# A Conceptual Model of Groundwater Flow in the Presidio and Redford Bolsons Aquifers

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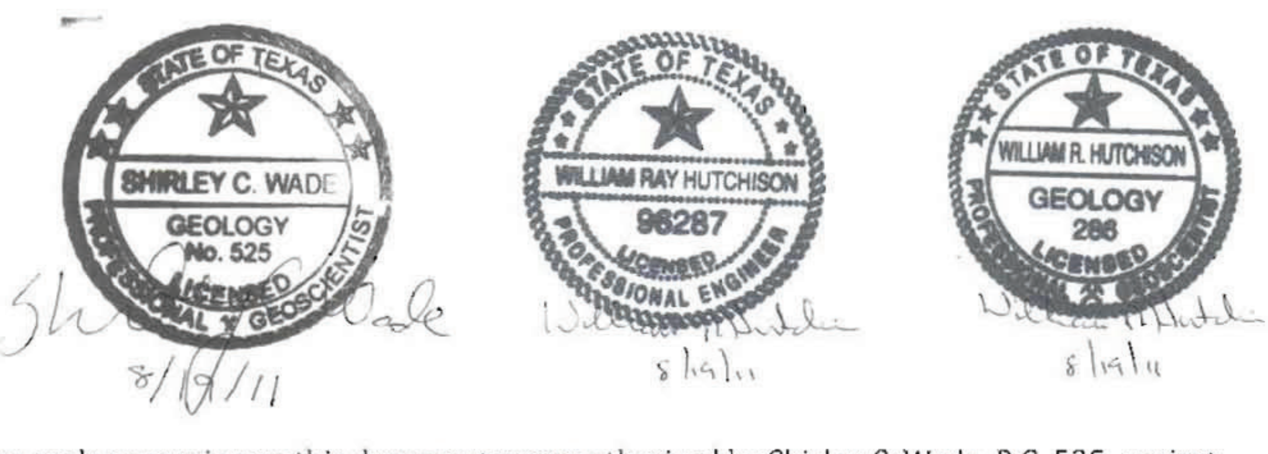


The seals appearing on this document were authorized by Shirley C. Wade, P.G. 525, project manager and William R. Hutchison, P.E. 96287 and P.G. 286. William R. Hutchison is Director of the Groundwater Resources Division and is responsible for technical oversight of work performed by Groundwater Resources Division employees working on Texas Water Development Board aquifer models. Co-author, Ali H. Chowdhury, P.G. 468, was responsible for work on this report until June 28, 2011.

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# TABLE OF CONTENTS

# EXECUTIVE SUMMARY

The Presidio-Redford Bolsons Aquifers are the main sources of drinking water, and water for livestock and irrigation, for the area surrounding Presidio, Texas and Ojinaga, Mexico. The area has been sparsely populated in the past; however, population growth and increased use of groundwater are likely in the future. In order to provide a tool to evaluate the effect of increased development of the aquifer and to better understand the aquifer system, a numerical model of the groundwater flow system is being developed. In the initial phase of the model development, all available geologic and hydrogeological information of the area including water levels and geochemistry data is compiled, reviewed, and analyzed. These hydrogeological and geochemical data are then used to develop a conceptual model of the groundwater flow system. In the final stage, this conceptualization of the flow system is used as the basis to construct and calibrate a numerical model of the aquifer flow system.

The study area is located in the basin and range physiographic province, characterized by north-south trending mountain ranges separated by basins. The basin and range province is the result of late Tertiary normal block faulting. The faulting was followed by accumulation of sediment deposits in the basins that was derived from erosion of the adjacent mountain blocks forming the aquifers. Geophysical survey and core data from several deep wells suggest that the bolson is up to 5,000 feet thick at the center of the basin. Excavation of the bolson deposits by the Rio Grande and sidestreams has added further complexity to the system and is responsible for the rugged topography seen in the study area.

Groundwater occurs in both the bolson deposits and in the more recent river and sidestream alluvial deposits. The degree of hydraulic connection between the bolson and the overlying younger units varies. The average horizontal hydraulic conductivity for the Presidio Bolson estimated from specific capacity measurements is about 8 feet per day. This value is similar to hydraulic conductivity values of other bolson aquifers in the region. The groundwater system can be generalized to consist of three units; the Rio Grande alluvium deposits, the bolson deposits, and the tertiary volcanic rocks and older cretaceous units.

Recharge occurs in the adjacent mountain blocks surrounding the bolson and through the coarse, permeable river and sidestream alluvium deposits during high flash-flood events. Diffuse precipitation recharge directly through the basin center bolson deposits is insignificant due to the presence of caliches and abundant clays that lower vertical permeability in these deposits. In addition, evaporation removes the small amount of rainfall before it can percolate into the ground. The estimated annual potential evapotranspiration is up to 90 inches per year and the unhindered vegetative evapotranspiration rates range from 50 to 60 inches per year; whereas, the average annual precipitation ranges from nine inches per year in the valleys to eighteen inches per year in the adjacent mountains blocks.

The total recharge for the study area has been estimated to lie between 3,600 and 7,000 acre-feet per year in other studies. Groundwater flows from areas of high elevation along the eastern and western boundaries toward the Rio Grande valley, a regional groundwater discharge area. However, in the Presidio and Redford Bolsons area the river flood plain is densely thicketed with vegetation which likely consumes much of the regional groundwater discharge as well as the surface flow in the river.

Away from the river, groundwater discharge from the bolson aquifer occurs as a result of spring discharge and groundwater pumping. Both hot and cold springs occur in the bolsons aquifers. Cold springs result from shallow groundwater discharge along formation contacts where sediment facies changes occur and through some faults. Hot springs are the result of upward discharges of groundwater from the deeper subsurface along faults.

Groundwater is pumped from the bolsons mainly for municipal, domestic, livestock, and irrigation use in both the United States and Mexico. A small amount of groundwater is permitted for railroad use in Mexico. The estimated annual groundwater pumping from the Bolson and alluvium aquifers is about 2,000 acre-feet per year in the United States portion of the study area and the permitted amount of groundwater in the Mexico portion of the study area is about 9,000 acre-feet per year.

Groundwater from the Presidio-Redford Bolson Aquifer along the mountain fronts/basin margins is mainly fresh and in the basin centers is slightly saline in composition. Low salinity of the groundwater along the mountain fronts is due to the presence of non-reactive minerals in the aquifers and also possibly the influx of recharge from the highlands. Lack of diffuse recharge, higher degrees of evaporation, water-rock interactions, and evaporite dissolution in the more clayey aquifer materials in the basin sediments result in slightly saline water. Groundwater from the Rio Grande Alluvium Aquifer receives recharge from multiple sources and has higher groundwater salinity. Multiple geochemical processes including evaporite dissolution, ion exchanges, and evaporation causes the development of higher salinity in the groundwater. Stratigraphic heterogeneity of the aquifer materials and abundance of clay interbeds may hydraulically compartmentalize the aquifers locally allowing for a greater variation in salinity distributions across the aquifers. Large variation in hydrochemical facies that include Na-Ca-$HCO_3$, Na-$HCO_3$ –$SO_4$ and Na-Ca-Cl- $SO_4$ hydrochemical facies are evidence of this hydraulic compartmentalization.

Examination of groundwater quality in the Presidio-Redford Bolson Aquifer against primary and secondary drinking water standards suggests that about 25 percent of the groundwater fails to meet the secondary drinking water standard for total dissolved solids. About 93 percent of the groundwater from the Rio Grande Alluvium Aquifer exceeds the secondary drinking water standard for total dissolved solids. In addition, some of the groundwater has high specific conductance with high salinity hazard for irrigation water use. Several samples also have high concentrations of arsenic, cadmium, lead, sulfate, and chloride.

# 1 Introduction

The Presidio and Redford Bolsons aquifers are the principal sources of drinking water in the southwest parts of Presidio County and the adjoining parts of the Mexican State of Chihuahua (Groat, 1972). The aquifers are also used for irrigation and livestock water supplies. Because of the low population density in the area the aquifer has seen limited groundwater development in the past. However, Presidio County's population is projected to increase more than 50 percent by 2060 (TWDB, 2007a) with an expected increase in groundwater development in the future. In 2003, the Texas General Land Office began to consider an application to lease public land in West Texas for the purpose of water development. In order to better understand the groundwater flow system and to better estimate the groundwater resources of the area a groundwater availability model for the Presidio-Redford Bolsons aquifer is being developed as part of the Texas Water Development Board's Groundwater Availability Modeling Program. The purpose of the program is to provide reliable and timely information on groundwater availability to the citizens of Texas to ensure adequate supplies or recognize inadequate supplies over a 50-year planning period. Our process includes substantial stakeholder input and results in standardized, thoroughly documented and publicly available numerical groundwater flow models and support information.

Following standard modeling protocols (Anderson and Woessner, 1992), the conceptual model was developed by gathering data on the hydrology and geology of the study area and identifying hydrostratigraphic units and model boundaries for the groundwater flow system. In the summer of 2004 a field program to collect water level and geochemistry data for the area was undertaken. Data from previous sampling and water level programs was assembled. The information from previous hydrogeology and water resource studies was reviewed to help define the water balance components such as recharge, evapotranspiration, spring discharge, groundwater pumping, and surface water-groundwater interactions. Groundwater flow properties from aquifer tests and other hydrologic and modeling studies of the area were also analyzed. Finally, historical water levels, springflows, and estimated stream baseflows were identified and compiled to use as calibration targets. The next phase of the project will be to construct and calibrate a numerical model from the conceptual model and hydrogeology data.

# 2 Study area

The Presidio and Redford Bolsons straddle the Rio Grande valley on the southwest edge of Presidio County in Far West Texas (Figure 2-1). The western portion of the Presidio Bolson is located in the state of Chihuahua, Mexico. The bolsons and surrounding upland areas cover approximately 1,900 square miles and are located between 104° and 105° west longitude and 29°and 30.25° north latitude. The U.S. portion of the study area is located in the Far West Texas Regional Water Planning Area E (Figure 2-2), the Presidio County Underground Water Conservation District, and Groundwater Management Area 4 (Figure 2-3).

The area around the towns of Presidio, Texas and Ojinaga, Mexico on the Rio Grande is believed to be the oldest continuously farmed area in Texas. Corn farmers of the Cochise culture settled there in about 1500 B.C. (Handbook of Texas Online, 2007a, b). The Cochise culture was replaced by a Pueblo type culture by about 900 A.D. They were in turn replaced by the Julimes and Jumanos people before the Spanish arrived in 1535 (Handbook of Texas Online, 2007a, b). The first Spanish settlement in the area was in 1684 when seven missions were established at seven pueblos. In 1759, a presidio, or fort, was built for the protection of the missionaries. In 1865, the fort and settlement were renamed Ojinaga for Manuel Ojinaga, governor of Chihuahua (Handbook of Texas Online, 2007c). The town of Presidio was incorporated in 1930 (Handbook of Texas Online, 2007d).

By the late 20$^{th}$ century (1980s) the economy of the area remained primarily dependent on agriculture (Handbook of Texas Online, 2007a). The total population of Presidio County peaked in 1920 at 12,200 people, but began to decline following World War II, reaching a low of 4,842 in 1970 (TWDB, 2007b). It is on the rise again and in 2000 the county population was 7,304. The population of the town of Presidio was 4,167 in the 2000 census (U.S. Census Bureau, 2007). The population of Ojinaga, which is also principally a rural community, was about 18,000 in the year 2000 (Kelly, 2001). The population had increased to 26,000 by the year 2010 (INEGI, 2011).

## 2.1 Physiography and Climate

The study area is located in the Mexican Highland section of the basin and range physiographic province which is characterized by north-south trending mountain ranges separated by valleys or basins (Figure 2-4). To the west of the study area are the Sierra Pinosa, Sierra de la Parra, and Sierra Grande ranges. The Presidio Bolson is bordered on the east by the Sierra Vieja and Chinati Mountain ranges. The Bofecillos Mountains lie east of the Redford Bolson (Figure 2-1). Elevations range from 2,518 feet along the Rio Grande (Handbook of Texas Online, 2007a) to 7,728 feet at Chinati Peak (Figure 2-5).

The Presidio and Redford Bolsons are located within the middle Rio Grande Basin and the Upper Rio Bravo Basin (Figure 2-6). Downcutting by the Rio Grande and its tributaries has dissected the Presidio Bolson and produced the rugged topography of terraces and surface remnants (Groat, 1972). In this section of the Rio Grande the river is about 125 feet wide with a large floodplain covered with salt cedar and mesquite. The bedload in the north is mainly coarse gravel, while in the south it is mainly sand and fine gravel. The drainage (arroyo) density in the Presidio Bolson segment of the Rio Grande is higher than upstream sections (Belcher, 1975).

The study area falls within the Chihuahuan Desert Region where typical plants include the yucca, mesquite, and creosote shrubs (Figures 2-7 and 2-8; TPWD, 1984). Vegetation coverage is very sparse except along the Rio Grande (Figures 2-9 and 2-10).

The climate is subtropical arid (Figure 2-11) characterized by summer precipitation influenced by mountainous relief (Larkin and Bomar, 1983). Annual potential evapotranspiration is between 80 and 90 inches (Scanlon and other, 2005) (Figure 2-12); while rainfall ranges from an average of nine inches per year in the Rio Grande valley to 18 inches per year in the peaks of the Chinati Mountains (Figure 2-13; Daly and Taylor, 1998; PRISM Group, 2004). Rainfall occurs principally in the summer months of June through September in the form of intense thunderstorms (Gabaldon, 1991; Figures 2-14 and 2-15).

The mean July temperature is 87° F and the mean January temperature is 50° F (Groat, 1972). Average annual daytime maximum temperatures range from 62 to 88° F (Figure 2-16). Average annual minimum temperatures range from 40 to 56° F (Figure 2-17). Temperatures above 100° F are common from May through September (Groat, 1972).

## 2.2 Geology

Geological evidence indicates that almost all of Trans-Pecos Texas is underlain by Precambrian rock similar to those that outcrop in the Franklin, Van Horn, and Sierra Diablo Mountains (Urbanczyk and others, 2001). Deep drilling in northern Presidio County has encountered Precambrian granite and arkosic sandstone that are correlated with Precambrian outcrops in the Van Horn area to the north (Figure 2-18) (Mraz and Keller, 1980). The area was intensely folded during late Precambrian and was eroded to produce a low-relief surface sloping to the south (Mraz and Keller, 1980).

Paleozoic marine sediments were deposited by the Sauk Sea transgressing from the south (Mraz and Keller, 1980). Fine clastics and reef limestones exposed just east of the Pinto Canyon area (Figures 2-19 and 2-20) are correlated with the Permian Basin, to the northeast. These strata imply that throughout most of the Paleozoic the Presidio Bolson area was not tectonically active (Mraz, 1977). The area was part of the stable shelf on the west of the Diablo platform and the eastern edge of the Chihuahua Trough (Figure 2-18). During the late Paleozoic, the Bolson area was downwarped forming a deep trough, and was not deformed again until the end of the Mesozoic (Mraz, 1977).

In the study area, the axis of the Chihuahua Trough (Figure 2-18), roughly parallels the Rio Grande basin and is bounded to the east by the Diablo Platform and to the west by the Aldama Platform. Marine deposition in the trough began during the Cretaceous (Figure 2-20); however, prior to that, probably during the Jurassic, halite and gypsum accumulated in much of the trough (Henry, 1979). Up to 18,000 feet of limestone and shale were deposited in the trough during the Cretaceous (Henry, 1979). These rocks were then intensely deformed during the Laramide Orogeny (Groat, 1972).

In the Cenozoic (Figure 2-20), following the Laramide activity, volcanic activity became widespread in the region during the middle Eocene to early Oligocene (Henry, 1979). The Chisos, Davis, and Chinati Mountains were eruptive centers. Tuffs and a few lava flows accumulated between the eruptive centers (Henry, 1979).

On the west side of the Presidio Bolson are the Sierra Pinosa and Sierra de la Parra (Figure 2-1), rugged ranges developed on structurally complex rocks of Cretaceous age. Tertiary volcanic rocks form the Cierros Prietos, a small cluster of hills in the Sierra de la Parra (Groat, 1972). Tertiary volcanics are also common on the western margin of the Bolsons south of Ojinaga (Groat, 1972). The mountains on the east side of the Bolsons in

Texas are fault blocks or Tertiary volcanic rocks and Cretaceous and Permian sedimentary rocks (Groat, 1972).

The mountain block and adjacent basins of the basin and range province were formed by late Tertiary normal faulting after most volcanic activity had ended. Region wide normal faulting began approximately 24 million years ago (Henry, 1979). Normal fault movement continues along the west side of Salt Basin and Lobo Valley, along the west side of the Eagle Mountains and along both sides of Presidio Bolson (Henry, 1979; Figure 2-21).

The block faulting was followed by basin filling (Figures 2-21 and 2-22), then subsequent dissection by the regional drainage system (Groat, 1972). Most of those basins were initially closed until integration of the Rio Grande drainage system during late Pleistocene. Some of those basins such as the Lobo Valley and Salt Basin remain closed (Henry, 1979). However, the Presidio Bolson has been dissected by tributaries of the Rio Grande. Tributaries or sidestreams such as Alamito and Cibolo Creeks (Figure 2-1) have been the dominant agents in excavating the Bolson with the Rio Grande serving mainly to lower the base level for the sidestreams (Groat, 1972).

# 3 Previous Work

A number of studies over the years have focused on the geology, geochemistry, and geophysics of the Presidio and Redford Bolsons area. The following paragraphs summarize the literature from which this study was principally drawn.

Groat (1972) conducted a detailed depositional and geomorphologic study of the bolson deposits. The study evaluated the depositional history and subsequent excavation of the bolson by the Rio Grande. The results of the project included a detailed map of the surface deposits and discussion of the water producing potential of the side stream alluvial aquifer and the bolson aquifer.

Kopp (1977) investigated areas of thermal water occurrence and the relationship to geology in Presidio County including the Presidio Bolson area. He observed that thermal springs and wells in the Candelaria-Ruidosa area within the bolson are located near or on normal faults and suggested that structure controls the movement of the hot water.

A later study by Henry (1979) focused on the geothermal potential in the Trans-Pecos area including the Presidio Bolson. The study included a detailed structural map of the bolson and geologic cross sections (Figure 2-21) with information on several hot and cold springs in the area. Henry (1979) proposed that the hot springs result from deep circulation of meteoric water. He also observed that cold springs appear in bolson fill along faults which act as barriers to ground-water flow. Henry (1979) concluded that the Presidio and Hueco Bolsons represent the best potential for geothermal development in the Trans-Pecos area.

Gates and Others (1980) conducted a study to determine the extent of groundwater reserves in the Trans-Pecos area including the Presidio Bolson area. The study involved collecting water level data and conducting geophysical surveys to estimate the saturated thickness of bolson deposits. The study also mapped the water quality of the aquifers. From the geophysical data they estimated bolson thicknesses up to 4,000 feet at the center. Most of the water above the Rio Grande floodplain was found to be fresh except northwest of Cibolo Creek where geophysical data indicate the fill is mostly lacustrine clay and silt. In the Rio Grande alluvium the groundwater ranged from fresh to very saline. The poor quality of the water near the river is attributed to groundwater discharge by plant transpiration along the river (Gates and others, 1980).

Mraz and Keller (1980), collected gravity data and interpreted the data using two cross-section gravity models (Figure 2-22). The models were used to estimate the regional structure of the graben area. A north cross section between Ruidosa and Candelaria estimated bolson thicknesses up to about 5,000 feet. A south cross-section running north-east through Presidio and Shafter indicates a maximum bolson thickness of about 3,200 feet (Figure 2-22). In addition to gravity data, the study also included lithology information from a number of wells in Presidio County including several in the bolson.

Gabaldon (1991) conducted a geochemistry study and developed a one layer groundwater flow model of the Presidio Bolson (Figure 3-1). Based on Groat's (1972) work, Gabaldon described three aquifers in the study area, the bolson fill aquifer, the stream deposit aquifer, and the river alluvium aquifer. In his study he analyzed geochemical data from the aquifers and identified two hydochemical facies: 1) Na-Cl-$SO_4$ and 2) Na-$HCO_3$. Best results for modeling were achieved using aquifer thicknesses from 200 to 300 feet and hydraulic conductivity values of 9.5 feet per day. He assumed that the deep flow systems were not significant. In the model, recharge was two percent of rainfall and concentrated along the mountain front (Gabaldon, 1991).

