic impulse from precipitation was shown to dissipate within 2-4 months of the precipitation event. Başağaoğlu et al. (2015) also showed that the hydraulic response to recharge is stage dependent, with shorter response times observed when aquifer stage is high.

There is a small component of flow in the lower Pecos basin, as modeled, that arrives from the upper Pecos River. This lateral boundary inflow is specified as a time-varying flow, with different constant values each month, that is passed to the domain via the Pecos Alluvium located within the Pecos River channel in the upper reach of the model domain. The boundary inflow is determined from the flow measured at the Girvin flow gauge (USGS gauge 08446500), which is immediately upstream of the model domain. The long-term average flow at the Girvin gauge was compared to the equivalent flow at the Langtry gauge (International Boundary and Water Commission gauge 08-4474.10), which is located near where the Pecos River discharges to the Amistad Reservoir. Imposed boundary flow into the model domain is on average <17% of the flow at Langtry, which corresponds to model discharge. This calculation substantiates the premise of this model in that most of the water discharged from the Pecos River to the Amistad Reservoir is sourced from the Live Oak Creek, Independence Creek, and Howard Draw watersheds.

Discharge

Pumping locations and volumes assigned to the model were taken from the Edwards-Trinity Aquifer Groundwater Availability Model (GAM) but are not significant (Anaya and Jones, 2004, 2009; Hutchison et al., 2011). With the exception of a limited number of irrigation and municipal wells near Sheffield and elsewhere, virtually all wells within the model domain are for domestic and stock purposes and have limited pumping capacity.

Model Calibration

The numerical groundwater model was first calibrated at steady state to verify the stability and efficiency of the model construction. Steady state of the model domain was determined using constant long term average recharge assigned to the 4km x 4km PRISM cells over the entire domain, steady-head boundary conditions at the Rio Grande, and constant flux from the upper Pecos. Recharge, hydraulic conductivity of the preferential pathways, and hydraulic conductivity of the inter-stream carbonates were varied to obtain realistic discharge values, match the regional observed heads, and match the location of perennial flow in the lower Pecos River. The numerical model reproduced the observed groundwater levels available from the Texas Water Development Board. The steady-state results are considered acceptable given that there were differences in the dates that water levels listed in the Texas Water Development Board database were measured and the fact that the steady-state calibration attempts to represent average annual conditions (Texas Water Development Board, 2015). A scatter plot of the observed groundwater elevations versus the calculated heads for the steady state groundwater elevations is shown in Figure 20.

During the steady-state calibration, the hydraulic conductivity of the preferential pathways in alluvial aquifer portion of the river was adjusted to 400 m/day. Groundwater surface contours at steady state are illustrated in Figure 21.

Model Simulation

Transient simulations were conducted for the period January 1, 1981 to July 15th, 2015. Recharge was calculated using Equation 1with monthly precipitation values.

Groundwater Elevation

Measured groundwater elevations at 13 wells within the model domain were selected as calibration targets (Figure 23). Locations of calibration targets represent most sections of the model domain, including downstream near the Amistad Reservoir, nearby and removed from the Pecos River (e.g., proximal and distal from the inferred preferential flow paths or conduits), and near the headwaters. The simulation period is 1981-2015; however, periods of recorded groundwater elevations are shorter.

Simulated groundwater elevations are compared with measured groundwater elevations with respect to: (i) absolute elevation; (ii) magnitude of variation in groundwater elevation; and (iii) flashiness in groundwater elevation variation. In general, the magnitude of the simulated groundwater elevations replicated the observed groundwater elevations.

Comparisons of simulated versus observed hydraulic head values at calibration wells 4449301, 4555702, and 5445502 are illustrated in Figure 24 through Figure 26, respectively. Responses at these three wells differ. State wells 4555702 and 5445502 have simulated groundwater elevations that are close in absolute magnitude and flashiness to observed elevations, although the magnitude of the flashiness is somewhat less than observed. The third well, 4449301, has a limited history of recorded groundwater elevations, but the simulated groundwater elevations have a much lower range of variation than observed elevations. These results are typical of all the transient data.