A groundwater availability model (GAM) for the Igneous Aquifer and parts of the West Texas Bolsons (Beach and others, 2004) in the eastern part of Presidio County includes an overlap area with this study. That model included Wild Horse Flat, Michigan Flat, Ryan Flat, and Lobo Flat aquifers along with the Tertiary Igneous Aquifer and underlying Cretaceous Rocks. The western portion of that model overlaps with the eastern portion of the study area for this project (Figure 3-1). They estimated the horizontal hydraulic conductivity for the Igneous Aquifer and Cretaceous age rocks to be 0.1 feet per day with a horizontal/vertical ratio of 200. They estimated hydraulic conductivity values of 4 to 50 feet per day for the bolsons. In their model distributed recharge was applied to mountain fronts and igneous outcrop areas. Focused recharge was applied to stream beds and alluvial fans in the bolsons, but distributed recharge was not assigned to bolson areas. Distributed rates in the upland areas in Presidio County ranged from less than one quarter inch to three quarters of an inch per year (Beach and others, 2004).

# 4 Hydrologic setting

## 4.1 Hydrostratigraphy

In the study area groundwater occurs in the Quaternary Rio Grande alluvium and side-stream alluvium deposits; the Quaternary-Tertiary bolson-fill; the Tertiary volcanic and volcaniclastics; and the underlying Cretaceous age rocks (Figure 2-20). The igneous and Cretaceous Age rocks are included to serve as a lower boundary condition and also because direct precipitation recharge to the Cretaceous age and igneous rocks in the higher elevations of the drainage basin provides underflow to the bolson. The Igneous Aquifer is an important aquifer in large parts of Presidio County and that aquifer is modeled explicitly in the West Texas Igneous and Bolson Groundwater Availability Model (Beach and others, 2004).

### 4.1.1 *Rio Grande Alluvium and Side-stream Alluvium Deposits*

Quaternary age deposits of poorly sorted sand, gravel, clay, and silt form the Rio Grande alluvial aquifer (Davis and Leggat, 1965). The extent of the floodplain-channel in the Presidio Bolson was mapped by Groat (1972). He estimated the alluvial deposits to be up to 65 feet thick ranging in width from 0.25 to 2 miles with an average width of 1.5 miles (Groat, 1972). Resistivity surveys and drillers' logs suggest that the alluvium is less than 100 feet thick (Gates and others, 1980). The shallow groundwater in the alluvial aquifer is under water-table conditions (Davis and Leggat, 1965).

Groat (1972) suggests that recharge to the Rio Grande alluvium occurs through underflow from upstream, infiltration from the Rio Grande, and underflow from sidestream alluvium and the bolson. However, Henry (1979) suggests that since basin-center facies are generally impermeable the Rio Grande is hydrologically isolated except when it crosses coarse-grained basin-margin sediments, bedrock, or major faults, or where sidestream alluvium deposits intersect the Rio Grande Alluvium.

Sidestream alluvium consists of gravel and sand eroded from bolson deposits and from surrounding mountains and transported toward the Rio Grande. Groat (1972) mentioned reports of wells with good supplies of water at less than 50 feet and sometimes less than 10 feet. He suggested that recharge to sidestream alluvium is by direct infiltration when the streams flow and in some cases by subsurface flow from adjacent mountain blocks; but also that the sidestream alluvium should not be considered a dependable source of groundwater development in the Presidio Bolson (Groat, 1972).

### 4.1.2 ***Bolson Deposits and volcaniclastics***

The Presidio Bolson was formed by middle Tertiary normal faulting. The basin filled with sediments eroded from the surrounding mountains. Exposed bolson-fill deposits range from conglomerate at the basin margins near the mountains to mudstone near the basin center (Groat, 1972). Two distinct facies were identified by Groat (1972) in the bolson: basin-margin facies and basin-center facies. The basin-margin facies consists of interbedded conglomerate and sandstone with less than ten percent mudstone. The basin center facies consists of interbedded fine sandstone and gypsiferous mudstone (Groat, 1972). The contact between basin margin and basin center facies is delineated based on the presence of ten percent conglomerate present in the sediments (Groat, 1972). The basin center facies outcrop over a much larger area than the basin margin facies (Groat, 1972).

Because of the presence of laterally discontinuous clay deposits, groundwater occurs both in unconfined and confined conditions. One well drilled to a depth of 1,320 feet near Presidio contained clay from 68 to 1,320 feet. Groundwater in the well rose to within 110 feet of the surface (Davis and Leggat, 1965). Deep wells next to Cibolo Creek and Alamito Creek had water levels 140 to 160 feet deeper than water levels in nearby shallow wells. Water depths generally increase towards the basin margin. The two Presidio Bolson wells located closest to the basin margin have water depths exceeding 300 feet. In much of the Presidio Bolson northwest of Cibolo Creek, the deep bolson is mostly fine-grained lacustrine deposits and most groundwater flow is in the ephemeral stream deposits (Gates, 1980). The lack of bolson water wells in this area may also be an indication of very low aquifer productivity.

Volcaniclastic deposits at the base of the bolson probably have similar hydrogeologic characteristics to the bolson-fill deposits (Beach and others, 2004) and will therefore be considered part of the bolson-fill for the purpose of the groundwater availability model.

#### 4.1.3 *Tertiary Volcanics and Cretaceous rocks*

Although the Igneous Aquifer is not the focus of this study, Tertiary igneous rocks underlie the bolson deposits and form parts of the eastern and western boundaries of the model. Beyond the study area, intrusive and extrusive volcanic rocks occupy a large area of Presidio County and supply moderate quantities of fresh water in some locations principally near Marfa (Davis and Leggat, 1965). The best production occurs in igneous rocks with primary porosity such as vesicular basalts, interflow zones in lava successions, sandstones, conglomerates, and breccias (Beach and others, 2004). Small quantities of water are supplied by wells that tap fractures in intrusive igneous rocks (Davis and Leggat, 1965).

The Cretaceous age rocks are mainly limestone with some sandstone and shale. They are not considered an aquifer in the study area or in the West Texas Igneous and Bolsons Groundwater Availability Model (Beach and others, 2004). However, along with the Tertiary volcanics they form parts of the eastern and western boundaries of the model and in some locations they receive direct precipitation recharge which supplies the bolsons as underflow.

## 4.2 Framework

The framework of the model is the elevation and extent of the tops and bottoms of each of the aquifer layers. The surfaces for the Presidio-Redford Bolsons aquifers are defined based on the following information: (1) land surface elevation from a Digital Elevation Model (DEM), (2) extent of the Presidio and Redford Bolsons mapped by Henry (1979), and (3) a bolson thickness map (Figure 4-1) created for this study from well logs and geophysical surveys and Henry's (1979) map.

The groundwater flow system can be conceptualized as three layers. The top layer represents the Rio Grande alluvium. The second layer consists of the Presidio and

Redford Bolsons, and the bottom layer represents the Tertiary volcanics and Cretaceous age rocks beneath and surrounding the bolson.

### 4.2.1 *Top of Model*

The top of the model is set at the land surface elevation defined by the 30-meter resolution Digital Elevation Model (DEM) (Figure 2-5).

### 4.2.2 *Base and Extent of Rio Grande Alluvium*

The extent of the Rio Grande alluvium was digitized from Groat's (1972) detailed geologic and geomorphic map (Figure 4-2). The thickness of the alluvium layer will be approximated as 100 feet except where the bolson deposits thin towards the edge of the basin. In those areas a minimum thickness of 50 feet will be assigned to both the alluvium and the bolson.

### 4.2.3 *Base of Presidio and Redford Bolsons*

The structural surfaces and thickness maps of the Bolsons were developed from three sources: (1) control points from the structure map of the bolson including map areas where the bolson fill thickness was less than about 330 feet (Henry, 1979), (2) well control points and gravity modeling results (Mraz and Kellar, 1980), and (3) well and geophysical data (Gates, 1980). The thickness map (Figure 4-1) was created by including all of the control points collected from these sources and contouring these control points. Two control points were added near the base of the bolson to smooth the contoured surface and produce a smoother surface. The base of layer 2 will be defined as the land surface elevation minus the bolson thickness. A minimum thickness of 50 feet will be assigned near the basin margins.

### 4.2.4 *Base of Model*

The base of the groundwater flow system for the purpose of modeling is assigned within the Cretaceous age rocks to allow hydraulic interaction between the bolson and the underlying rocks. The elevation of the base of the model will be set at 2,500 feet below sea level, deep enough to ensure that pumping from deep wells can be included in the model without excessive drawdown resulting from proximity to a no-flow boundary.

To ensure consistency between the two models in the small overlap area in eastern part of Presidio County the base of the Presidio-Redford Bolson groundwater availability model will smoothly transition to match the base of the groundwater availability model for the Igneous Aquifer and parts of the West Texas Bolsons (Beach and others, 2004).

## 4.3 Water Levels and Regional Groundwater Flow

Water level measurements have been collected through time in 22 wells completed in the Rio Grande Alluvium and six wells completed in the Presidio Bolson. Water levels have changed only slightly over the last 50 years in most of those wells (Figures 4-3, 4-4, and 4-5). Gabaldon (1991) also observed no significant changes to water levels between 1950 and 1991. A large data collection program took place in 1973 through 1974 as part of the groundwater availability study of Gates and others (1980) and a second in 2004 through 2005 as part of this project. Many wells measured during both sampling programs showed little change in water levels over the 31 year period.

In a relatively shallow well in the northern part of the Presidio Bolson (Figure 4-3; State Well Number 5151807 (PRBL); depth 84 feet) water levels are similar to water levels in a nearby Rio Grande alluvium well (Figure 4-4; State Well Number 5151802 (RGRD); depth 45 feet. However, comparing State Well Number 7439502 (RGRD), a shallow Rio Grande Alluvium well (11 feet depth), and State Well Number 7439504 (PRBL), a deep (Redford) bolson well at 214 feet depth, (Figure 4-5) the bolson water levels are about 30 feet below the Rio Grande levels.

A composite water level map was developed using the 1973 through 1974 and 2004 through 2005 water level measurements along with other water level measurements information from the Texas Water Development Board's Groundwater Database (TWDB, 2006). Groundwater depth data were also digitized from subsurface hydrology maps from Mexico (INEGIa, date unknown). In some areas little or no water level data were available. To supplement the water level data, a regression equation between elevation and depth to water was derived from well data. In key locations, such as surface water divides or where well data were very sparse, the DEM and regression equation were used to estimate a water level. The observed water level measurements and estimated water level elevations at locations were contoured to create a water level map to show regional flow directions (Figure 4-6).

General groundwater flow directions as well as proposed model boundaries are shown on the water level map (Figure 4-6). Regional groundwater flow is directed from the mountains along the eastern and western boundaries of the study area towards the basin center. The Rio Grande flows from the northwest to the southeast and serves as a major regional discharge area for all tributaries that originate in the mountains and surface water runoff from the upland areas.

## 4.4 Recharge

Recharge to the Bolsons takes place along the mountain front in the channels of Cibolo and Alamito Creeks and other ephemeral streams (Gates and others, 1980). The Rio Grande also recharges the alluvium when river stage is above groundwater elevations. Gates and others (1980) estimated an average annual recharge volume of 7,000 acre-feet for the Presidio and Redford Bolsons. This estimate is based on an assumption of recharge equal to one percent of precipitation over the total area of the aquifer and drainage basin (1,100 square miles) with an average rainfall of 12 inches per year. Most precipitation in the area takes place during torrential rainstorms in the summer months and the recharge probably results when those storms cause surface flow (Gates and others, 1980). LBG-Guyton and Associates (2001) agree that the recharge occurs mainly at higher elevations through alluvial fans and faults in the Chinati Mountains and along stream channels such as Cibolo Creek and Alamito Creek. They estimate the recharge area as 620 square miles and, again assuming that one percent of rainfall contributes to recharge, they estimate an average annual recharge of 3,630 acre-feet (LBG-Guyton and Associates, 2001). Gabaldon (1991) used two percent of annual precipitation, or 0.186 inches per year for developing a groundwater flow model. He tried model runs using both distributed recharge and focused mountain front recharge. His best results were obtained using the focused mountain front recharge.

Field studies using $^{14}C$ and tritium along with groundwater modeling conducted for the Eagle Flat and Red Light Draw aquifers to the north indicate that for those aquifers the recharge area is limited to mountain and upland areas and does not occur in the alluvial fans or basin center (George and others, 2005; Hibbs and Darling, 1995; Darling, 1997). They estimated recharge to be 0.6 percent of rainfall in the upland areas which constitute about 20 percent of the total area.  Field studies by Scanlon and others (2000) found that interdrainage areas have low downward water flux based on chloride sampling which also supports the lack of direct recharge on the basin floors.

Chemical and isotopic analyses were performed on 29 groundwater and 7 spring samples for this study. Those data were supplemented with additional information from the TWDB groundwater database. The isotope data suggest that direct recharge to the Presidio Bolson aquifer is minimal and episodic and occurs primarily through underflow from the underlying volcanics and cretaceous units which are recharged at high elevations and through stream bed seepage in the basin floor during high flow events (Chowdhury and others, 2006).The chloride mass balance method was used on 15 of the groundwater samples to estimate recharge rates. The estimates range from 0.05 to 0.45 inches per year (Figure 4-7) which represents about 0.05 to 3.5 percent of average precipitation for 1970 to 2000. (Chowdhury and Wade, in prep). The higher percentages were estimated in the higher elevations along the basin margins and the lower percentages occur at the basin center.

Also as part of this study radiocarbon isotope data were used with a geochemical model (NETPATH) to estimate groundwater ages and groundwater recharge rates. The groundwater recharge estimated by groundwater age gradients is about 0.6 inches per year (Chowdhury and Wade, in prep).

For the model, recharge to the Presidio-Redford Bolsons, Rio Grande Alluvium, and surrounding rocks will be modeled as a function of rainfall, elevation, and geology (Figures 2-5, 2-13, and 4-2). Two sets of distributed rainfall data are available for the study area. One is the Parameter-elevation Regressions on Independent Slopes Model or PRISM data from Oregon State University (PRISM, 2004 and 2010).  PRISM data includes annual average distributions of rainfall in the United States on a 2.485 mile (4 km) resolution grid. The other set of rainfall data is monthly rainfall in Mexico on a 30 mile resolution grid. (Universidad Nacional Autonoma de Mexico, 2010). The Mexico data has been summed to annual rainfall.  Because the PRISM data is higher resolution it will be used to estimate recharge where it exists and will be supplemented with the Mexico rainfall data where it is missing.

Recharge for the model will be calculated using a modified version (Hutchison and others, 2011; Hutchison, 2008) of the algorithm developed by Maxey and Eakin (1949).

Recharge for each upper-most model cell will be calculated as a fraction of precipitation depending on the cell elevation. The threshold elevations and percentages will be determined during calibration. The precipitation values will also be adjusted with a dampening factor to account for lag time associated with travel through the unsaturated zone (Hutchison, 2008).

## 4.5 Rivers and Streams

Generally, the Rio Grande valley is expected to be a regional groundwater discharge area. However, between Fort Quitman in south central Hudspeth County and the confluence of the Rio Conchos just above Presidio, the Rio Grande is a losing stream over much of its length (Darling, 1997; Miyamoto and others, 1995; Teasley and McKinney, 2005).

Teasley and McKinney (2005) analyzed the segment of the Rio Grande from Fort Quitman to just above the confluence of the Rio Conchos with the Rio Grande (the Forgotten River). One of the purposes of their study was to determine if significant hydrologic changes have occurred along that segment of the Rio Grande. One of their conclusions was that during the period 1925 to 1945 the segment was losing 58 percent of the time and during the period 1984 to 2004 it had increased to losing 64 percent of the time. They also found that the largest losses occur in July and October. Teasley and McKinney (2005) did not do a separate analysis of the segment from Candelaria to the gauge above Presidio. They suggest that flow at Candelaria was not properly recorded by the stream gauge because, for several time periods, the Candelaria hydrograph shows flow increasing linearly with time while the upstream and downstream gauges show variation over time. In addition, the Candelaria gauge shows several extremely large peaks that do not occur at the Fort Quitman gauge or at the gauge above Presidio (Teasley and McKinney, 2005).

A total of six stream gauges are located in the study area, three International Boundary Waters Commission (IBWC) gauges on the Rio Grande and one International Boundary Waters Commission gauge on the Rio Conchos. United States Geological Survey gauges are located on Alamito Creek and Cibolo Creek.  The gauges on the Rio Grande are located near Candelaria, just above Presidio, and just below the confluence of the Rio Conchos with the Rio Grande (Figure 4-8).

For most of the time, flow at Candelaria is greater than flow at a gauge north of Presidio above the Rio Conchos (Figure 4-9). Those decreases may be due to stream losses or they may be due to errors in the Candelaria gauge mentioned by Teasley and McKinney (2005) or both. Except for some small springs, flow in Alamito and Cibolo Creek, tributaries to the Rio Grande, occurs mainly in response to rainfall. Runoff is rapid and tributary flow is sudden and short-lived (Groat, 1972) resulting in flashy hydrographs (Figure 4-10). Flow in the Rio Conchos and in the Rio Grande below the Rio Conchos is much more significant (Figure 4-11).

Streamflow is generally made up of three components: surface runoff, interflow, and baseflow. Surface runoff travels directly over the ground surface to the stream channel. Interflow is water which infiltrates the soil and moves laterally through the upper soil layers until it enters a stream channel (Linsley and others, 1982). Baseflow is the component resulting from groundwater discharge to the stream. The surface runoff and interflow are often combined and the streamflow is considered to consist of two components, direct runoff and baseflow (Linsley and others, 1982). Streamflow hydrographs can be separated, using various techniques, into the two components. The premise behind separation is that the rising limb of a hydrograph peak is influenced by the storm event. The point of inflection at the peak marks the time at which surface inflow ends. The receding or falling limb represents withdrawal of water from storage within the basin (Linsley and others, 1982). Nathan and McMahon (1990) developed an automated recursive digital filtering technique for baseflow separation based on techniques originally used for signal processing. The filter equation is

$$q_t = \beta q_{t-1} + (1+\beta)/2 * (Q_t - Q_{t-1}) \tag{1}$$

Where $q_t$ is the filtered surface runoff at time step $t$, $Q_t$ is the original streamflow, and $\beta$ is the filter parameter. Baseflow is then given by

$$b_t = Q_t - q_t \tag{2}$$

The filter is iteratively passed over the streamflow data forward, backward, and forward, each time reducing the percentage of estimated baseflow. Although the method has no physical basis, it is objective and reproducible (Arnold and others, 1995). The method was tested by Arnold and others (1995) and compared with another automated technique. They found it to be comparable in predicting the manually separated baseflow.

The baseflow separation technique described by Arnold and others (1995) was applied to the gauge data from the Rio Grande above Candelaria and the gauge above Presidio (Figure 4-9). However, it should be noted that flows in the Rio Grande and Rio Conchos are influenced by upstream reservoirs, which increases the uncertainty in estimates of baseflow.

Annual average estimates of baseflow at three Rio Grande gauges and the Rio Conchos gauge located at the upstream and/or downstream ends of four river segments (Figure 4.8) are listed in Appendix A. Long-term average baseflow estimates (Table 4.1) between Candelaria and the gauge above Presidio suggest the Rio Grande was net losing between 1976 and 2003. If the stream gauge data at Candelaria is accurate and the segment of the Rio Grande from Candelaria to Presidio is losing, one possible explanation to account for the Rio Grande losing water in a regional discharge area is the dense vegetation, principally mesquite and saltcedar, along the river. Groundwater discharge through evapotranspiration is discussed further in section 4.7.2.

The MODFLOW river package (USGS, 2000) will be used to model discharge along the Rio Grande and Rio Conchos. Groundwater discharge in those areas probably includes both riparian evapotranspiration and baseflow (see section 4.7.2). Therefore, for calibration purposes net river and evapotranspiration discharge estimates will be compared with modeled river discharge values along each of four river segments.