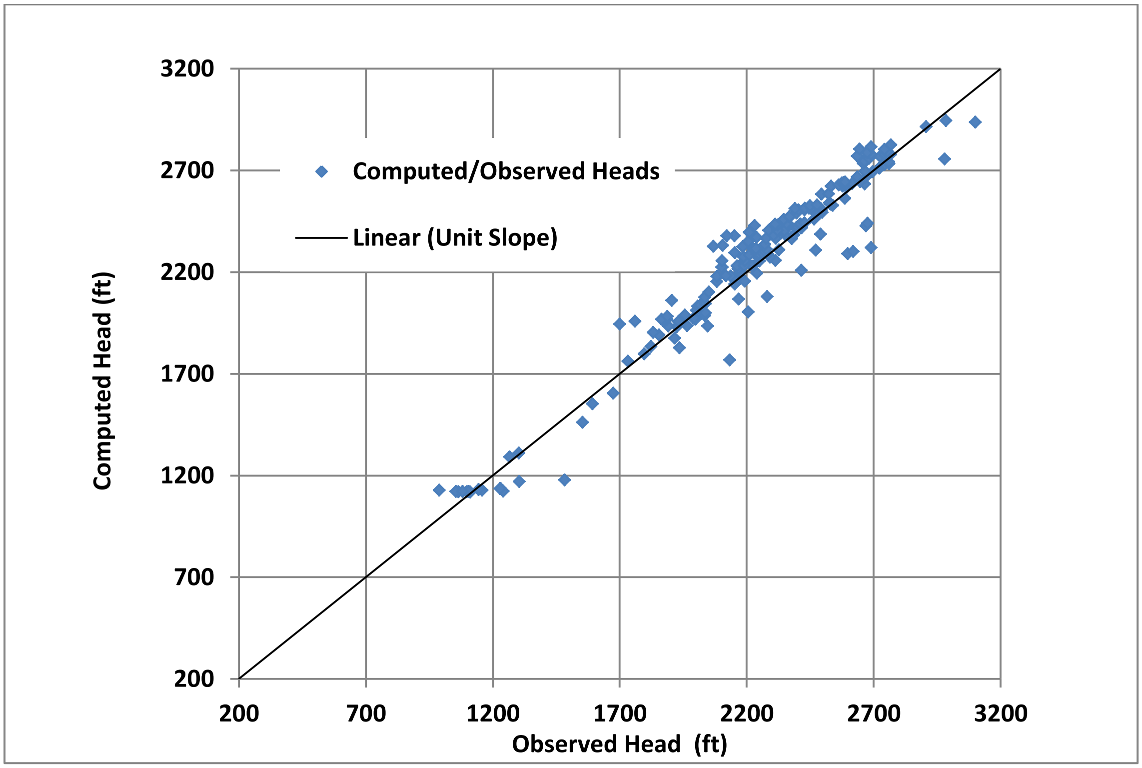


Figure 20. Steady-state simulation results. Simulated groundwater elevations (ft) are plotted versus observed groundwater elevations (ft).groundwater elevations (ft).

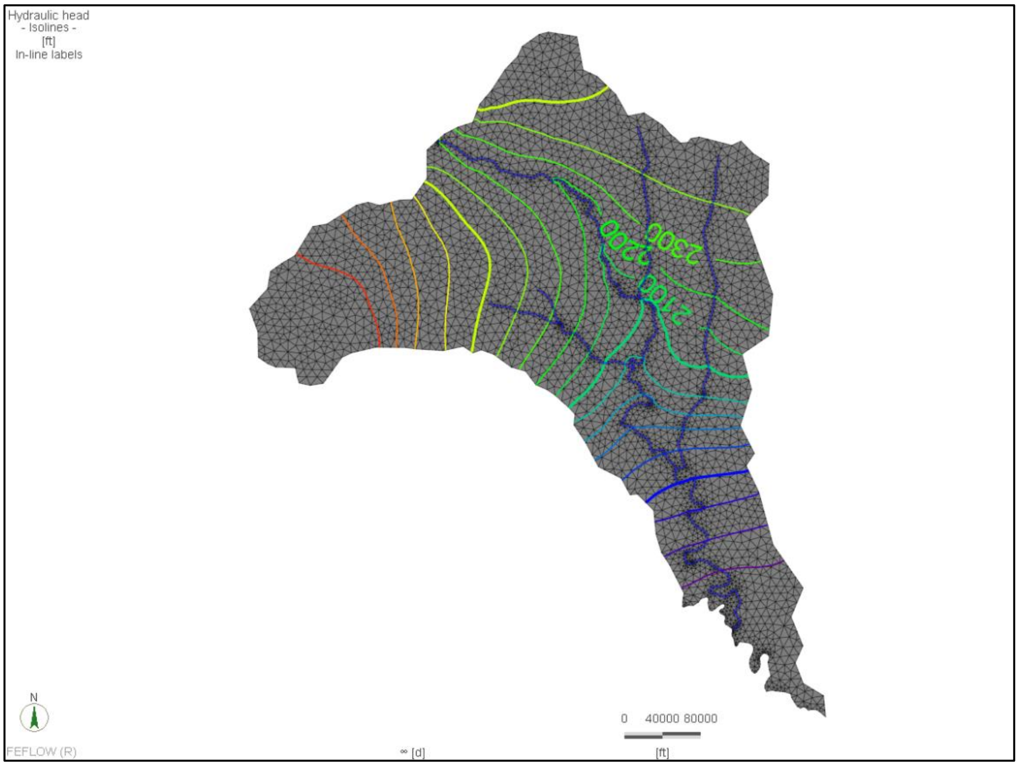


Figure 21. Steady-state simulation results. Groundwater elevation contours at steady state (ft).