**Table 4-1 Baseflow estimates at four stream gauges. Gauge locations shown in Figure 4.8.**

| Gauge | Cubic feet per second | Acre-feet per year |
|---|---|---|
| Rio Grande at Candelaria (1976 – 2003) | 35 | 25,135 |
| Rio Grande above Presidio (1976 – 2003) | 32 | 23,054 |
| Rio Grande above Presidio (1924 – 2004) | 21 | 14,883 |
| Rio Conchos just above confluence with Rio Grande (1954 – 2005) | 107 | 77,250 |
| Rio Grande below Presidio (1931 – 2005) | 170 | 123,180 |

## 4.6 Hydraulic Properties

Changes in water levels due to pumping in an aquifer are a function of the hydraulic conductivity and storage properties of an aquifer. These properties are determined through aquifer tests such as multi-well pumping tests or single-well specific capacity tests. Specific capacity data are available for six Presidio Bolson wells and two Rio Grande alluvium wells (Table 4-2; Figure 4-12). Data were not available for any multi-well pumping tests.

Transmissivity and hydraulic conductivity can be estimated from specific capacity data using an iterative method (Mace, 2001). The following equation is solved by making an initial guess for transmissivity, T, then iteratively calculating until the differences between the T's on both sides are small:

$$T = \frac{S_c}{4\pi} \ln\left(\frac{2.25Tt_p}{r_w^2 S}\right), \tag{3}$$

where $S$ is the storativity of the aquifer, $S_c$ is specific capacity, $t_p$ is the time of pumping, and $r_w$ is the well radius (Mace, 2001).

Transmissivity estimates for the eight wells were developed using the Mace (2001) approach. Hydraulic conductivity estimates were then developed from the transmissivity results and well depth data (Table 4-2). The geometric mean hydraulic conductivity for the bolson wells was 2.3 feet per day and the average was 7.8 feet per day.

**Table 4-2 Hydraulic conductivity estimated from specific capacity data for the study area**

| State Well Number | Depth (feet) | Aquifer | Hydraulic Conductivity (feet/day) |
|---|---|---|---|
| 7403305 | 300 | Presidio Bolson | 0.5 |
| 7429612 | 147 | Presidio Bolson | 1 |
| 7429617 | 88 | Presidio Bolson | 30 |
| 7430606 | 530 | Presidio Bolson | 13 |
| 7439202 | 400 | Presidio Bolson | 2 |
| 7439904 | 135 | Presidio Bolson | 0.5 |
| 7429604 | 29 | Rio Grande alluvium | 1977 |
| 7429606 | 18 | Rio Grande alluvium | 2356 |

The estimated values of hydraulic conductivity based on the specific capacity data are consistent with information from other studies in the area or in similar hydrogeologic settings in nearby areas (Table 4-3). In developing the model for the Hueco Bolson aquifer system, Heywood and Yager (2003) assigned horizontal hydraulic conductivity values of 2.95 feet per day for lacustrine-playa facies and 22.31 feet per day for alluvial-fan facies. The Source Water Assessment Project (TCEQ, 2002) data lists a value of 5 feet per day for the Presidio Bolson. Gabaldon (1991) estimated a hydraulic conductivity value of 9.5 feet per day from his model calibration. Although hydraulic conductivity values estimated for the Rio Grande Alluvium (Table 4-3) are much higher than for the Presidio Bolson, they are in the middle of the range for gravel deposits (Freeze and Cherry, 1979).

Vertical hydraulic conductivity is generally either determined from multi-well, multi-aquifer pumping tests or from numerical modeling. Values of vertical hydraulic conductivity have been estimated by Beach and others (2004) and Haywood and Yager (2002) for their models (Table 4-3).

The storage parameter for unconfined aquifers, specific yield ($S_y$), is defined as the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in head (Freeze and Cherry, 1979). Freeze and Cherry (1979) reported that specific yield values for unconfined aquifers range from 0.01 to 0.30 . Confined storage parameters include specific storage ($S_s$) and storativity (S). Specific storage is the volume of water that a unit volume of aquifer releases from storage under a unit decline in head (Freeze and Cherry, 1979). The units of specific storage are 1/ length. Storativity is equal to specific storage times saturated thickness and is dimensionless. Storage parameters can be estimated from multi-well and/or multi-depth aquifer tests. Although, those data are not available for this area, storage properties have been estimated for other aquifers in similar hydrogeologic settings (Table 4-3).

**Table 4-3 Hydraulic properties from other studies in the area.**

| Reference | Specific Storage (1/feet) | Storativity | Specific yield | Vertical hyd. conductivity (feet/day) | Horizontal hyd. conductivity (feet/day) |
|---|---|---|---|---|---|
| **Bolson Deposits** | | | | | |
| Gabaldon ( 1991 ) | na | na | na | na | 9.5 |
| Beach and Others (2004) | na | na | 0.06 | 0.0001 - 0.35 | 4 - 50 |
| Heywood and Yager (2003) | 2.00E-06 | na | 0.18 | 0.004 - 0.4 | 2.95 - 22.31 |
| TCEQ (2002) | na | na | na | na | 5 |
| Bedinger and Others (1989) | na | na | na | na | 0.13 |
| Hibbs and Others (1997) | | | | 1 | 10 |
| **Tertiary Igneous** | | | | | |
| Beach and Others (2004) | na | 3.00E-05 | 0.01 | 0.00008 - 0.1 | 0.2 - 1 |
| Bedinger and Others (1989) | na | na | na | na | 0.0013 |
| **Cretaceous** | | | | | |
| Beach and Others (2004) | na | 3.00E-05 | 0.01 | 0.0001 - 0.1 | 0.1 - 1 |
| Bedinger and Others (1989) | na | na | na | na | 0.0007 |

na: not applicable

## 4.7 Discharge

Groundwater discharge from the Presidio and Redford Bolsons occurs through springs, evapotranspiration, river baseflow, and groundwater pumping.

### 4.7.1 *Springs*

Locations (Figure 4-13) and flow data (Table 4-4) for the springs for the United States portion of the study area are available from the Springs of Texas Study (Heitmuller and Reece, 2003). Additional information about the springs was obtained from Henry (1979), including identification of hot or cold springs and locations and flow data for three springs in the Mexico portion of the study area.

Both cold and hot springs occur in the bolson and surrounding areas. Springs with surface temperatures approximately 15° F ( 8° C) above mean annual temperature are hot or thermal springs (Henry, 1979). Springs in the study area qualify as thermal if the surface temperature is greater than 86° F (30° C). However, this definition excludes springs which have cooled below 86° F because of mixing with other water. Other information such as chemical composition can help identify those thermal springs (Henry, 1979). The hot springs in the Presidio Bolson and surrounding areas likely result from deep

circulation of groundwater along faults created during late Tertiary extension (Henry, 1979). The Presidio-Redford Bolsons groundwater availability model will not consider the deep flow system. However, some of the thermal springs may be mixing with shallow groundwater so all of the springs will be included in the model (Table 4-4; Figure 4-13), although temperature gradients will not be considered in the model. The flow from the hot springs will be compared with model spring discharge inversely proportional to the temperature of the spring. The assumption is that the hotter the spring the less the contribution from the shallow cold flow system. The total reported flow (Heitmuller and Reece, 2003; Henry, 1979) from the hot springs in the study area is about 140,000 to 186,000 cubic feet per day (1,170 to 1,560 acre-feet per year).
The cold springs in the area result from shallow groundwater discharge along bedding contacts where facies changes occur and along hydraulically conductive faults (Groat, 1972). All of the cold springs (Table 4-4; Figure 4-13) identified in the model area will be included in the model, although facies changes and faults are not explicitly included in the model. The total reported flow (Heitmuller and Reece, 2003; Henry, 1979) from the cold springs in the study area is about 180,000 cubic feet per day (1,510 acre-feet per year).

**Table 4-4 Measured flows and temperatures of springs in the study area (Heitmuller and Reece, 2003; Henry, 1979).**

| State well number | Name | Aquifer | Temperature (°F) | Spring flow (gal. per minute) | Flow (cubic feet per day) | Thermal spring |
|---|---|---|---|---|---|---|
| 101 | Ojos Calientes | NA | 140-194 | 264 | 50,827 | yes |
| 102 | Rancho Cipres | NA | 95 | NA | NA | yes |
| 103 | Peguis | NA | 97 | 264 | 50,827 | yes |
| 5152201 | Vasquez Spring | Volcanics | 75 | NA | NA | no |
| 5152501 | Capote Springs | Volcanics | 99 | 106 | 20,408 | yes |
| 5152502 | Mexican Springs | Rio Grande Alluvium | 73 | 5 | 963 | no |
| 5152701 | Adobe Ruin Spring | Volcanics | 72 | 4 | 770 | no |
| 5152702 | Nixon Spring | Volcanics | $72^{+}$(90*) | 1 | 193 | yes |
| 5159202 | NA | Presidio Bolson | 70 | 3 | 578 | no |
| 5159203 | Ranchita Spring | Presidio Bolson | 81 | 4 | 770 | no |
| 5159204 | Rancho Spring | Presidio Bolson | 79 | 4 | 770 | no |

| State well number | Name | Aquifer | Temperature (°F) | Spring flow (gal. per minute) | Flow (cubic feet per day) | Thermal spring |
|---|---|---|---|---|---|---|
| 5159302 | La Cienaga seepage area | Presidio Bolson | 70 | 29 | 5,583 | no |
| 5159601 | Sanguijuela Springs | Presidio Bolson | 81 | 2 | 385 | no |
| 5159603 | Chupadera Pila Spring | Presidio Bolson | 73 | 3 | 578 | no |
| 5159802 | NA | Presidio Bolson | 75 | 1 | 193 | no |
| 5159807 | Ocotillo Spring | Presidio Bolson | 81 | NA | NA | no |
| 5159901 | Negley Springs (south) | Presidio Bolson | NA | 54 | 10,397 | no |
| 5159902 | Negley Springs (north) | Presidio Bolson | 75 | 25 | 4,813 | no |
| 5159903 | La Cienega Springs | Presidio Bolson | NA | 107 | 20,600 | no |
| 5160601 | Ojo Carrizo Spring | Presidio Bolson | NA | NA | NA | no |
| 5160701 | Ruidosa Hot Spring 1 | Presidio Bolson | 113 | 31 (20) | 5,968 (3,851) | yes |
| 5160702 | Ruidosa Hot Spring 2 | Presidio Bolson | 82 | 35 | 6,738 | yes |
| 5161405 | Ojo Frio Spring | Volcanics | NA | NA | NA | no |
| 7403301 | Torres Springs | Presidio Bolson | NA | 27 | 5,198 | no |
| 7403302 | NA | Presidio Bolson | 72 | 120 | 23,103 | no |
| 7403303 | NA | Presidio Bolson | 72 | 280 | 53,908 | no |
| 7403304 | Shannon Spring | Presidio Bolson | 72 | 15 | 2,888 | no |
| 7403601 | Shannon Springs | Presidio Bolson | NA | NA | NA | no |
| 7404301 | Ojo Jardin Spring | Cretaceous | 81 | 35 | 6,738 | no |
| 7404402 | Section 32 Spring | Presidio Bolson | 66 | 9 | 1,733 | no |
| 7404403 | NA | Presidio Bolson | 66 | 3 | 578 | no |

| State well number | Name | Aquifer | Temperature (°F) | Spring flow (gal. per minute) | Flow (cubic feet per day) | Thermal spring |
|---|---|---|---|---|---|---|
| 7404803 | Indian Spring | Presidio Bolson | 77 | 15 | 2,888 | no |
| 7412102 | San Jose Spring | Presidio Bolson | 70 | 2 | 385 | no |
| 7413601 | Spencer Springs | Presidio Bolson | NA | 10 | 1,925 | no |
| 7413701 | La Cienaga Springs | Presidio Bolson | 86 | 33 (264) | 6,353 (50,827) | yes |
| 7421801 | Chupadera Springs | Presidio Bolson | NA | 6 | 1,155 | no |
| 7423601 | Alamo Springs | Volcanics | 77 | 22 | 4,236 | no |
| 7423602 | Cottonwood Springs | Volcanics | 77 | NA | NA | no |
| 7424401 | Alamo Springs | Volcanics | 77 | NA | NA | no |
| 7430804 | NA | Presidio Bolson | 72 | 33 | 6,353 | no |
| 7430805 | NA | Presidio Bolson | NA | 22 | 4,236 | no |
| 7430901 | NA | Presidio Bolson | 72 | 90 | 17,328 | no |
| 7431402 | Rabago y Teran Springs | Presidio Bolson | 79 | 6 | 1,155 | no |

Note: When two values are listed for temperature or flow the first value is from Heitmuller and Reece (2003) and the value within parenthesis is from Henry (1979).

NA - Not available
+ Heitmuller and Reece (2003)
(*)Henry (1979)

### 4.7.2 *Evapotranspiration*

Evaporation from bare soil and open water bodies and transpiration of soil water and groundwater by plants are combined into the term evapotranspiration. Evapotranspiration is controlled by energy supply and water supply (Scanlon and others, 2005). Phreatophytes are plants that have their roots in the capillary fringe and feed on groundwater all or most of the growing season (Dreesen and Fenchel, 2010). Groundwater evapotranspiration can be a significant component of groundwater discharge for many aquifers where the water table is shallow and/or where phreatophytes are abundant (Scanlon and others, 2005).

Mesquite and saltcedar, an exotic invasive phreatophyte species, are densely thicketed along the Rio Grande south of Fort Quitman located in south central Hudspeth County and are a significant source of groundwater discharge (TWDB, NMWRRI, 1997). Saltcedar was introduced into the Rio Grande basin upstream in New Mexico in 1926 when it was planted along the Rio Puerco, a tributary, for erosion control. By 1935 it had reached Candelaria and by 1967 aerial photographs showed that most of the farmland near Presidio had been abandoned and overgrown with salt cedar (Teasley and McKinney, 2005). Landsat satellite imagery of the study area shows that a one-half to three quarter mile strip adjacent to the Rio Grande is densely covered with plants.

Davis and Leggat (1965) summarized the flow system for the area by noting that groundwater from the upland areas is discharged by subsurface flow into the alluvial deposits in the valley where it is either discharged into the Rio Grande or by evapotranspiration. In 1965, they observed that evapotranspiration from the dense growth of saltcedar between Presidio and Candelaria accounts for a large fraction of the aquifer system discharge (Davis and Leggatt, 1965). In his work on the Red Light Draw and Green River Valley Bolsons, Darling (1997) highlighted the importance of evapotranspiration from the Rio Grande alluvium.

Owens and Moore (2007), estimated daily water use from saltcedar at a young monoculture site along the Rio Grande and a mature site on the Pecos River. At the Pecos River site they estimated approximately 4 inches per year (61.2 liters per day over 100 square meters) and for the Rio Grande site they estimated approximately 82 inches per year (573 liters over 238 square meters) (Owens and Moore, 2007). Blaney (1958), estimated evapotranspiration rates of 72 inches per year at sites along the Pecos at Carlsbad, New Mexico and Balmorhea and Ft. Stockton Texas. Based on maps of potential evapotranspiration rates and representative crop coefficients, Scanlon and others (2005) estimated unhindered vegetative evapotranspiration rates throughout Texas. They estimated 50 to 60 inches per year for the study area (Scanlon and others, 2005).

In light of other studies (Davis and Leggatt, 1965; TWDB, NMWRRI, 1997; Darling, 1997) which suggest the importance of evapotranspiration in the Presidio-Redford Bolson aquifer system discharge, average annual discharge volumes were estimated along riparian segments in the model area (Table 4-5) for comparison with modeled aquifer discharge along the river.

### 4.7.3 *Groundwater Pumping*

Groundwater from the Presidio and Redford Bolsons aquifers is used for irrigation, livestock, municipal, and rural domestic supply (Table 4-6; Figure 4-14).

**Table 4-5. Estimates of average evapotranspiration volumes in acre-feet per year along four river segments. See Figure 4-8 for the location of the upper and lower ends of the segments.**

| Segment | Area (square miles) | Owens and Moore (2007) 4 in/yr | Owens and Moore (2007) 82 in/yr | Scanlon and others (2005) 50 in/yr | Scanlon and others (2005) 60 in/yr | Blaney (1958) 72 in/yr |
|---|---|---|---|---|---|---|
| Rio Grande Candelaria to above Presidio | 12.9 | 2,752 | 56,416 | 34,400 | 41,280 | 49,536 |
| Rio Conchos Just above confluence with Rio Grande | 8.0 | 1,707 | 34,987 | 21,333 | 25,600 | 30,720 |
| Rio Grande Above Presidio to below Presidio | 3.2 | 683 | 13,995 | 8,533 | 10,240 | 12,288 |
| Rio Grande Below Presidio to end of model | 4.1 | 875 | 17,931 | 10,933 | 13,120 | 15,744 |
| Total | 28.2 | 6,016 | 123,328 | 75,200 | 90,240 | 108,288 |

It was reported that 5,400 acre-feet of water was pumped for irrigation from 24 wells in 1960 from the Rio Grande Alluvium Aquifer (Groat, 1972). By 1997 both irrigation and livestock use in Presidio County had declined to less than half of 1980 rates. The Texas Water Development Board's estimates of historic groundwater use for irrigation and livestock are reported on a county-wide basis for each aquifer. For this study, groundwater pumping assigned for irrigation and livestock will be determined by scaling the county-wide total to the proportion of livestock and irrigated land use (Figures 4-16, and 4-17; Table 4-6). Spatial distribution of livestock and/or irrigation wells from the groundwater database confirms that it may be reasonable to use land use coverage for distributing the pumping across the model area (Figures 4-16 and 4-17).

The rural domestic use is estimated to range from 204 to 279 acre-feet per year from 1980 to 1997 (Table 4-6) respectively, based on census data for the study area (Figure 4-18) and a state-wide per capita use estimate. Population within the city boundaries of Presidio is excluded from the calculation of rural domestic pumping which will be distributed based on population density. The location of wells listed in the Texas Water Development Board's groundwater database that are described as domestic wells generally confirm that population density coverage is appropriate for distributing the domestic pumping (Figure 4-18).

The municipal use for the City of Presidio was reported as 146 acre-feet in 1948 (Broadhurst and others, 1948) and 86 acre-feet in 1960 (Davis and Leggatt, 1965). By 1980 the municipal use for Presidio was reported as 246 acre-feet (Figure 4-14; Table 4-6) and had risen to 879 acre-feet in 2002 (TWDB, 2007b). Municipal pumping will be distributed to model cells based on the municipal well location (Figure 4-15). Beginning in 1995 the Redford Water Supply Corporation (WSC) and the Candelaria Water Supply Corporation began reporting their groundwater use to the Texas Water Development Board. The maximum amount of use for Redford WSC was 21 acre-feet in 1999 and the maximum amount of use for Candelaria WSC was 11 acre-feet in 2002 (Table 4-6). Location information is available for those WSC wells (Figure 4-15); however, it is likely that distributed pumping based on population density will result in a similar amount of pumping per grid cell.

In Mexico surface water and groundwater belong to the federal government. The federal government grants concessions to use water and Mexico's National Water Commission (Comisión Nacional del Agua or CNA) issues permits to withdraw water (Arreguín-Cortés and López-Pérez, 2007). The locations (Figure 4-20) and permitted extraction rates (Figure 4-19) are available from an online database from the National Water Commission website (CNA website, 2008). Information on the permitted water use is also available in the database. The total amount of permitted use is about 9,000 acre feet per year compared with about 2,000 acre-feet per year (1997) on the UnitedStates side. This groundwater use ratio (9,000 acre-feet per year permitted to 2,000 acre-feet per year) is consistent with the population ratio of 18,000 to 4,000. In Mexico, most of the groundwater use is municipal; whereas, in the U.S. the largest use is irrigation followed by municipal.It should be noted that the values listed for Mexico are permitted use rather than actual use. Actual use is often less than permitted use.

**Table 4-6. Historical estimates of groundwater use in the United States portion of the study area reported in acre-feet per year. Unless stated otherwise in text water use estimates are from TWDB (2007b).**

| Year | City of Presidio | Candelaria W . S. C. | Redford W . S. C. | Rural Domestic | Irrigation | Livestock |
|---|---|---|---|---|---|---|
| 1948 | 146 | NA | NA | NA | NA | NA |
| 1960 | 86 | NA | NA | NA | 5,400 | NA |
| 1980 | 246 | NA | NA | 204 | 4,377 | 458 |
| 1981 | 251 | NA | NA | 210 | 3,582 | 457 |
| 1982 | 312 | NA | NA | 215 | 2,788 | 343 |
| 1983 | 358 | NA | NA | 221 | 1,994 | 285 |
| 1984 | 340 | NA | NA | 227 | 1,200 | 228 |

| Year | City of Presidio | Candelaria W . S. C. | Redford W . S. C. | Rural Domestic | Irrigation | Livestock |
|---|---|---|---|---|---|---|
| 1985 | 346 | NA | NA | 232 | 1,276 | 314 |
| 1986 | 370 | NA | NA | 238 | 811 | 149 |
| 1987 | 318 | NA | NA | 244 | 190 | 142 |
| 1988 | 370 | NA | NA | 249 | 872 | 165 |
| 1989 | 525 | NA | NA | 255 | 1,546 | 213 |
| 1990 | 498 | NA | NA | 261 | 1,546 | 209 |
| 1991 | 493 | NA | NA | 263 | 165 | 214 |
| 1992 | 483 | NA | NA | 266 | 867 | 212 |
| 1993 | 532 | NA | NA | 269 | 695 | 210 |
| 1994 | 641 | NA | NA | 271 | 442 | 254 |
| 1995 | 750 | 4 | 18 | 274 | 504 | 210 |
| 1996 | 646 | 3 | 19 | 276 | 516 | 160 |
| 1997 | 618 | 4 | 20 | 279 | 814 | 160 |
| 1998 | 686 | 9 | 21 | NA | NA | NA |
| 1999 | 755 | 11 | 21 | NA | NA | NA |
| 2000 | 853 | 11 | 18 | NA | NA | NA |
| 2001 | 879 | 11 | 18 | NA | NA | NA |
| 2002 | 879 | 11 | 18 | NA | NA | NA |

NA: Not available

W.S.C.: Water Supply Corporation

**Table 4-7. Total reported irrigation pumping for Presidio County (TWDB, 2007a). The irrigation pumping for the model will be apportioned to the percent of county irrigated area within the model area.**

| Year | Presidio County irrigation pumping (acre-feet per year) |
|---|---|
| 1958 | 4,199 |
| 1964 | 4,415 |
| 1969 | 5,520 |
| 1974 | 7,909 |
| 1979 | 8,317 |
| 1984 | 3,349 |
| 1989 | 4,317 |
| 1994 | 1,725 |
| 2000 | 2,564 |
| 2003 | 4,110 |
| 2004 | 4,395 |
| 2005 | 3,738 |

A preliminary well file (Figure 4-14) has been developed for the model using information in Tables 4-6 and 4-7 and other information such as population and land use. For rural domestic pumping, 1990 population values were first distributed to model grid cells using 1990 US Census polygons. Next annual total population values were interpolated from decadal data from 1950 to 2009. Finally a ratio between a given year and 1990 total population was applied to each 1990 cell population value and was multiplied by 110 gallons per capita per day to get a cell pumping rate.

Livestock pumping was distributed to the model grid based on 1980 rangeland land use. Then 1960, 1974, 1977, and 1980 county livestock pumping estimates were used to interpolate and extrapolate total annual livestock pumping for each year of the model. A ratio between 1980 livestock totals and interpolated totals for other years was applied to 1980 cell pumping rates to get cell pumping rates for other years.

Irrigation pumping was distributed to the model grid based on 1984 agricultural land use coverage. County irrigation estimates are available for 1958, 1964, 1969, 1974, 1979, 1984,1989, 1994, 2000, 2003, 2004 and 2005. County totals for other years were estimated by interpolating between years. A ratio relative to 1984 was used to estimate cell values for other years.

Municipal pumping was assigned to the model based on City of Presidio pumping totals for 1948, 1960, and 1980 through 2004 and pumping well locations from the TWDB groundwater database. Pumping totals for other years were interpolated. Well data from TWDB database and well count from Water Use survey were used to assign well specific pumping from 1948 to 2004. The annual total estimated municipal pumping was divided by the annual well count. The active wells for each year were determined based on the year wells were drilled. It was assumed that preference was given to the newest wells.

For pumping located in Mexico, permitted amounts and locations will be used from the CNA website (Comisión National del Agua (CNA), 2008). Some wells have coordinates which place them in the US. Those locations are excluded. Annual pumping amounts will be varied by the ratio of population for a particular year to the 2004 Presidio County population. The assumption is that pumping is generally a function of population and that population in the Mexico part of the study area varies through time in the same way that Presidio County population varies through time.

## 4.8 Water Quality

Water quality is defined by the types of chemical constituents and their concentrations present in groundwater. Availability of an abundant quantity of groundwater may not always ensure that the water can be consumed safely. Water is a good solvent and may readily derive various dissolved constituents from natural processes or anthropogenic activities. For example, rainwater that falls in the outcrop areas of an aquifer has very little dissolved minerals, but as it infiltrates through the unsaturated zone, reaches the water table of the aquifer, and moves laterally following hydraulic gradients, it continually reacts with the aquifer minerals and progressively acquires more dissolved solids. An increase in the salinity continues until the water becomes saturated resulting in the precipitation of these dissolved solids. Human activities, such as irrigation, disposal of contaminants on the land surface, and/or accidental release of contaminants may also lead to groundwater contamination if these contaminants find their way into the aquifer. Therefore, chemical concentrations in the groundwater are compared to federal and state standards to determine whether the groundwater is acceptable for different types of water use.

### 4.8.1 *Methods*

Groundwater quality from the Presidio-Redford Bolson and the Rio Grande Alluvium aquifers were gathered and used to characterize the groundwater based on its geographic occurrence in the basin. For example, wells located to the east at higher elevations along the mountain fronts following the basin margins and fault zones have been denoted as “basin margin or mountain front water” and wells located farther downdip from the mountains at lower elevations in the valley towards the Rio Grande have been designated as “basin center waters”. Groundwater quality can also be characterized based on total dissolved solids content following classification by the Texas Groundwater Protection Committee per Section 26.401 of the Texas Water Code. Under this classification scheme, groundwater is grouped into four classes depending on total dissolved solids content of the water:

- fresh water—less than 1,000 mg/l,
- slightly-saline water — 1,000 – 3,000 mg/l,
- moderately-saline water —3,000 – 10,000 mg/l, and
- very-saline water — more than 10,000 mg/l.

In order to evaluate trends in the groundwater quality, the following analyses were completed: (1) the spatial distribution of chemical constituents in the groundwater from the Presidio-Redford Bolson were evaluated, (2) chemical constituents were plotted against depth to observe whether there is any preferential occurrence of the constituents at any specific depth which may reveal lithologic controls on water quality, (3) groundwater samples were plotted in Piper diagrams to group them into distinct hydrochemical facies, and (4) various cross-plots of the chemical constituents were used to determine their potential sources. To determine suitability of the groundwater for irrigation purposes, we calculated sodium adsorption ratio (SAR) using the following equation:

$$SAR = Na/\sqrt{(Ca+Mg/2)}$$

where Na = sodium, Ca = calcium, and Mg = magnesium in milliequivalents per liter (US Salinity Laboratory, 1954).

### 4.8.2 *Results*

The spatial distribution of total dissolved solids, chloride, sulfate, and sodium show higher concentrations in the basin centers and fresher groundwater more commonly occurs along the mountain fronts (Chowdhury and others, 2008). Plots of the various chemical constituents with well depths also show some trends (Figure 4-21). For example, total dissolved solids, sulfate, bicarbonate, and chloride concentrations progressively decrease with increasing well depths. We compared the constituents to drinking water standards as per the Texas Administrative Code (Table 4-8). We observed that many of the chemical constituents, such as arsenic, cadmium, and lead exceed the primary drinking water standard by about 28, 28, and 100 percent, respectively.

Chloride, sulfate, and total dissolved solids exceed the secondary drinking water standard by 10, 29, and 25 percent, respectively (Table 4-8). Sodium adsorption ratios in the Presidio-Redford Bolson and the Rio Grande Alluvium aquifers are low (less than 5) and therefore, the waters generally do not pose a high irrigation hazard (Table 4-8). Trace element concentrations in the groundwater from the Rio Grande Alluvium Aquifer are not reported because of insufficient data.

Groundwater classification into hydrochemical facies suggests that groundwater from the basin margins/mountain fronts, basin centers, and the Rio Grande Alluvium have different chemical compositions (Figure 4-22). For example, groundwater from the basin margins is mainly Na-Ca-$HCO_3$ type, groundwater from the basin-centers is mainly Na-$HCO_3$ –$SO_4$, and groundwater from the Rio Grande Alluvium Aquifer is mainly Na-Ca-Cl- $SO_4$ type.

A plot of total dissolved solids versus sulfate shows that they are strongly correlated with correlation coefficients of 0.73 for groundwater in the Presidio-Redford Bolson Aquifer near the basin-margins, 0.67 for groundwater in the Presidio-Redford Bolson Aquifer near the basin-centers, and 0.9 for groundwater in the Rio Grande Alluvium Aquifer (Figure 4-23) (Chowdhury and others, 2008). Plot of chloride/bromide ratios versus chloride indicate that groundwater in the Presidio-Redford Bolson Aquifer near the basin-margins have lower chloride/bromide ratios (up to 200), groundwater in the Presidio-Redford Bolson Aquifer near the basin-centers have moderate chloride/bromide ratios (up to 600), and groundwater from the Rio Grande and Rio Grande Alluvium Aquifer have high chloride/bromide ratios (up to 1,400) (Figure 4-24) (Chowdhury and others, 2008).

A plot of sodium versus chloride suggests that groundwater from the Presidio-Redford Bolson Aquifer near the basin-margins has excess sodium, groundwater from the Presidio-Redford Bolson Aquifer near the basin-centers has depleted sodium, and groundwater from the Rio Grande Alluvium Aquifer has mainly excess sodium when compared to sodium that would be expected if the sodium was completely derived from dissolution of halite. Dissolution of halite produces an equal amount of sodium and chloride ions (Figure 4-25).

### 4.8.3 ***Discussion***

Occurrences of varying groundwater compositions (Chowdhury and others, 2008) at different geographic locations in the basin suggest that the geochemical and recharge processes have differed in these areas. For example, it is commonly postulated that groundwater in arid, mountain bounded basins mostly derive a dominant component of groundwater recharge from subsurface inflow to the basin from adjacent mountain blocks and infiltration through stream channels along the mountain fronts with minimal recharge through the valley floors and channels at lower elevations (Blasch and Bryson, 2007).

This recharge scenario is probably caused by higher rainfall in the mountains that naturally collects and disperses groundwater into the basin as underflow or fracture flow, but in the valley floors recharge is minimal due to high evaporation. Infiltration into the aquifer is further reduced due to the presence of clayey aquifer materials. However, this scenario of recharge could further be altered if there is a local hydraulic disconnection between the mountain front areas and the basins imposed by impermeable faults that bound the basin and water level elevations in the mountain blocks that are at lower elevations than that in the basin.

A lower total dissolved solids along the basin margins although may suggest that these waters could possibly represent fresh groundwater recharge, isotopic data suggest otherwise. Much of these waters are old and were probably recharged during the late Pleistocene period when the atmospheric temperature was much cooler (Chowdhury and others, 2008). Lower salinity of the groundwater along the basin margins is probably attributed to the nature of the aquifer materials that are not as chemically reactive as the basin-fill materials. The basin-fill materials are much more weathered allowing greater contribution of dissolved ions when they come in contact with water. The salinity gradient in the groundwater from the basin-margins to the basin-centers could be interpreted simply as a function of groundwater residence time, groundwater with a short residence time having low salinity and groundwater with longer residence times during its flow from the basin margins into the basin-centers having greater salinity. However, this is not the case as interpreted from isotopic data and stratigraphic hetereogenity of the aquifer materials.

Differences in hydrochemical facies across the Presidio-Redford Bolson Aquifer and the Rio Grande Alluvium Aquifer suggest that groundwater in these aquifers were probably derived by different geochemical and recharge processes. For example, an abundance of clays and their erratic distribution in the subsurface could possibly hydraulically compartmentalize the groundwater flow system locally (Chowdhury and others, 2008). Therefore, some of the recharge water will infiltrate slowly over some areas allowing higher evaporation. Higher degrees of groundwater salinity observed in the Rio Grande Alluvium Aquifer is probably attributed to higher degrees of evaporation, lateral inflow of groundwater from the Presidio-Redford Bolson Aquifer, local influx of surface water from the Rio Grande, and upward flow from the deeper subsurface (Chowdhury and others, 2008). However, at the present time there is not enough data to estimate various components of recharge to the Rio Grande Alluvium Aquifer.

Long-term use of groundwater for irrigation requires that the groundwater meets certain water quality requirements such that the irrigation does not increase shallow groundwater salinity, sodicity or sodicity-induced water infiltration decline in the soils, ion toxicities, effects of certain ions on produce quality and irrigation infrastructure (Gill, 2005). Sodification is the build-up of sodium in the soil that may lead to the development of poor soil structure, poor water infiltration, poor water use efficiency of irrigation and rain water, crop emergence problems, and an eventual low crop yield (Gill, 2005). Development of potential sodicity in soils are measured by the sodium adsorption ratio and specific conductance. Although sodium adsorption ratios observed in the groundwater from the Presidio-Redford Bolson Aquifer are low (Table 4-8), a high specific conductance of the groundwater with ranges from 363 to 9,620 (average = 1,072 micro siemens per centimeter, standard deviation = 1,039) also suggests that the waters could require pre-treatment to meet irrigation water quality requirements. Similarly, although the sodium adsorption ratios of groundwater from the Rio Grande Alluvium Aquifer are lower than the screening level, specific conductance of the waters remains high with ranges from 945 to 18,500 (average = 5,132 microsiemens per centimeter, standard deviation =3,659).

An increase in the sodium/calcium ratio in the groundwater from the basin-margins to the basin-centers suggests that sodium has been progressively replaced for calcium. This ion exchange more commonly occurs in clayey aquifer materials where the sodium attached on the clay surfaces replaces dissolved sodium ions. This exchange reaction occurs at 2:1 ratio, that is, for each calcium ion removed from the groundwater two sodium ions are added from the clay surfaces. Therefore, the ion exchange reactions also will contribute to an excess concentration of sodium in the waters. A reverse ion exchange may occur when sodium from the groundwater is removed by calcium. The observed excess sodium in the Rio Grande Alluvium Aquifer is probably caused by progressive ion exchange, but depletion of sodium in the groundwater from the basin centers are probably caused by reverse ion exchange. Relatively higher sodium in the groundwater from the basin-margins and the spring waters are probably functions of evaporation and/or weathering reactions (Chowdhury and Wade, in prep.).

A decrease in the chemical constituents observed with well depths suggests that the groundwater salinity is mainly controlled by near surface processes (Figure 4-21). Evaporation of the rainwater prior to infiltration and interaction with evaporites and clayey sediments particularly in the basin centers, would favor development of high groundwater salinity in these areas. A progressive increase in chloride/bromide ratios in groundwater is moving from the higher elevations along the basin margins to lower elevations along the basin centers and the Rio Grande Alluvium suggest increasing effects of halite dissolution as more chloride is dissolved than the amount of bromide released into the groundwater. Therefore, the higher chloride/bromide ratios suggest greater degrees of halite dissolution (Figure 4-24). Groundwater quality comparison with regard to the Texas Administrative Code standards suggests that several groundwater samples analyzed do not meet primary and secondary drinking water standards. Several samples have high arsenic, cadmium, lead, sulfate, chloride and dissolved solids that would require treatment prior to their use.

**Table 4-8. Percent exceedance of various chemical constituents from the Presidio-Redford Bolson Aquifer under the Texas Administrative Code. Trace element concentrations of groundwater from the Rio Grande Alluvium Aquifer are not reported because of insufficient data.**

| Category | Constituent | MCL | Percent exceedance | Average | Standard deviation | No. of samples |
|---|---|---|---|---|---|---|
| Primary | Arsenic | 10 $\mu$g/l | 28.3 | 9.3$\mu$g/l | 7 | 52 |
| | Barium | 2 mg/l | 0 | 47.88$\mu$g/l | 41.22 | 52 |
| | Cadmium | 5 $\mu$g/l | 28.3 | 3.6$\mu$g/l | 4.11 | 52 |
| | Chromium | 100 $\mu$g/l | 0 | 8.67$\mu$g/l | 8.37 | 52 |
| | Lead | detection | 100 | 15.28$\mu$g/l | 22.32 | 52 |
| | Nickel | 100 $\mu$g/l | 0 | 2.04$\mu$g/l | 1.36 | 16 |
| Secondary | Chloride | 300 mg/l | 10.16 | 157 mg/l | 369 | 59 |
| | Copper | 1 mg/l | 0 | 7.78$\mu$g/l | 7.9 | 52 |
| | Sulfate | 300 mg/l | 28.81 | 237 mg/l | 283 | 59 |
| | Total dissolved solids[2] | 1,000 mg/l | 25.42 | 918 mg/l | 793 | 59 |
| | Total dissolved solids[3] | 1,000 mg/l | 93 | 2,650 mg/l | 1,559 | 29 |
| | Iron | 0.3 mg/l | 0 | 0.13 mg/l | 0.34 | 59 |
| | Manganese | 50 $\mu$g/l | 2 | 45$\mu$g/l | 253 | 56 |
| | Zinc | 5 mg/l | 0 | 0.053 mg/l | 0.073 | 52 |
| Irrigation hazard | Sodium adsorption ratio[1] | na | 0 | 2.7 | 3.2 | 41 |
| | Sodium adsorption ratio[2] | na | 0 | 4.5 | 4.5 | 30 |

1. Presidio-Redford Bolson Aquifer, 2. Rio Grande Alluvium Aquifer, na: not applicable

# 5 Conceptual Model of Groundwater Flow in the Aquifer

Groundwater in the Presidio-Redford Bolson aquifers flows regionally from the adjacent mountains towards the center of the valley. Groundwater enters the bolson through cross-formational flow at depth (Figure 5-1) and precipitation recharge enters the groundwater in part of the upland areas of the drainage basin. Precipitation recharge also occurs along areas of moderate slope such as sidestream channels containing coarse gravel and conglomerates. Isotopic and geochemical data supports this conceptualization of groundwater recharge and flow characteristics in the Presidio-Redford Bolson aquifers (Chowdhury and others, 2008). The total recharge for the study area has previously been estimated to be between 3,600 and 7,000 acre-feet per year (LBG-Guyton and Associates, 2001; Gates and others, 1980). Some groundwater discharges from springs along faults and where facies changes occur within the bolson (Henry, 1979; Groat, 1972). In recent years approximately 2,000 acre-feet per year was pumped for domestic, livestock, and irrigation use on the United States side of the study area (Table 4-6). The Comisión National del Agua (CNA) website lists approximately 9,000 acre-feet per year of permitted use on the Mexico side of the study area (Comisión National del Agua (CNA), 2008). Groundwater ultimately discharges from the bolson into the Rio Grande Alluvium. However, the presence of fine-grained sediments in the basin centers suggests that vertical hydraulic conductivities in these sediments are quite low (Table 4-2) limiting upward flow. Along most of the length of the Presidio Bolson, the Rio Grande is a losing channel. Much of the water moving downward from the Rio Grande into the alluvium, and the water entering the alluvium from the bolson may be consumed by evapotranspiration from dense mesquite and saltcedar and the interaction between the river alluvium, the bolson and the Rio Grande and the phreatophytes may comprise a significant portion of the total flow budget for the entire groundwater flow system.