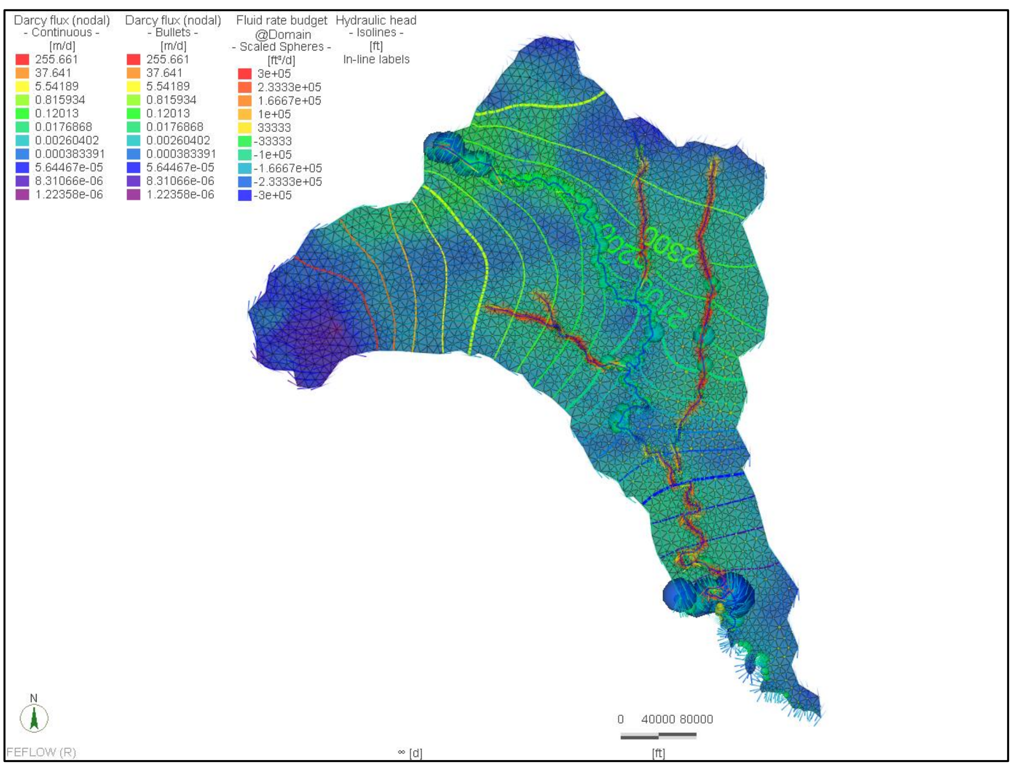


Figure 22. Darcy flux

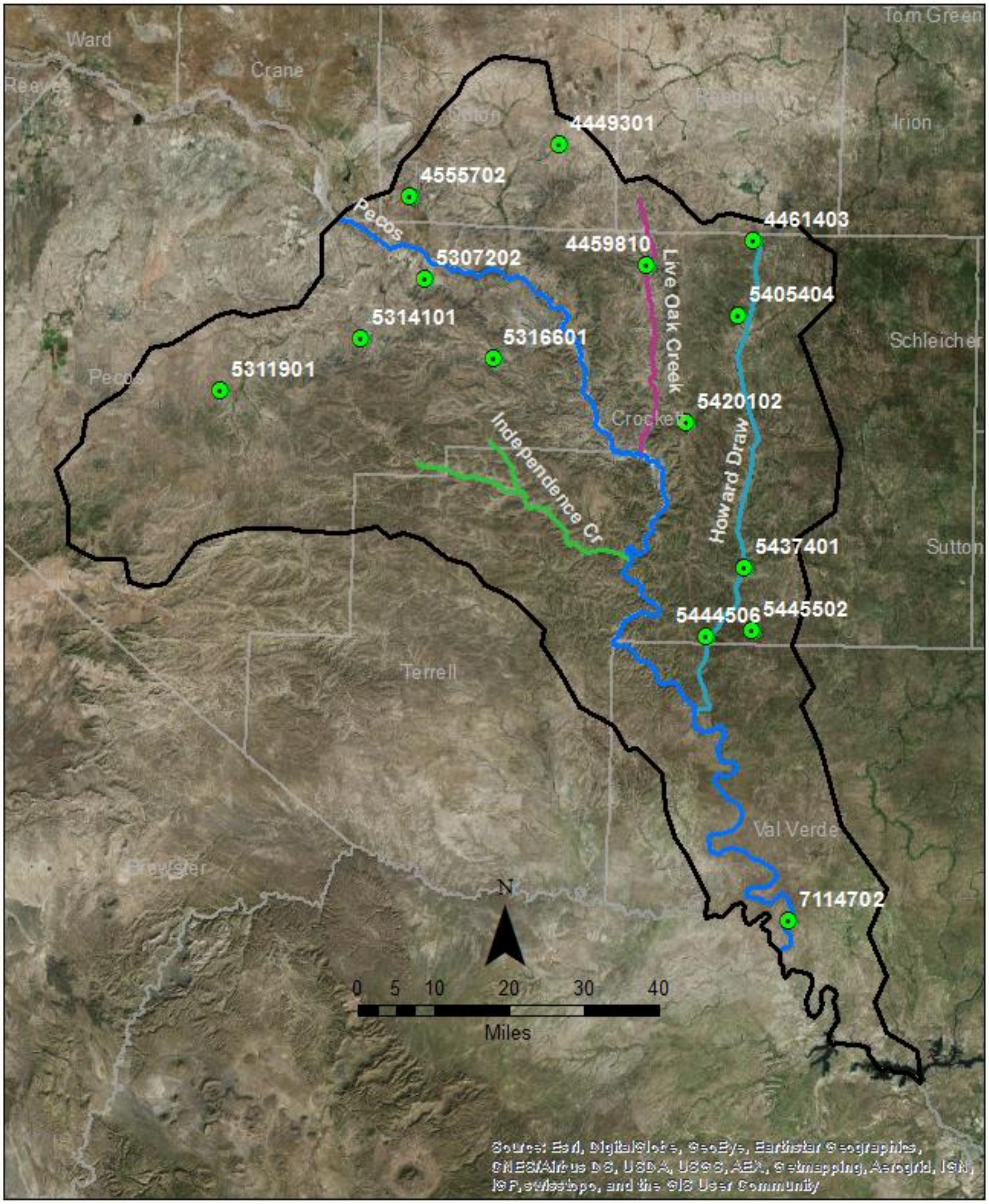


Figure 23. Locations of wells whose groundwater elevations were selected as calibration targets