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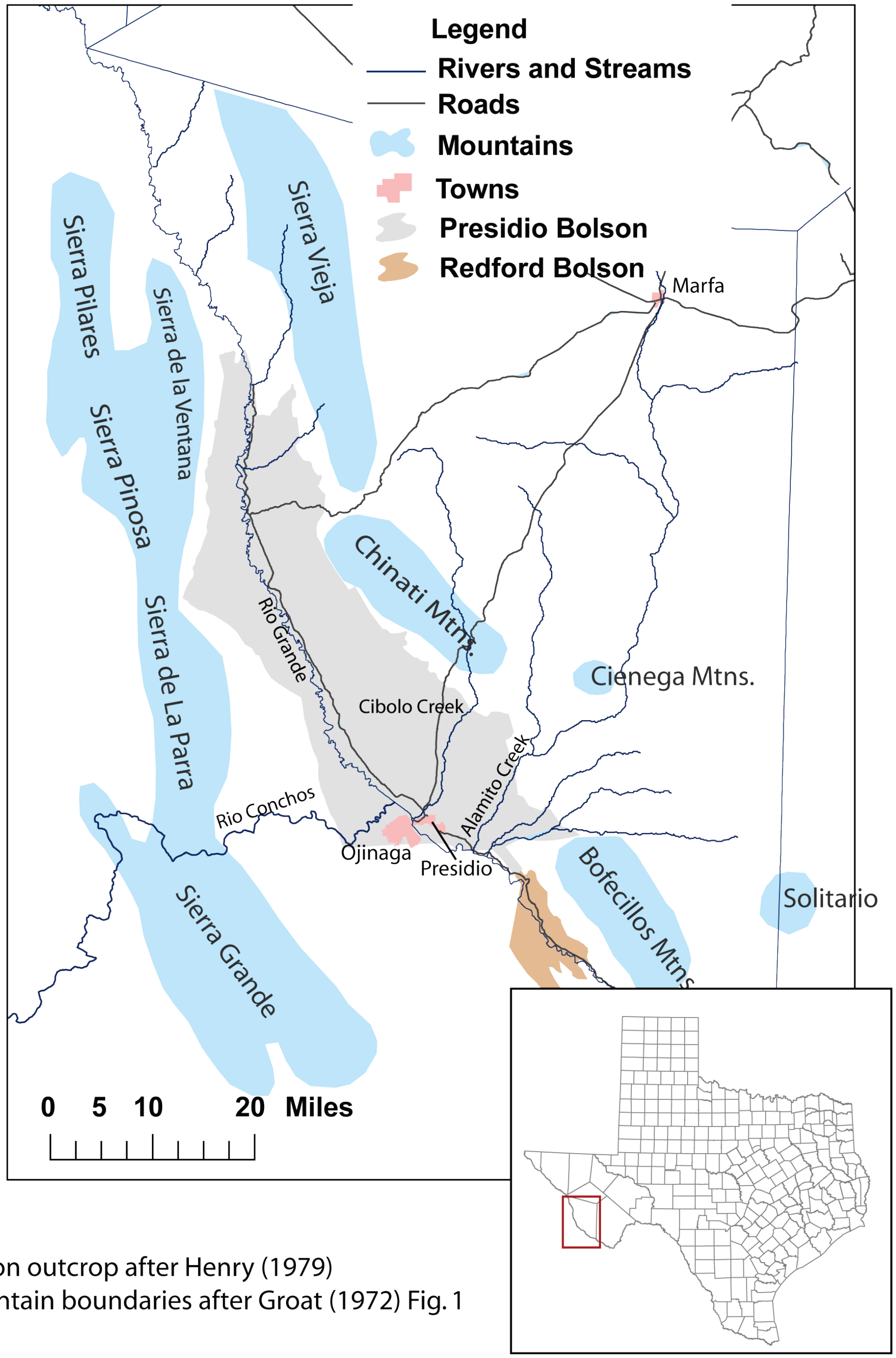



Bolson outcrop after Henry (1979)
Mountain boundaries after Groat (1972) Fig. 1

**Figure 2-1. Map of the study area showing the outcrops of the Presidio and Redford Bolsons aquifers, mountains, rivers/streams, towns and roads.**

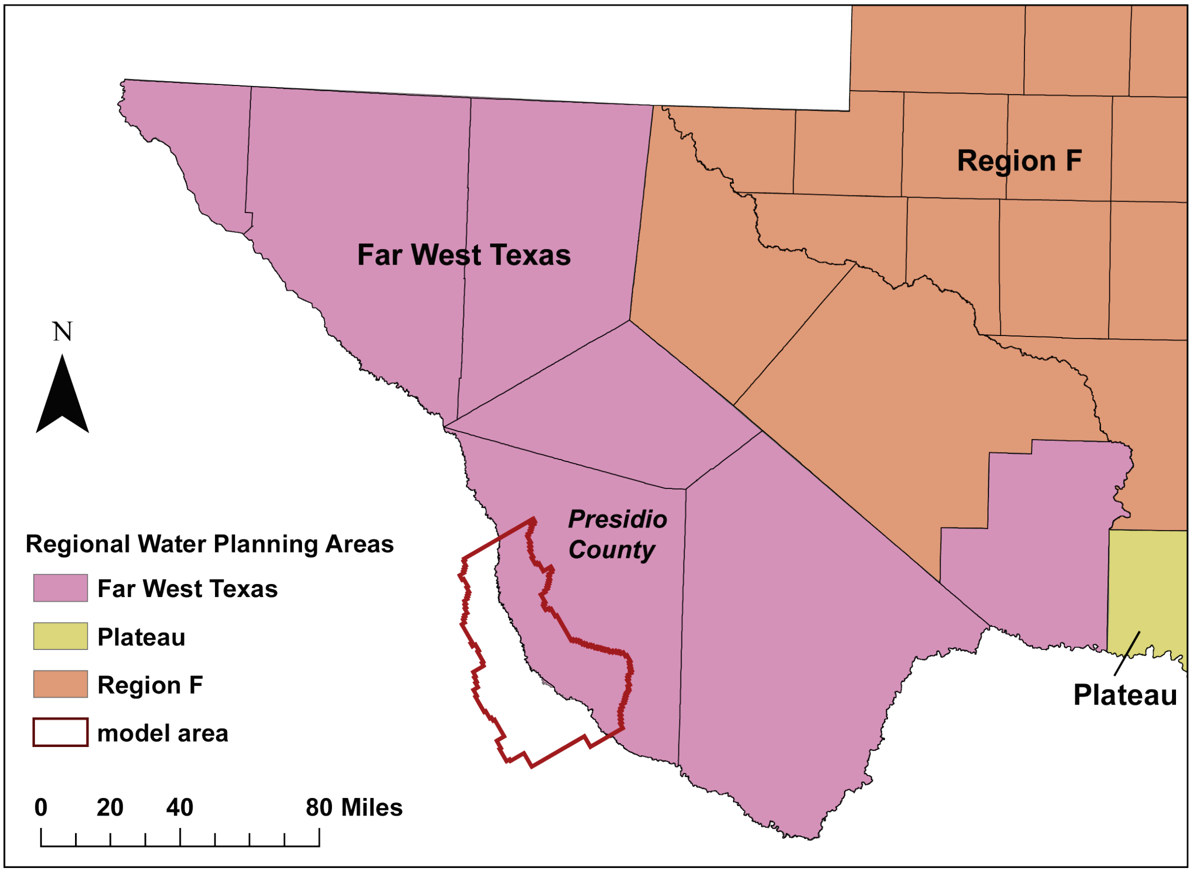



**Figure 2-2. Map of the Regional Water Planning Groups in the study area.**

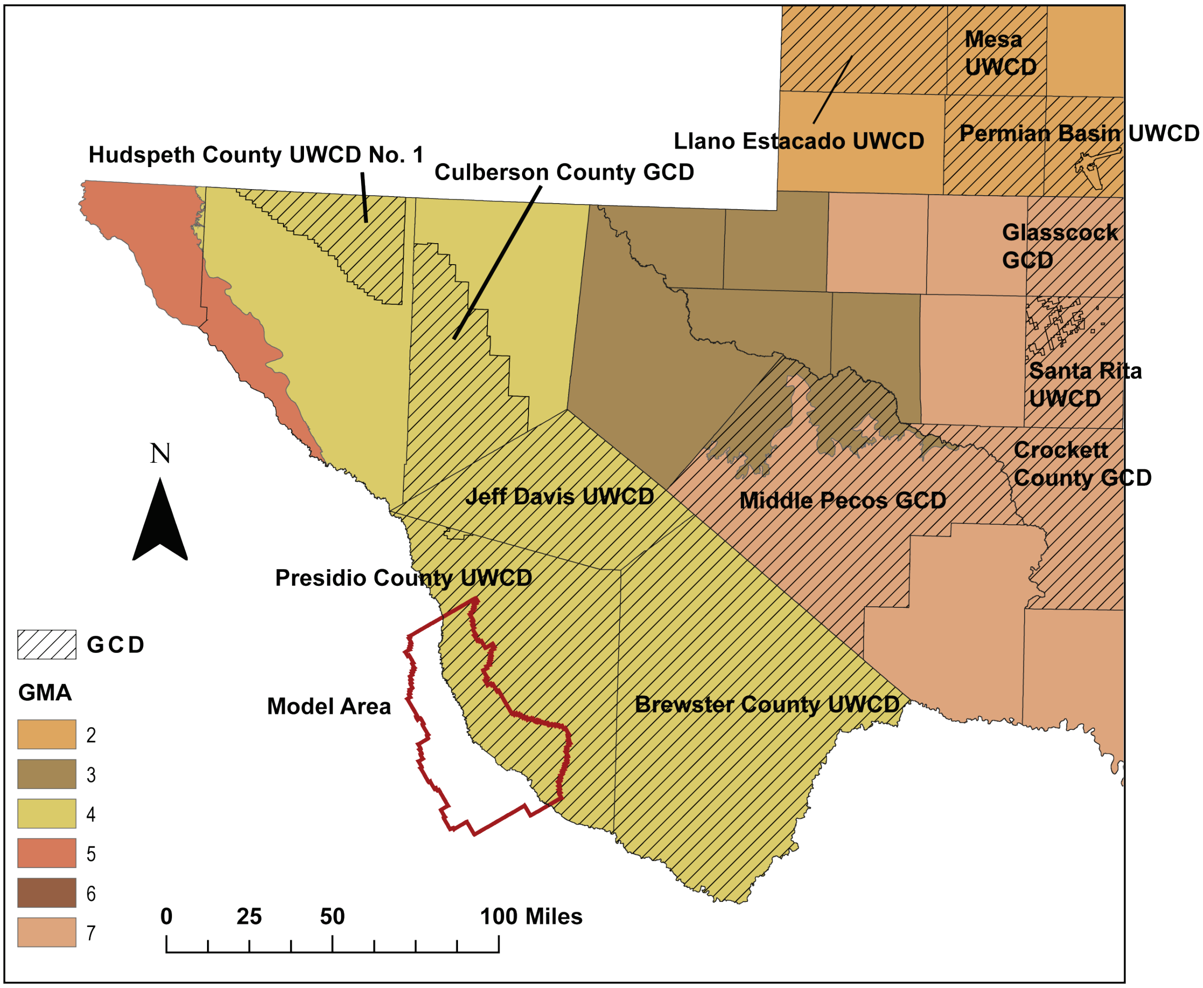



**Figure 2-3. Location of groundwater management areas (GMA) and groundwater conservation districts (GCD) in the area as of August 12, 2010 (TWDB, 2010).**

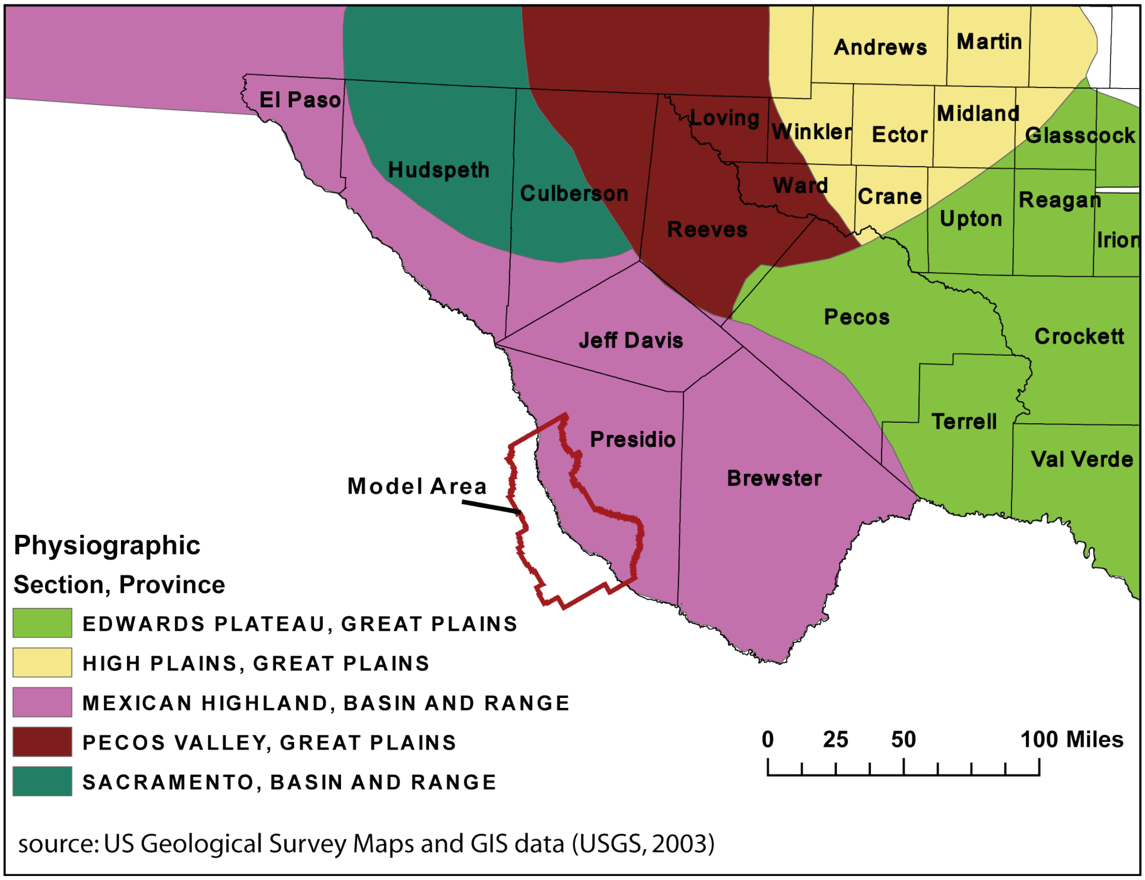



**Figure 2-4. Physiographic provinces in West Texas (USGS, 2003).**

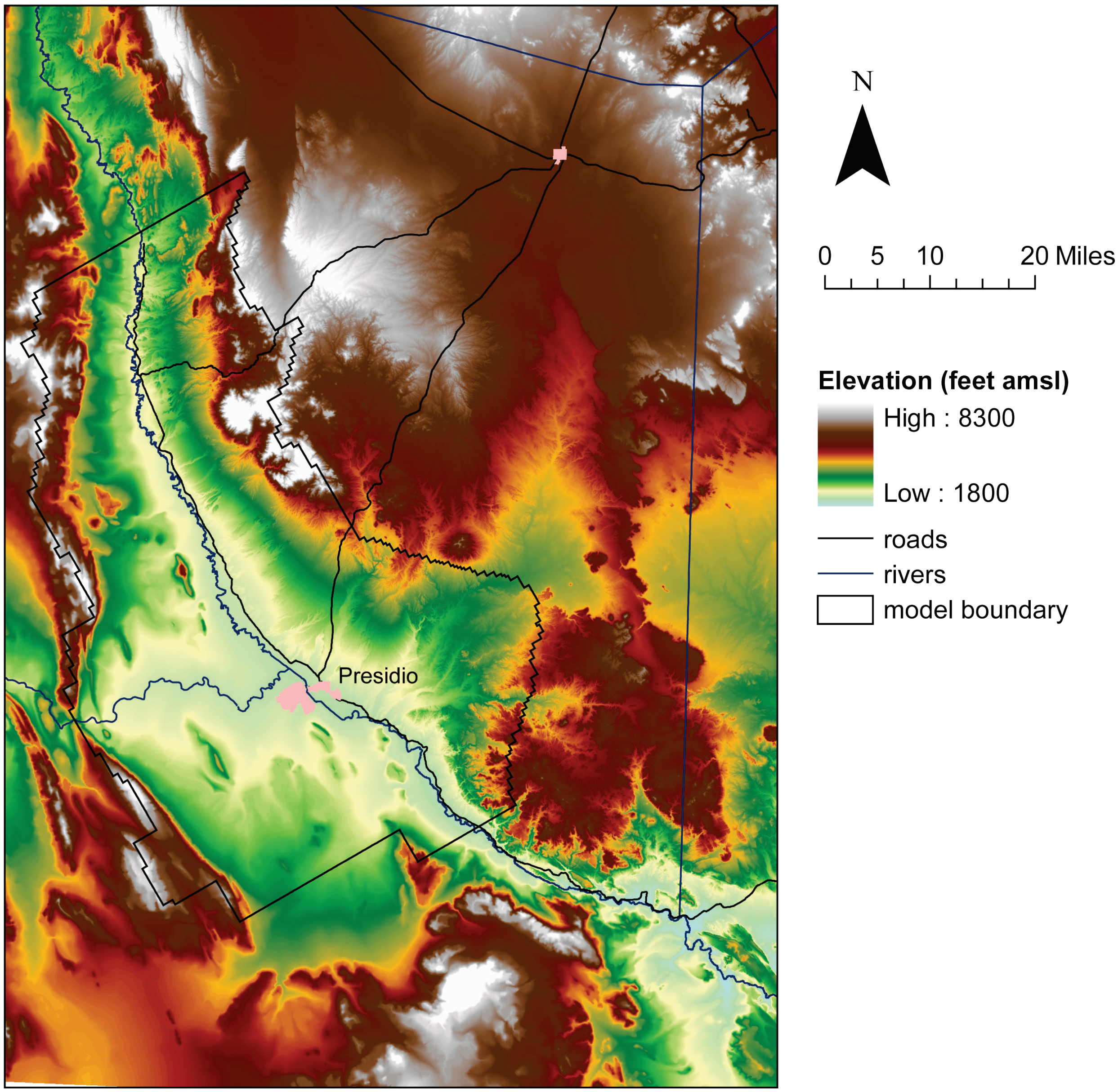



**Figure 2-5. Topographic elevation in the study area (USGS, 2007). Amsl = above mean sea level. Note steep slopes from the mountains to the bolsons along the bottoms of the valley.**