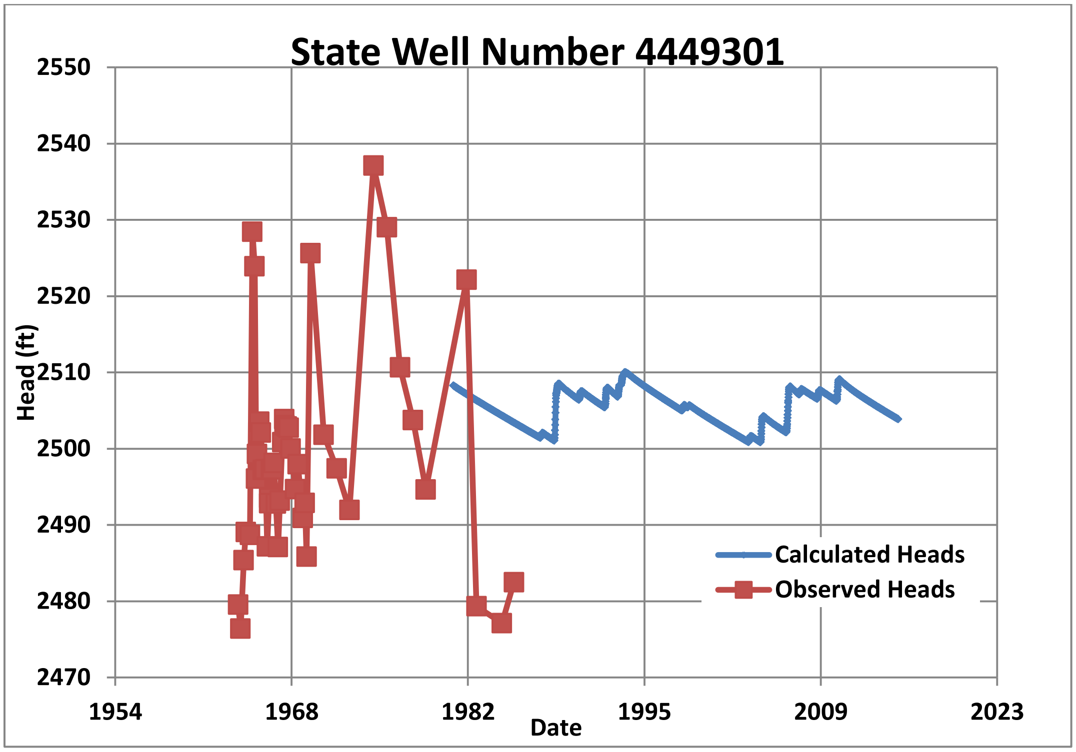


Figure 24. Time histories of calculated and observed hydraulic heads at well 4449301

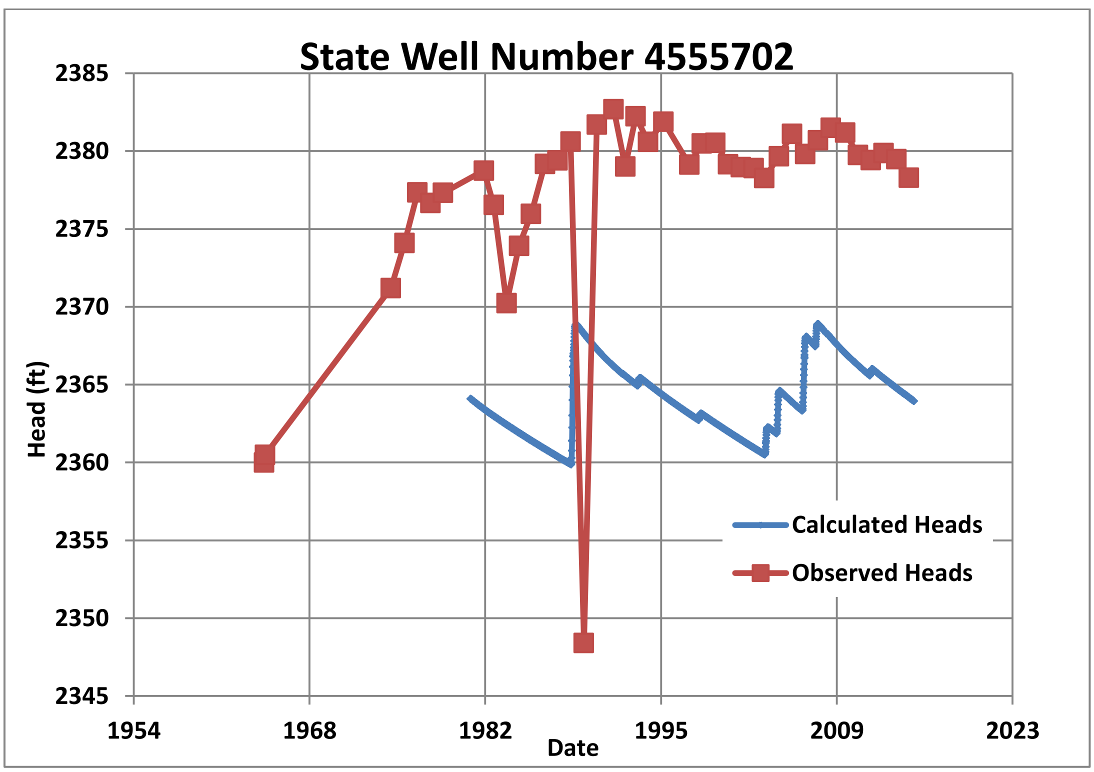


Figure 25. Time histories of calculated and observed hydraulic heads at well 4555702