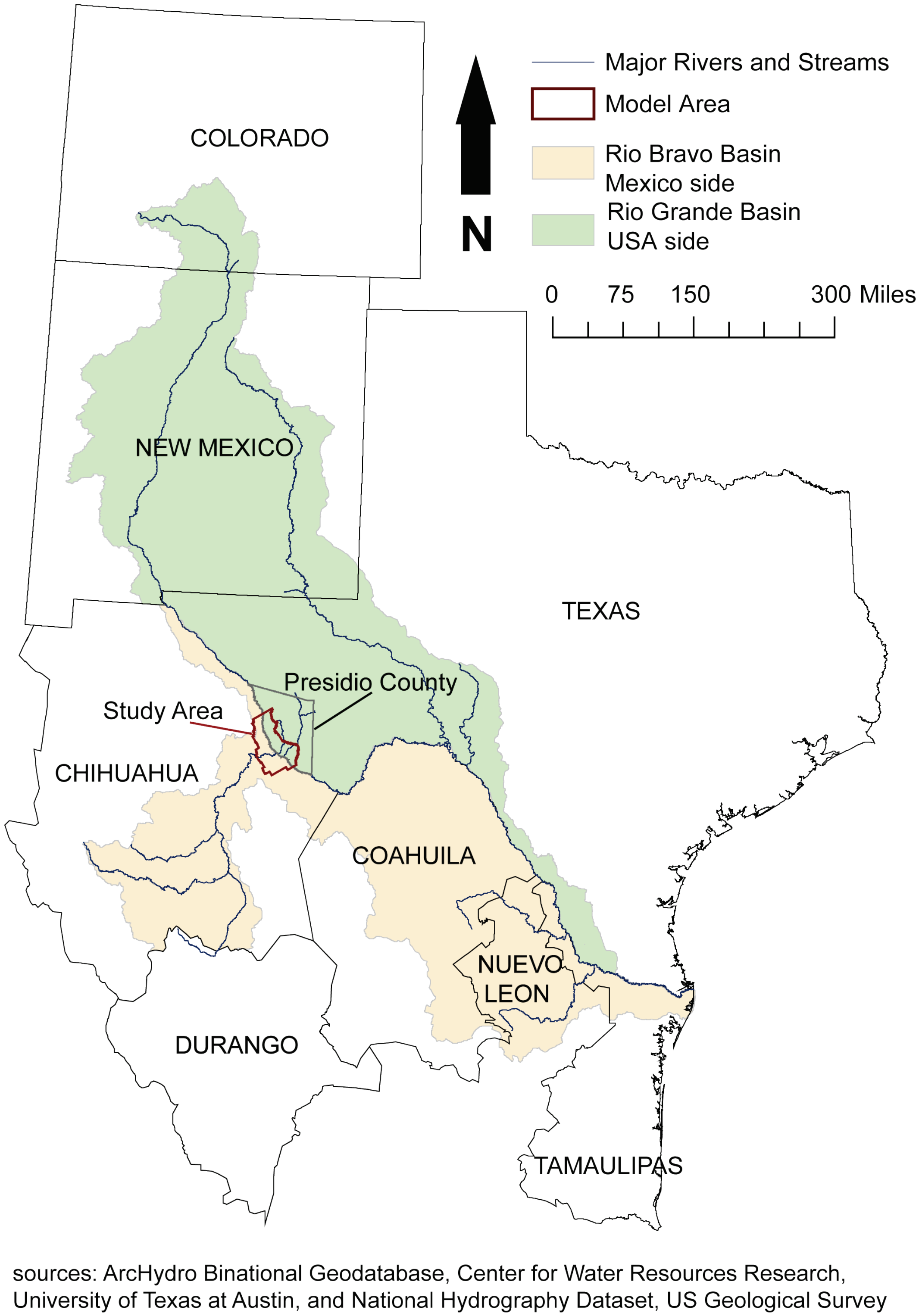



**Figure 2-6. The study area is located in the Rio Grande Basin.**

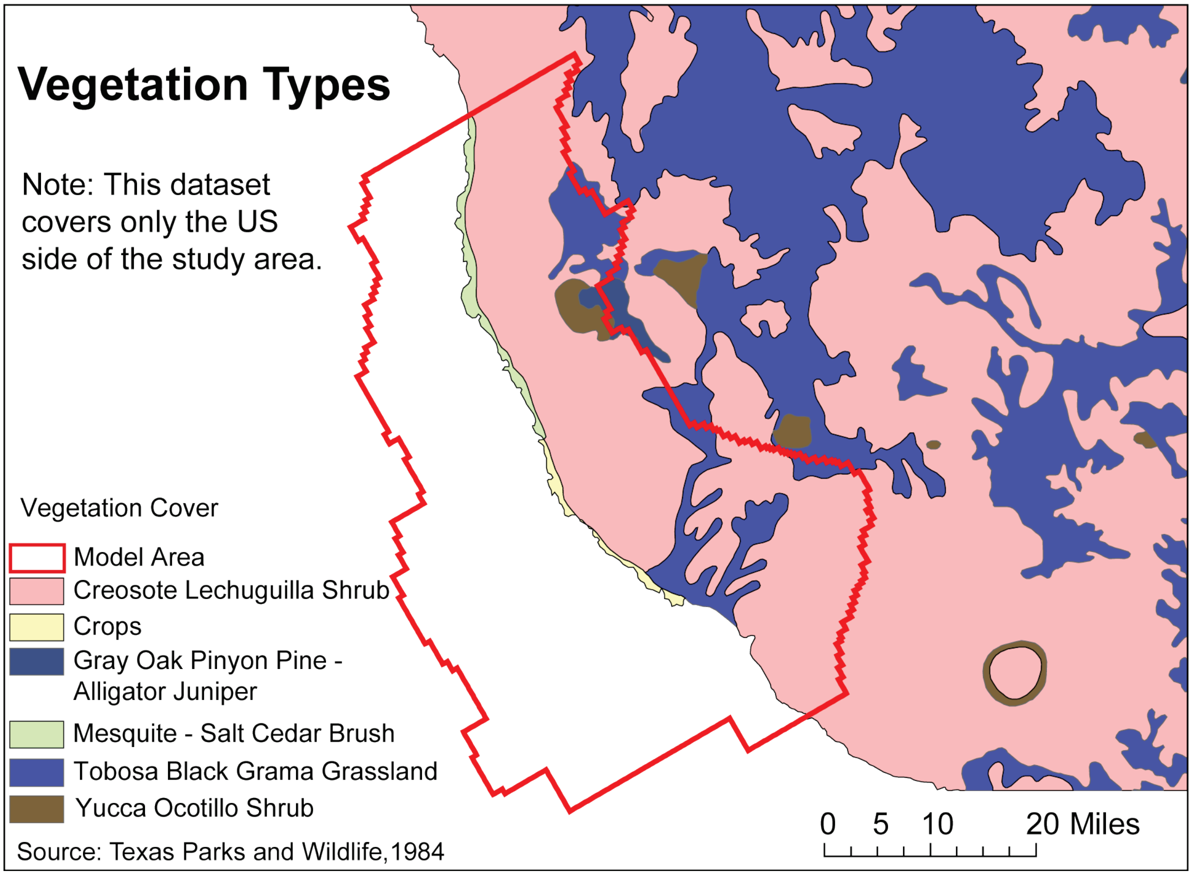



**Figure 2-7. Vegetation types in the U.S. portion of the study area.**

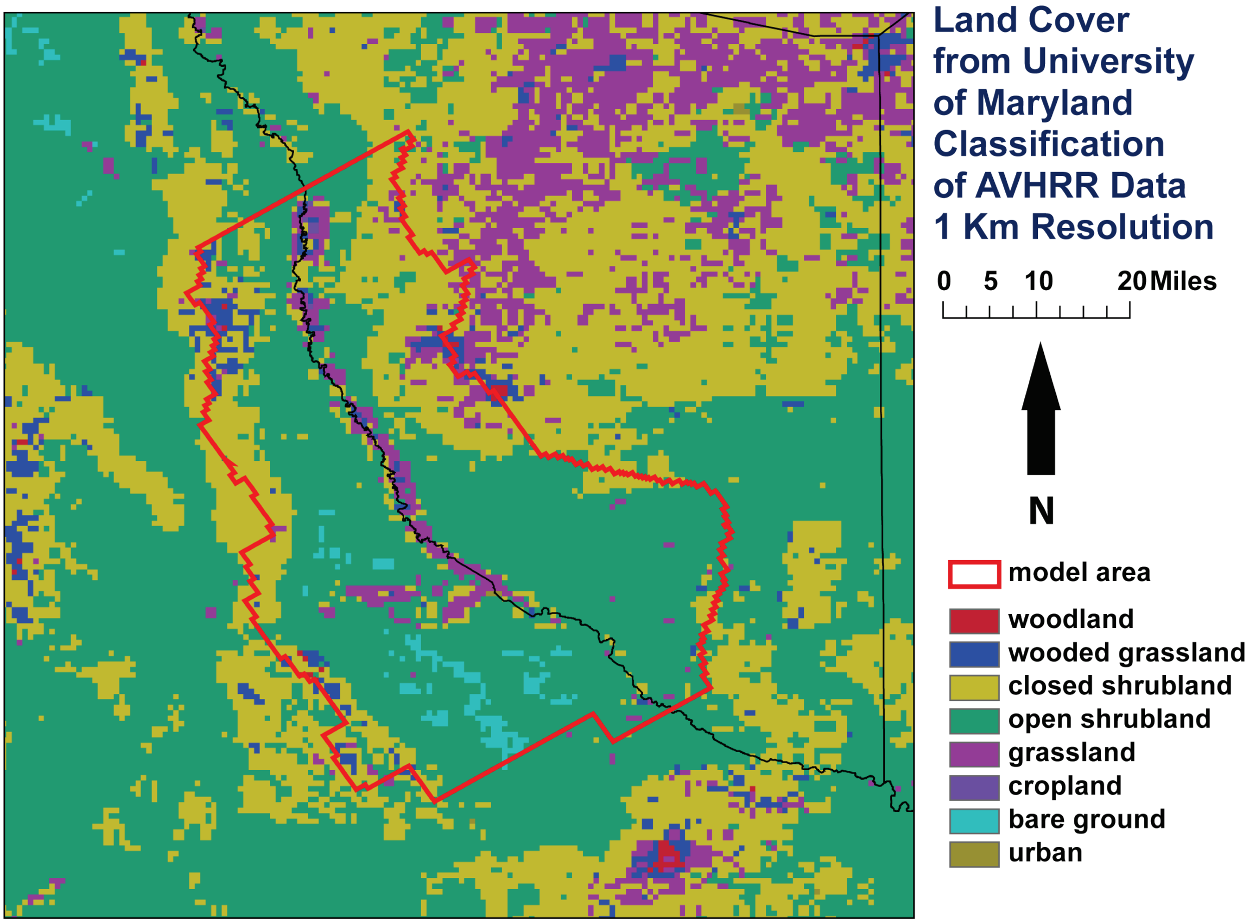
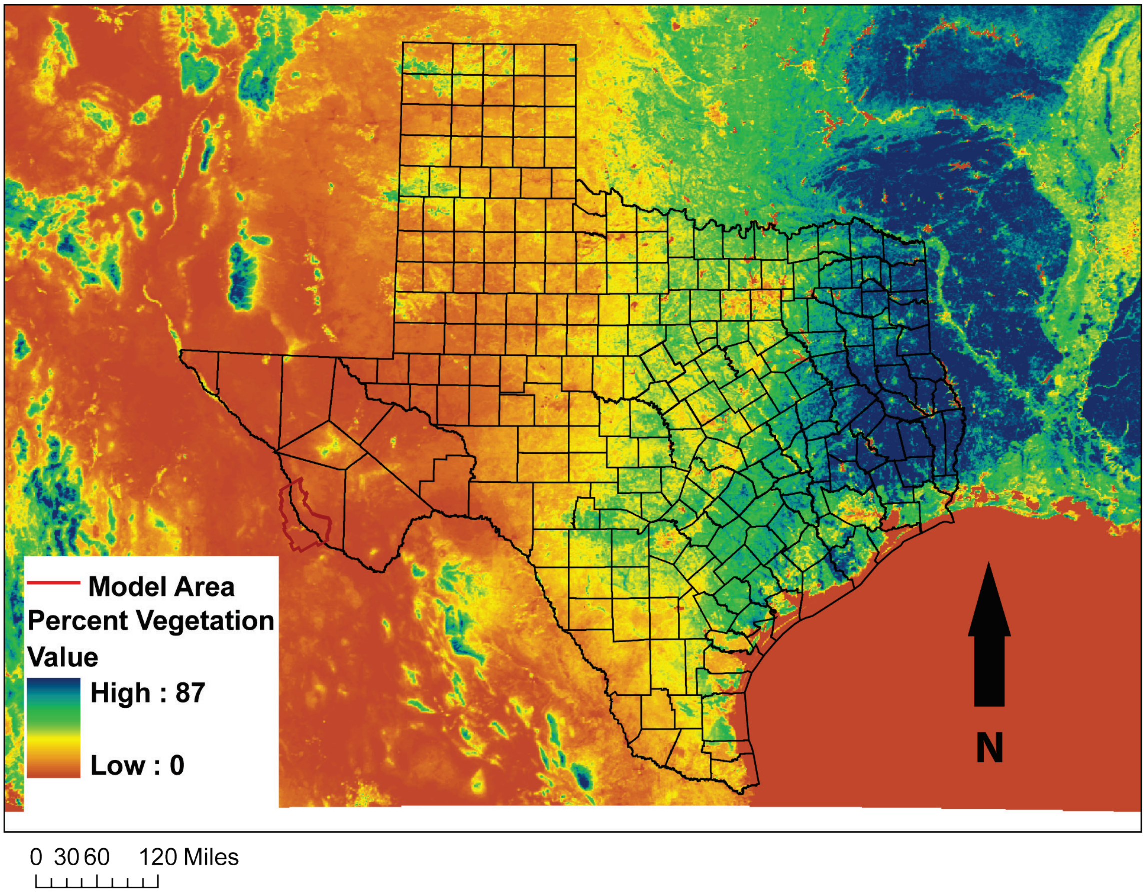
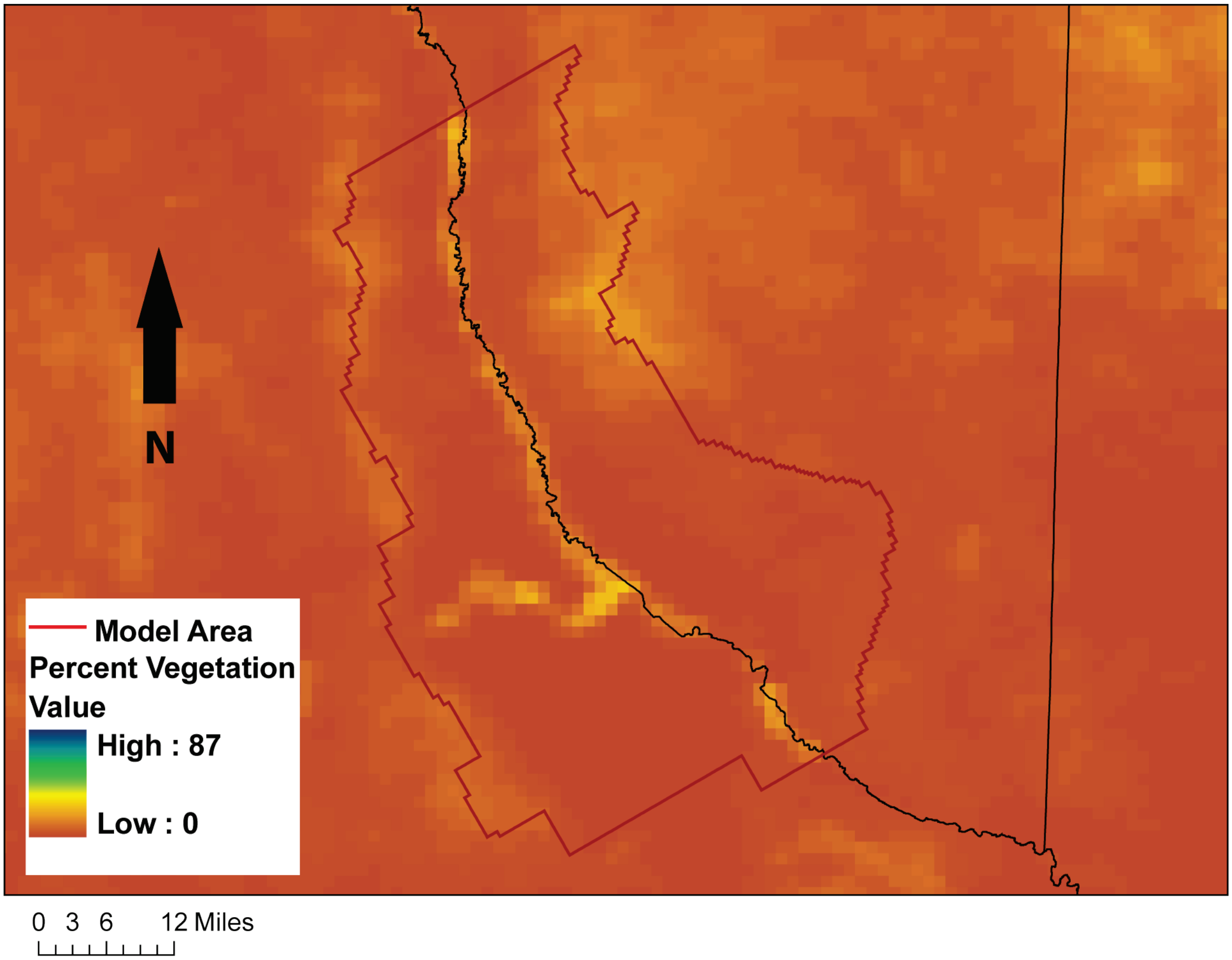



**Figure 2-8. General types of vegetation for complete study area.**




Source: Earth System Science Center (ESSC) Pennsylvania State University 1990 - 1999 average from AVHRR data

**Figure 2-9. Statewide percent vegetation based on satellite data.**




Source: Earth System Science Center (ESSC) Pennsylvania State University
1990 - 1999 average from AVHRR data

**Figure 2-10. Percent vegetation in study area based on satellite data.**

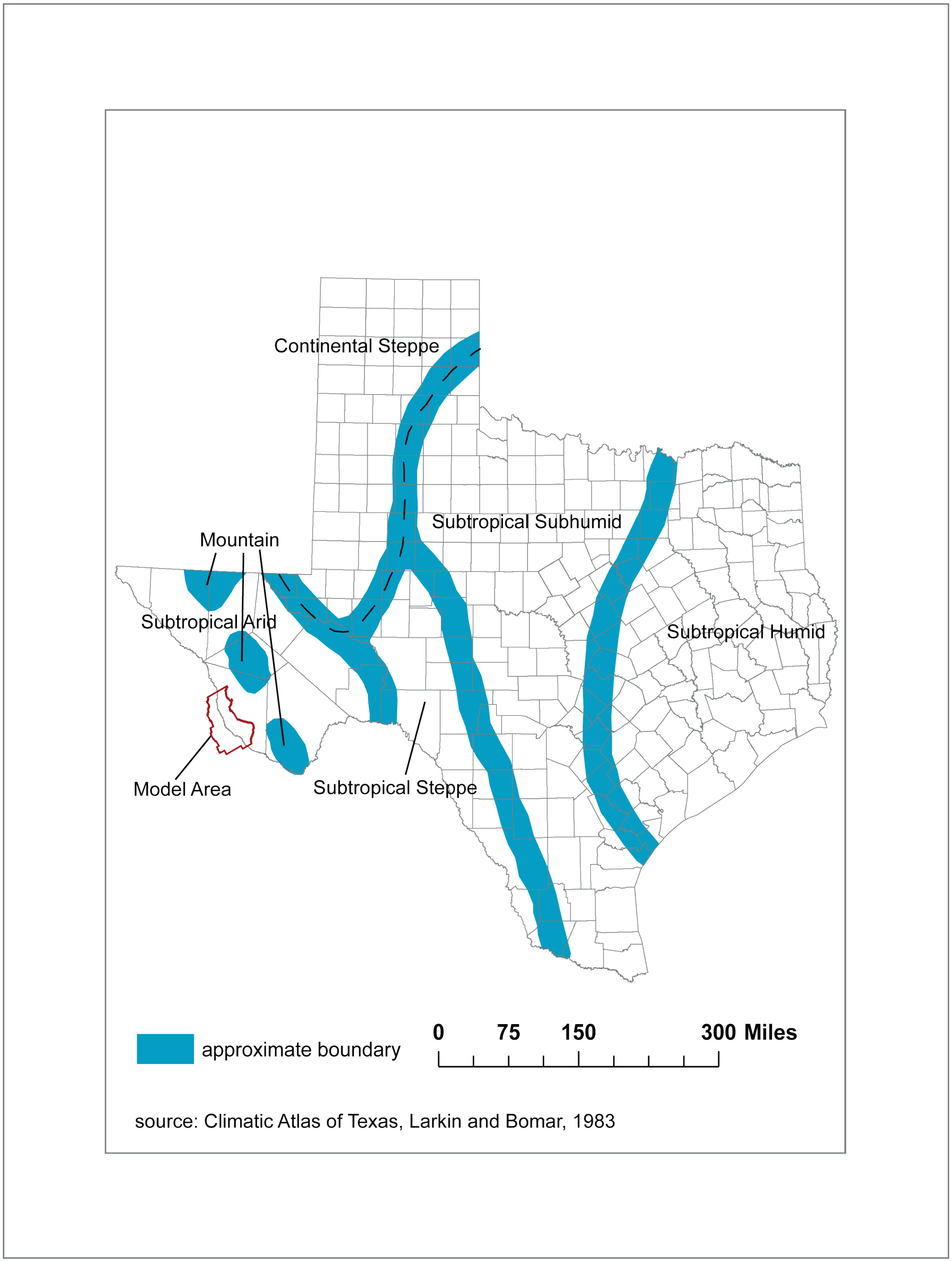



**Figure 2-11. Climate zones of Texas.**

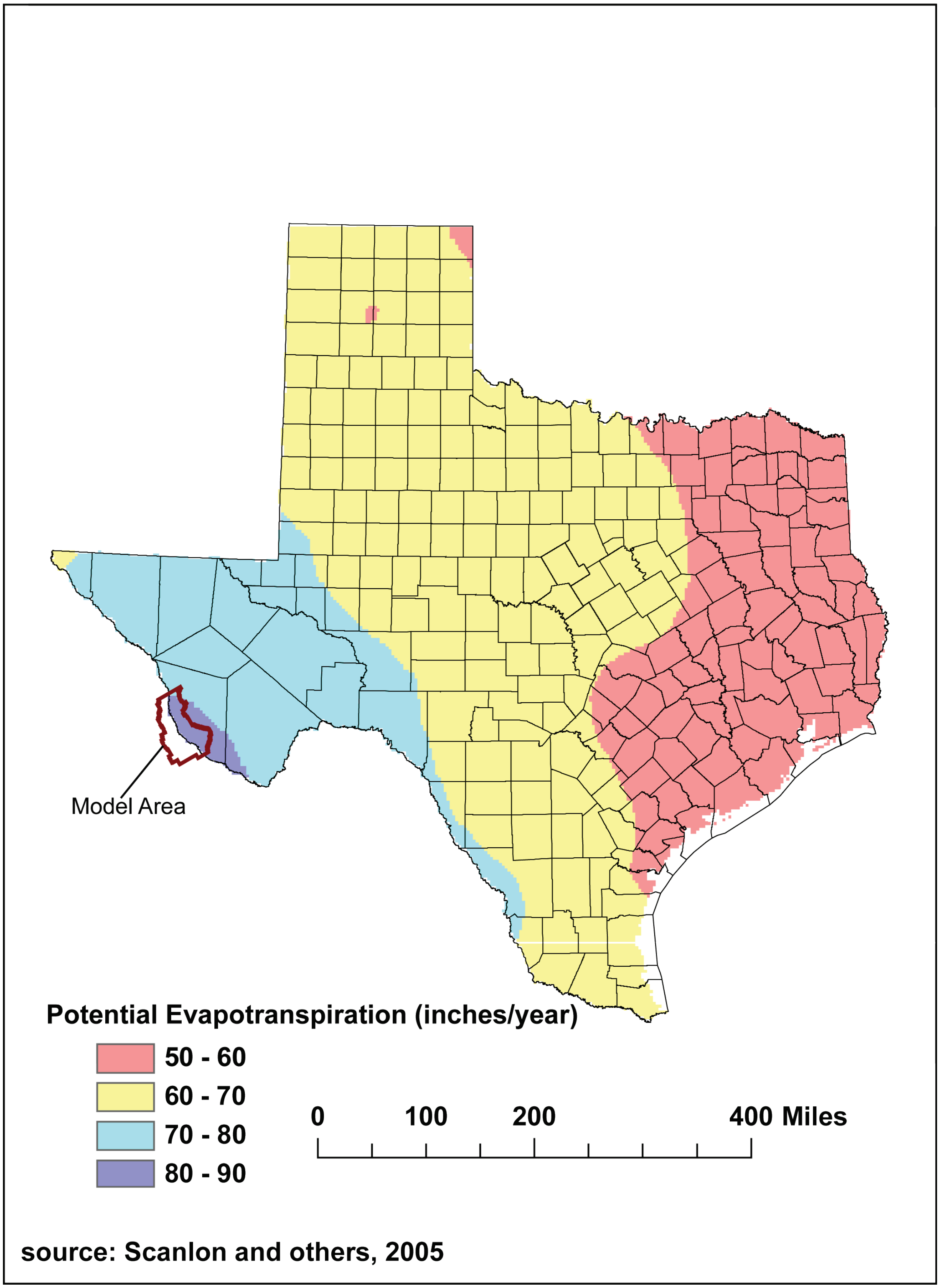



**Figure 2-12. Long-term (30-yr) annual grass reference crop ET (from Scanlon and others, 2005, based on Borrelli and others, 1998).**