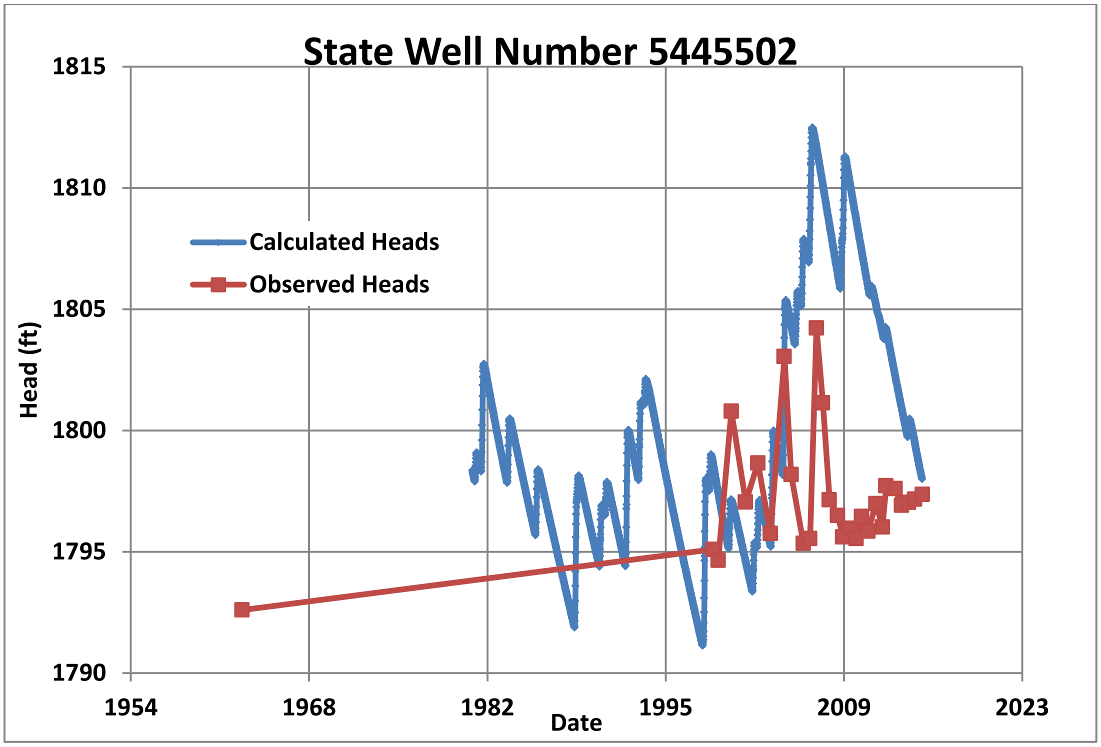


Figure 26. Time histories of calculated and observed hydraulic heads at well 5445502

Model Discharge

Simulated discharge from the Pecos River to the Amistad Reservoir is compared with river flow measured at the Pecos River flow gauge at Langtry (International Boundary and Water Commission gauge 8447410) in Figure 27. Differences between the modeled discharge and the observed flow at Langtry are attributed to several limitations of the model. The model inherently cannot capture high flow because the groundwater model reported in this document does not explicitly include surface flow, and only simulates Pecos River baseflow. Thus, the large observed river flows due to surface-water runoff are not part of the simulation. The model includes evapotranspiration as a limiting factor on recharge, but does not consider evaporation from surface water. Evaporation may substantially reduce stream flows. The model uses a 30-day timestep. This has the effect of averaging the hydraulic driving forces over a period of 30 days. Employing a shorter timestep may improve the model's ability to capture short periods of low flow. Another source of uncertainty is the recharge model. The current model calculates recharge from precipitation using state evapotranspiration values that essentially cuts off low precipitation events when the precipitation fails to attain a minimum value. This is how the recharge model captures antecedent moisture conditions. Lastly, the manner in which the recharge model accommodates flow focused in river channels may need adjustment. It is possible that higher levels of recharge are concentrated in channels and incised tributaries and that less recharge is distributed, which essentially spreads the recharge across the model domain. The average annual recharge is quite low, often times averaging less than 15 inches/yr, which supports this last observation.

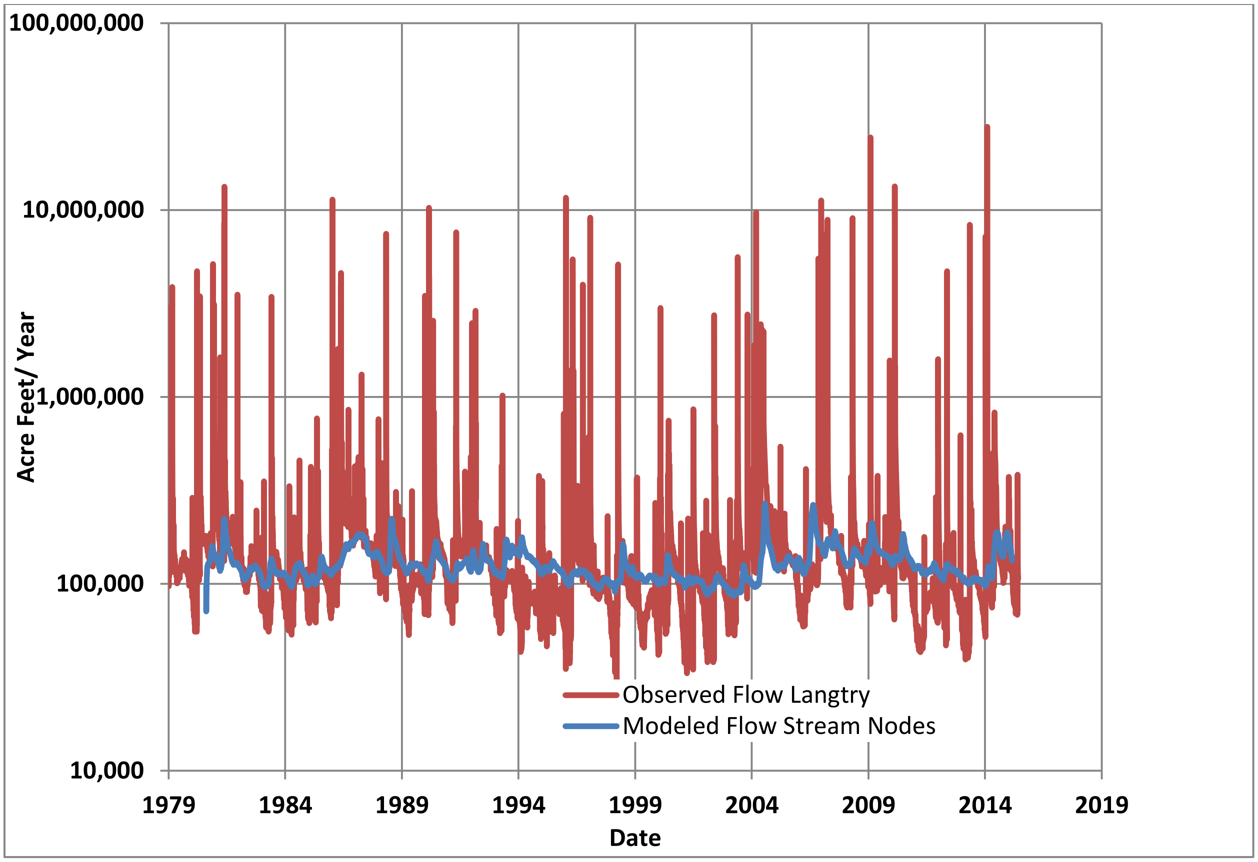


Figure 27. Discharge on the Pecos River measured at the Langtry gauge versus simulated Pecos River baseflow

Discussion and Conclusions

A groundwater flow model was developed to simulate the hydraulic response of a karst aquifer located in a semi-arid environment with preferential flow paths aligned along the major river channels. The lower Pecos River watershed in south-central Texas provides an average of 193,000 acre-ft/year to the Amistad Reservoir as stream flow, even though the watershed is in a semi-arid environment. The lower Pecos River watershed was characterized independently from the upstream reach of the Pecos River. This independent evaluation is justified because streamflow into the lower Pecos River reach is greatly reduced by groundwater and surface water extraction from the upper Pecos River watershed. As a result, most of the water discharged from the Pecos River to the Amistad Reservoir is sourced from within the lower Pecos River watershed. The principle sub-basin watersheds that contribute to the lower Pecos River watershed are the Live Oak Creek, Independence Creek, and Howard Draw watersheds.

Development of the conceptual model and construction of the numerical model are predicated on an assortment of data and analyses including well logs, geophysical surveys to image the subsurface of river channels, groundwater elevations, and aquifer hydraulic response to recharge events. Annual precipitation in the area varies widely, but is typically under 20 in/yr, a common threshold used to specify a semi-arid environment.

The numerical model was developed using FEFLOW (Diersch, 2014), a sophisticated and flexible finite-element groundwater flow simulator that includes numerous options to accommodate coupled diffuse and conduit flow. The lateral boundaries of the groundwater model domain are defined to be coincident with the surface watershed. Although groundwater basins and surface watersheds are not necessarily coincident, particularly in karst carbonate aquifers, there are no compelling data or information that support establishing groundwater basin boundaries different than the surface watershed boundaries.

The modeled grid was constructed with higher resolution and smaller elements along the major river channels and with less resolution using larger elements in the interstream regions away from the rivers. This gridding was incorporated to accommodate large gradients in hydraulic head and hydraulic properties near the river channels. In the absence of aquifer test results, hydraulic properties for the matrix were assigned based on technical literature. Hydraulic properties for the preferential flow paths along the river channels were determined during calibration. Hydraulic head values were the most valuable data used when calibrating the model.

Recharge was calculated from precipitation records. Monthly precipitation values for the period 1981-2015 were used to establish steady-state hydraulic conditions. Transient simulations were then conducted for the same period at monthly time steps. Simulated groundwater elevations were compared with measured groundwater elevations at 13 wells spaced across the model domain. Steady-state and transient runs of the model are consistent with observed data. Simulated groundwater elevations were within 25-30 ft of observed groundwater elevations with few exceptions. The degree of flashiness of hydraulic response was captured at some, not all, monitoring wells. Simulations of wells located near inferred preferential flow paths or conduits appeared to correctly replicate the hydraulic response of the aquifer proximal to the preferential flow paths.

The average recharge of the Pecos River watershed with an area of 5,957 mi^2 calculated by the model was 226.8ft^3/sec (164,200 acre-ft/year). Average baseflow to the Pecos River calculated by the model between 1981 and 2015 was 138,400 acre-ft/yr. This baseflow is approximately 71% of average flow reporting to Langtry. Additional flow measured in the river where it discharges to the Amistad Reservoir is attributed to surface runoff, river flow that was not derived from groundwater. In comparison, the baseflow component of discharge measured at Langtry on the Pecos River for the period 1960-2009 was calculated using baseflow separation to be 74% of total flow. These two independent measures of baseflow are within 10 percent, which reduces uncertainty in calculation of actual recharge.

This independent corroboration of recharge suggests the conceptual model and the ensuing numerical model are valid representations of the lower Pecos River watershed. In summary, the numerical model is considered capable of replicating the hydraulic response of a carbonate aquifer whose flow is dominated by the preferential flow paths and whose recharge is limited and highly variable.

Future Work

As demonstrated throughout the during of work on the lower Pecos River watershed by Southwest Research Institute, conceptualization of the groundwater and surface water regimes has significantly evolved (Green et al., 2014). Numerical model results support the premises on which this refined conceptual model is predicated. Through this process, additional tasks have been identified that would continue to bolster the technical foundation on which the conceptual and numerical model are formulated. The current model only captures baseflow in the river. Improved simulation of the hydraulics of the lower Pecos River watershed requires that surface water dynamics also be included. It is recommended that a surface water model be coupled to the groundwater model developed during this process. The current FEFLOW groundwater model would be likely coupled with MIKE, a surface water simulator compatible with FEFLOW.

Acknowledgements

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