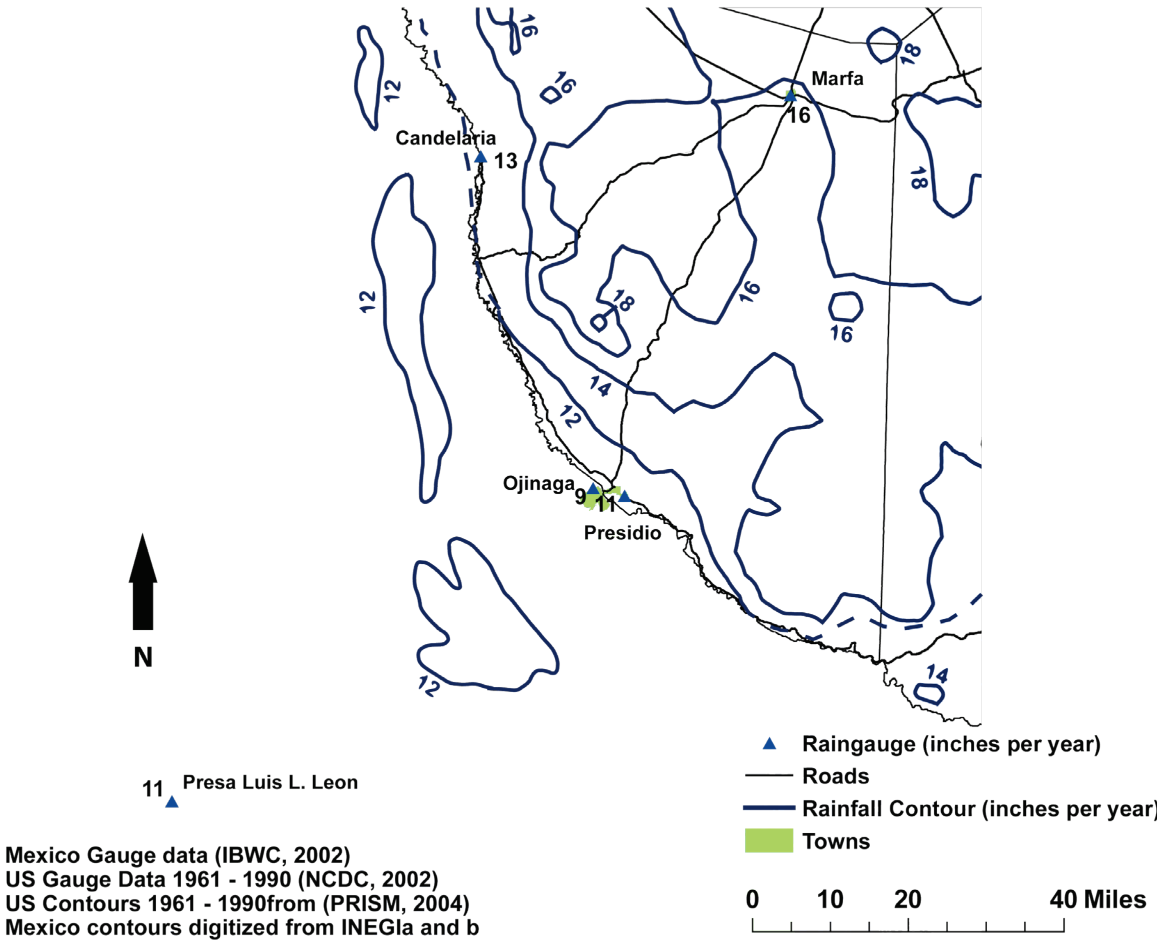



**Figure 2-13. Long term average (1961-1990) rainfall contours with gauge data and locations.**

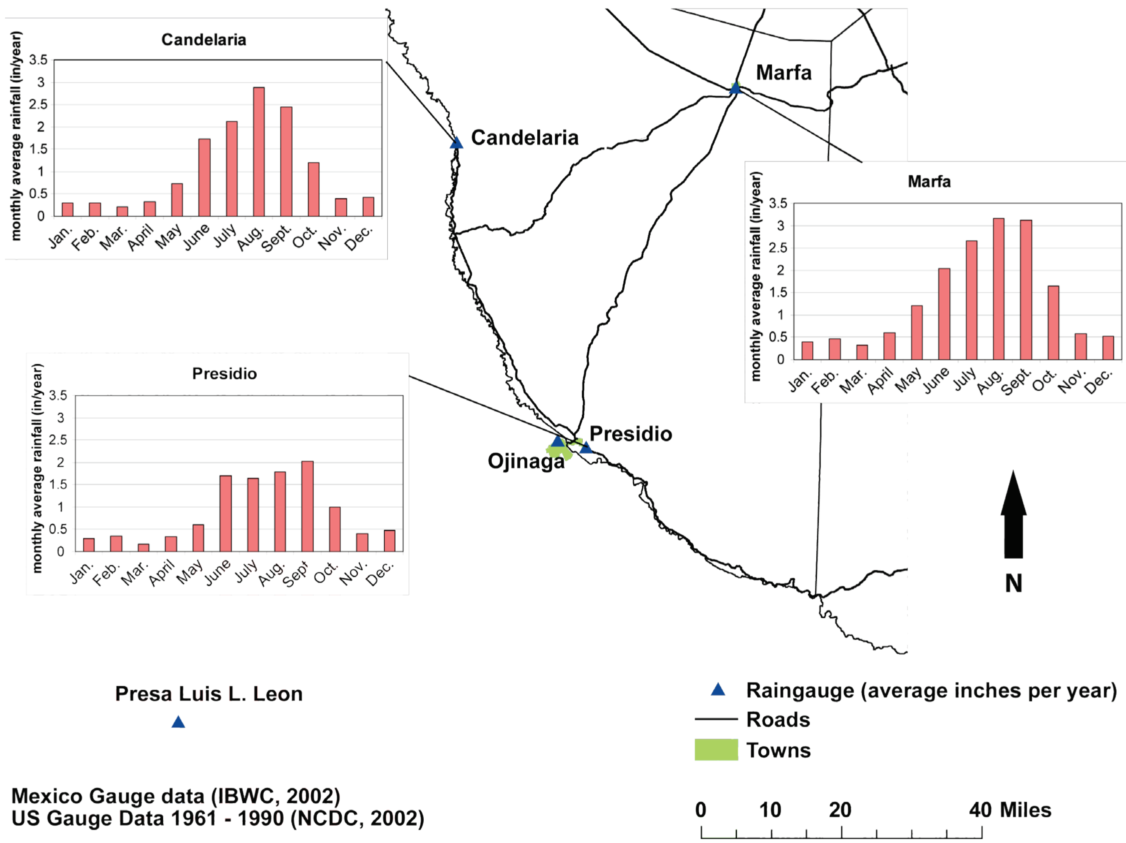



**Figure 2-14. Thirty-year average monthly rainfall at three United States raingauges.**

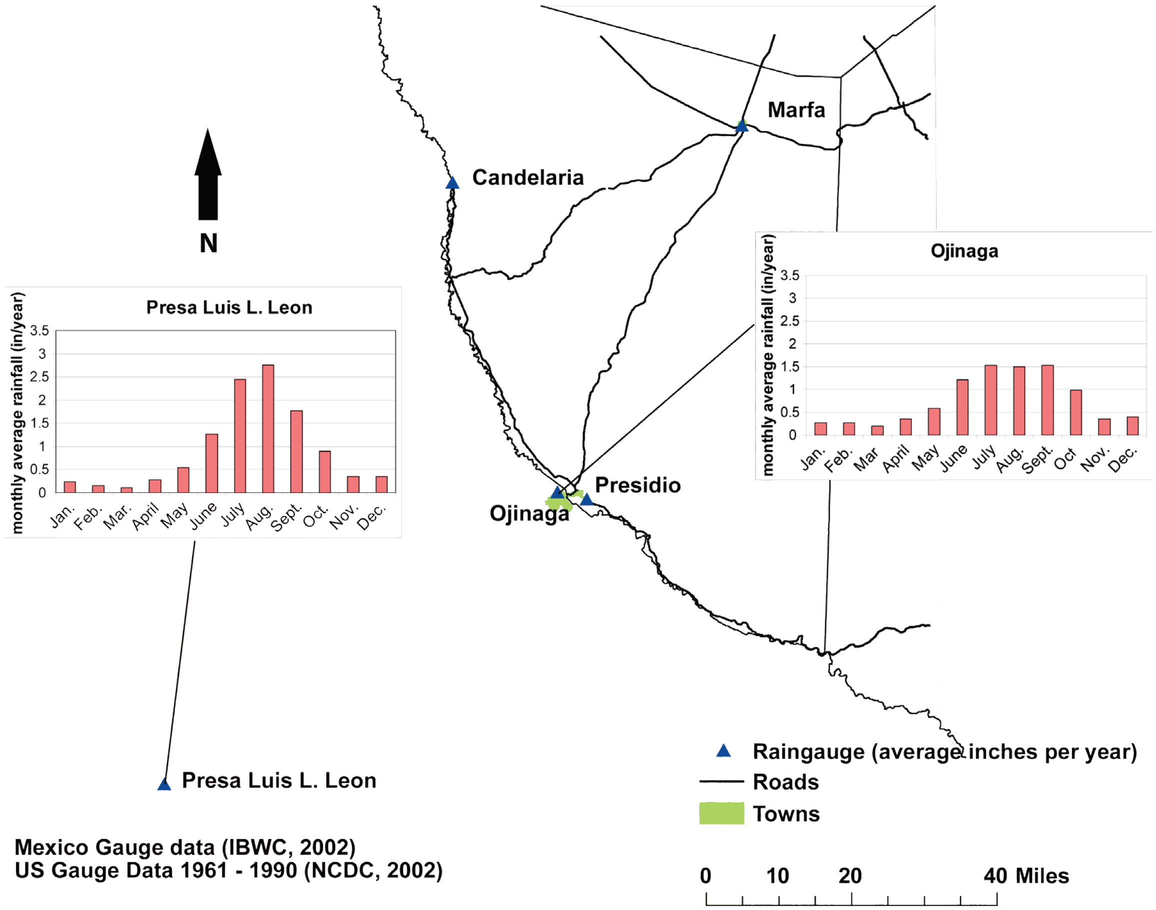



**Figure 2-15. Average monthly rainfall at two Mexico gauges.**

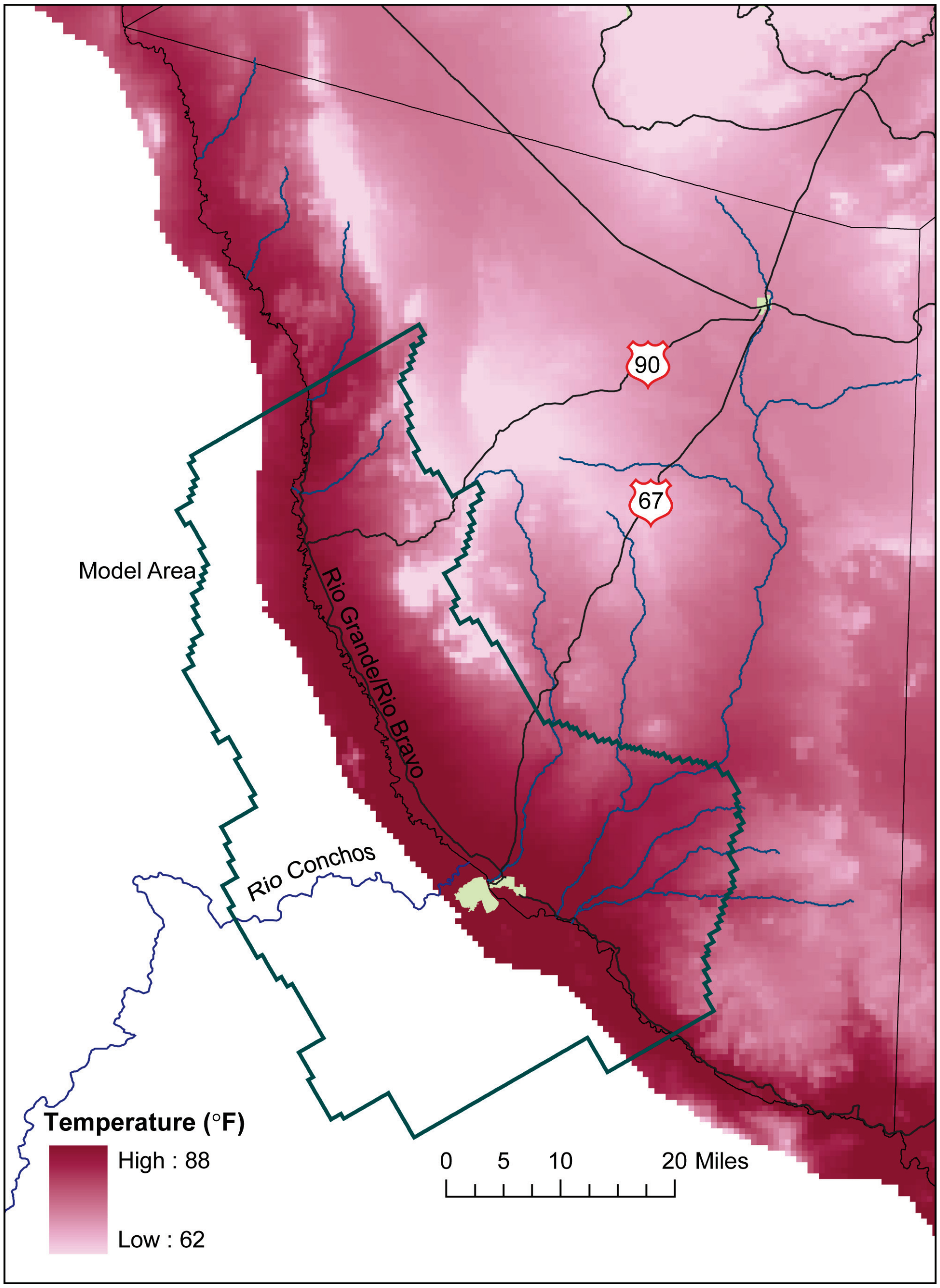



**Figure 2-16. Average annual daytime maximum temperature (PRISM, 2004)**

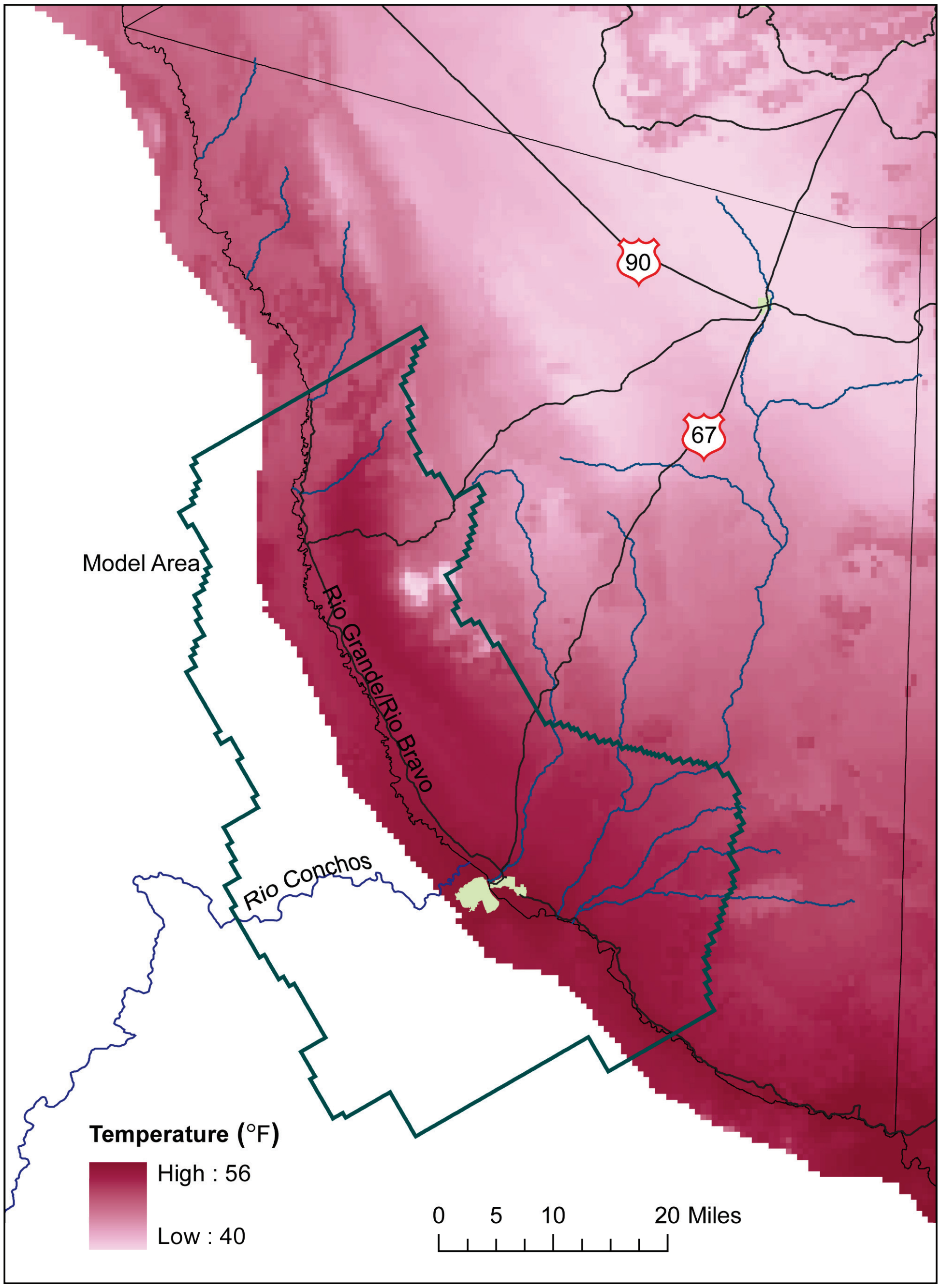
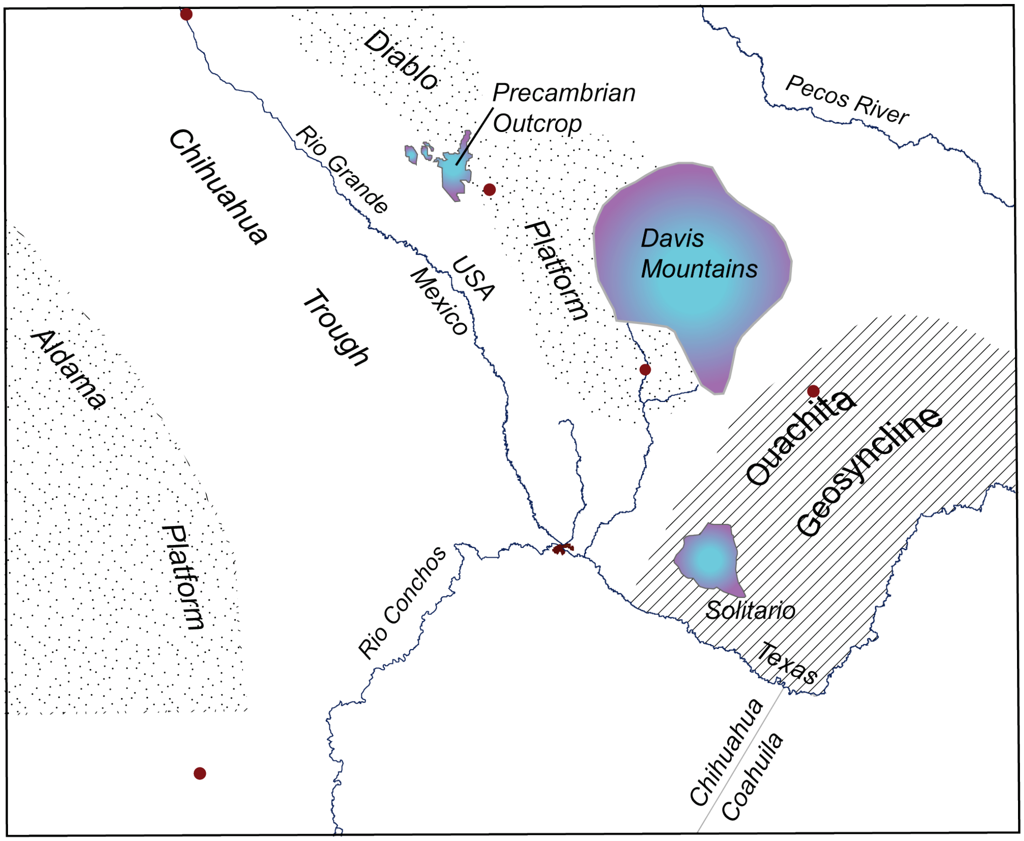



**Figure 2-17. Average annual minimum temperature (PRISM, 2004).**




source: Henry (1979)

• *major cities or towns*

0 25 50 100 Miles

**Figure 2-18. Generalized geology and structure.**

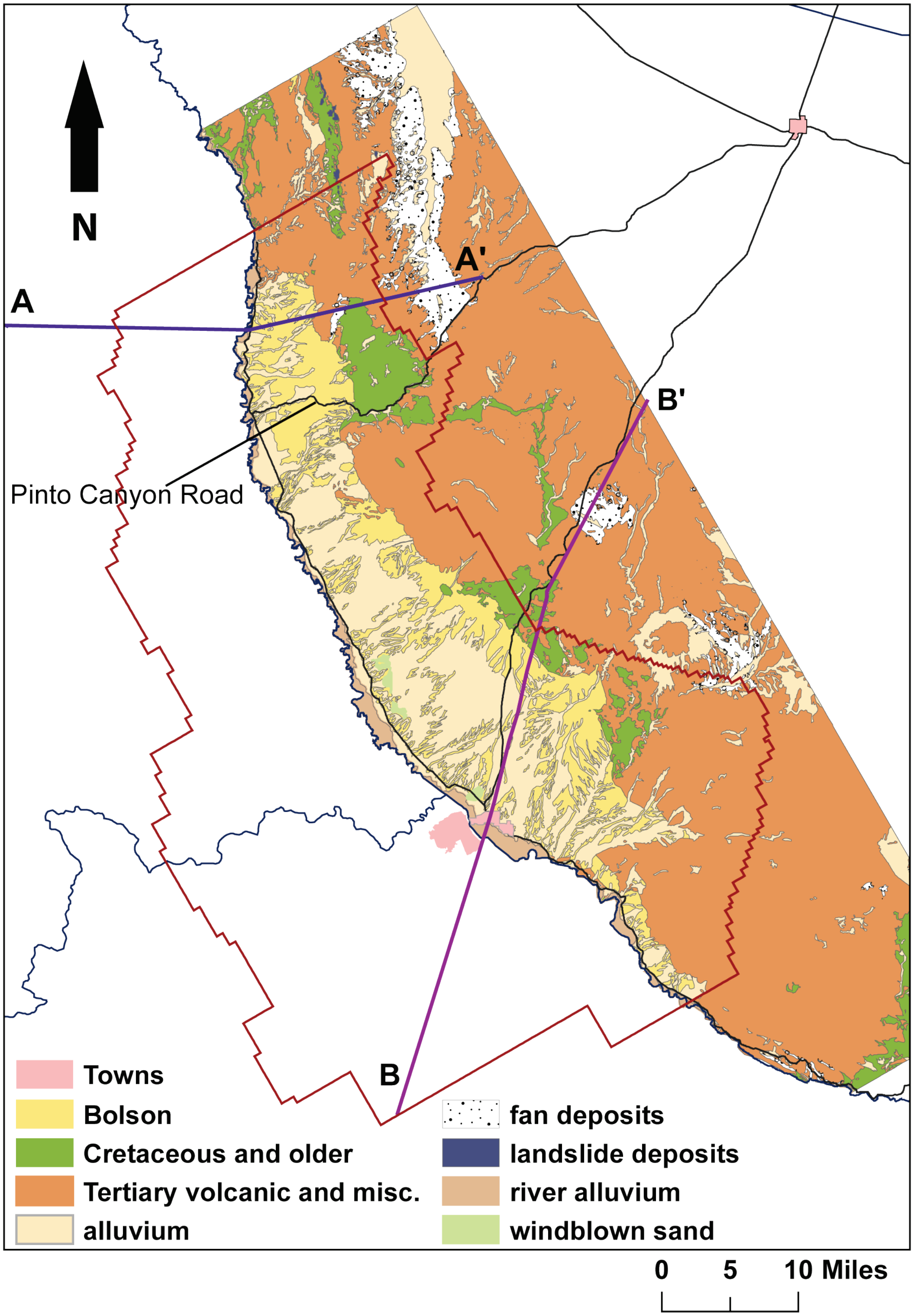



**Figure 2-19. Surface Geology (source Geological Atlas of Texas, Bureau of Economic Geology)**

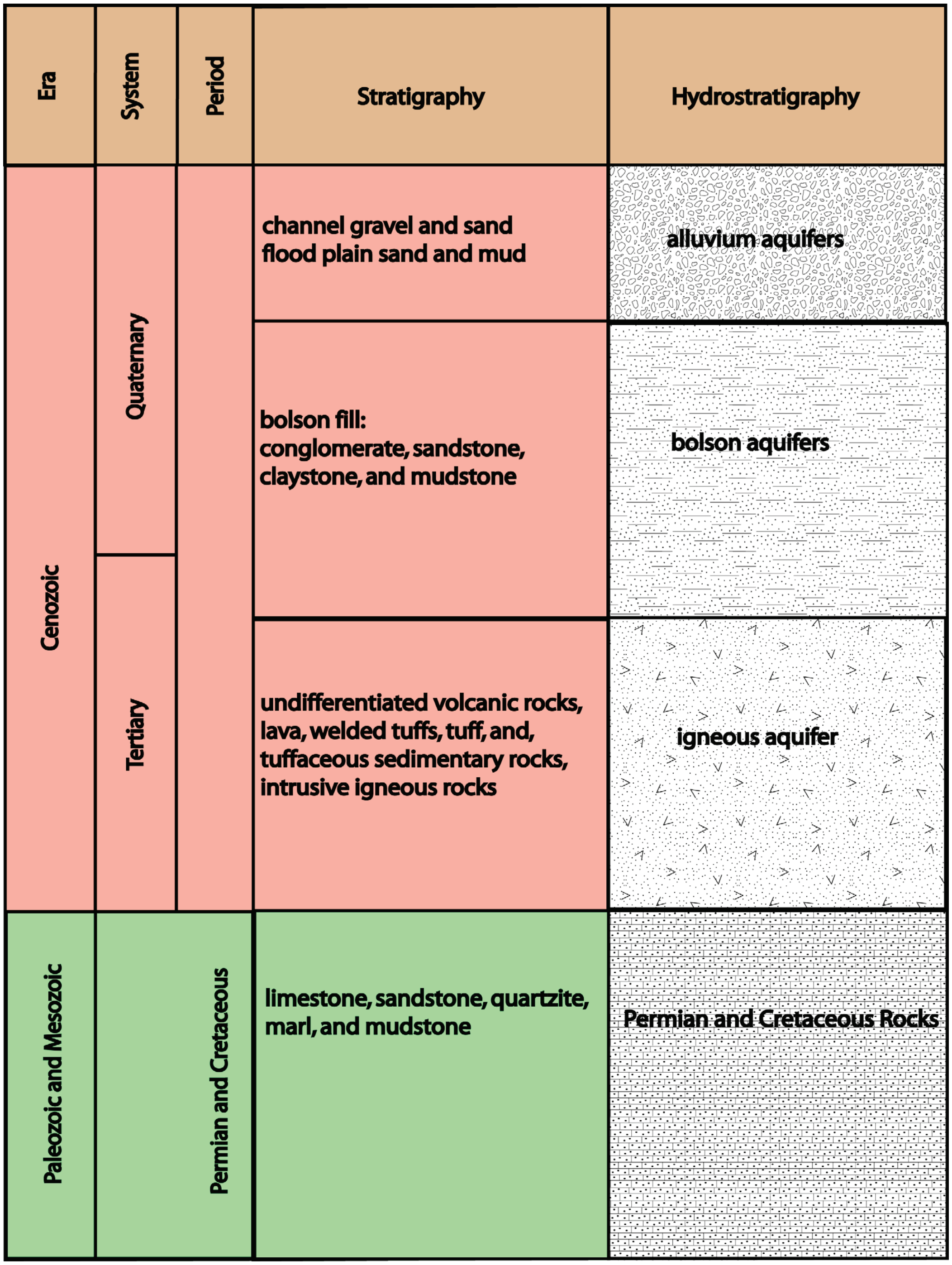



**Figure 2-20. General Stratigraphy and Hydrostratigraphy (modified from Groat (1972), Kopp (1977), Gabaldon (1991), and Beach and others (2003).**

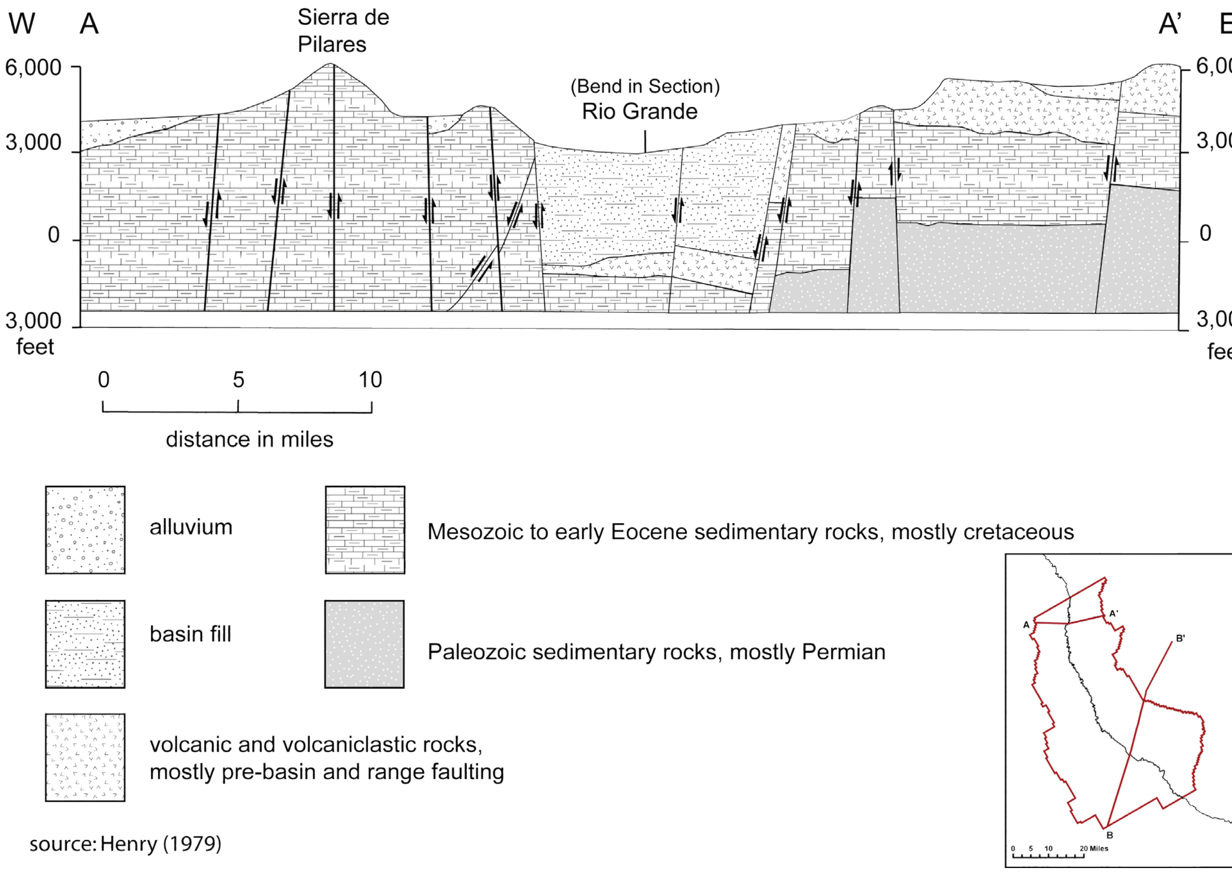
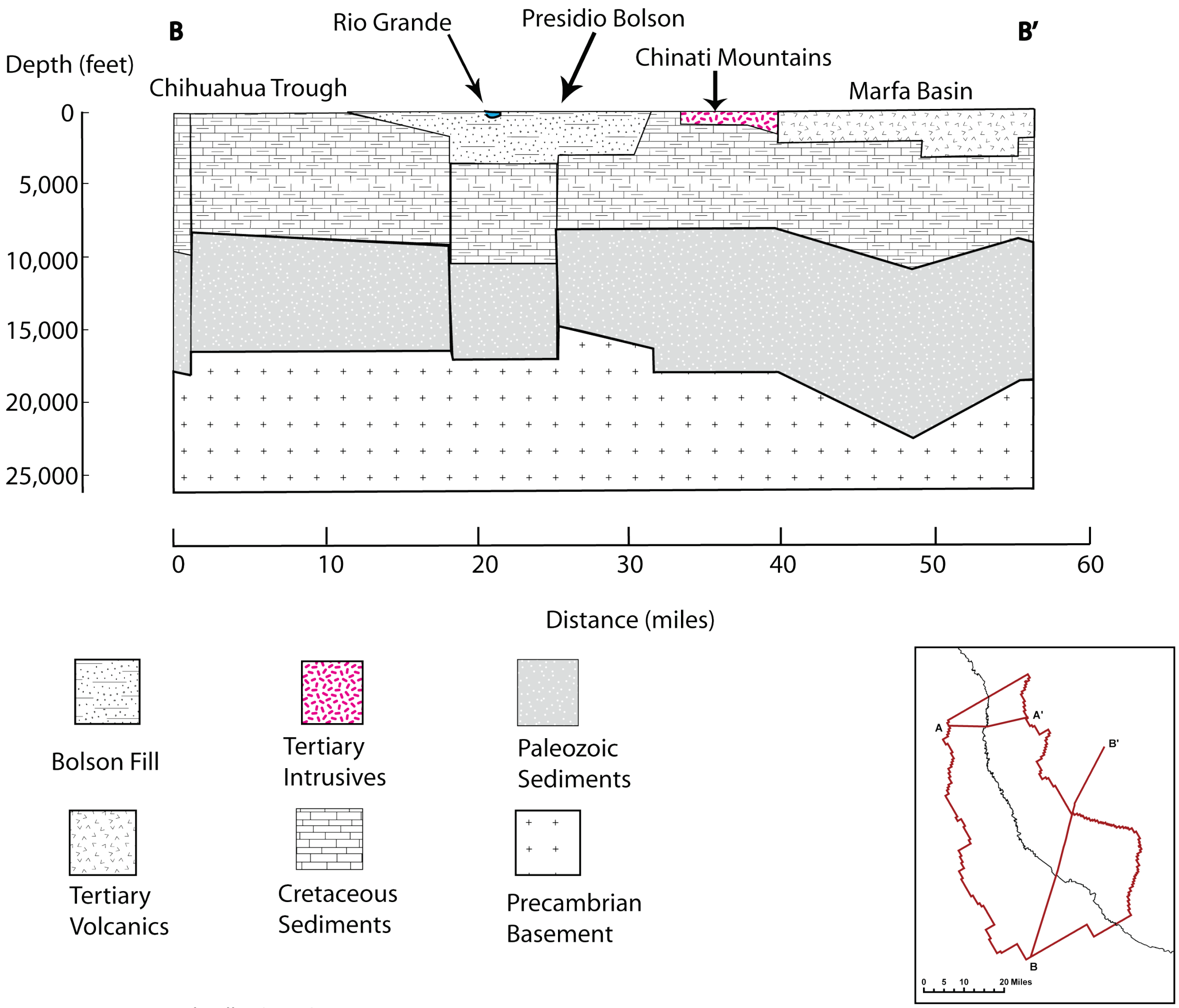



**Figure 2-21. Cross section A - A' through the northern portion of the bolson (from Henry, 1979).**




source: Mraz and Keller (1980)

**Figure 2-22. Cross section B-B' through the southern portion of the bolson interpreted from gravity modeling (modified from Mraz and Keller, 1980).**

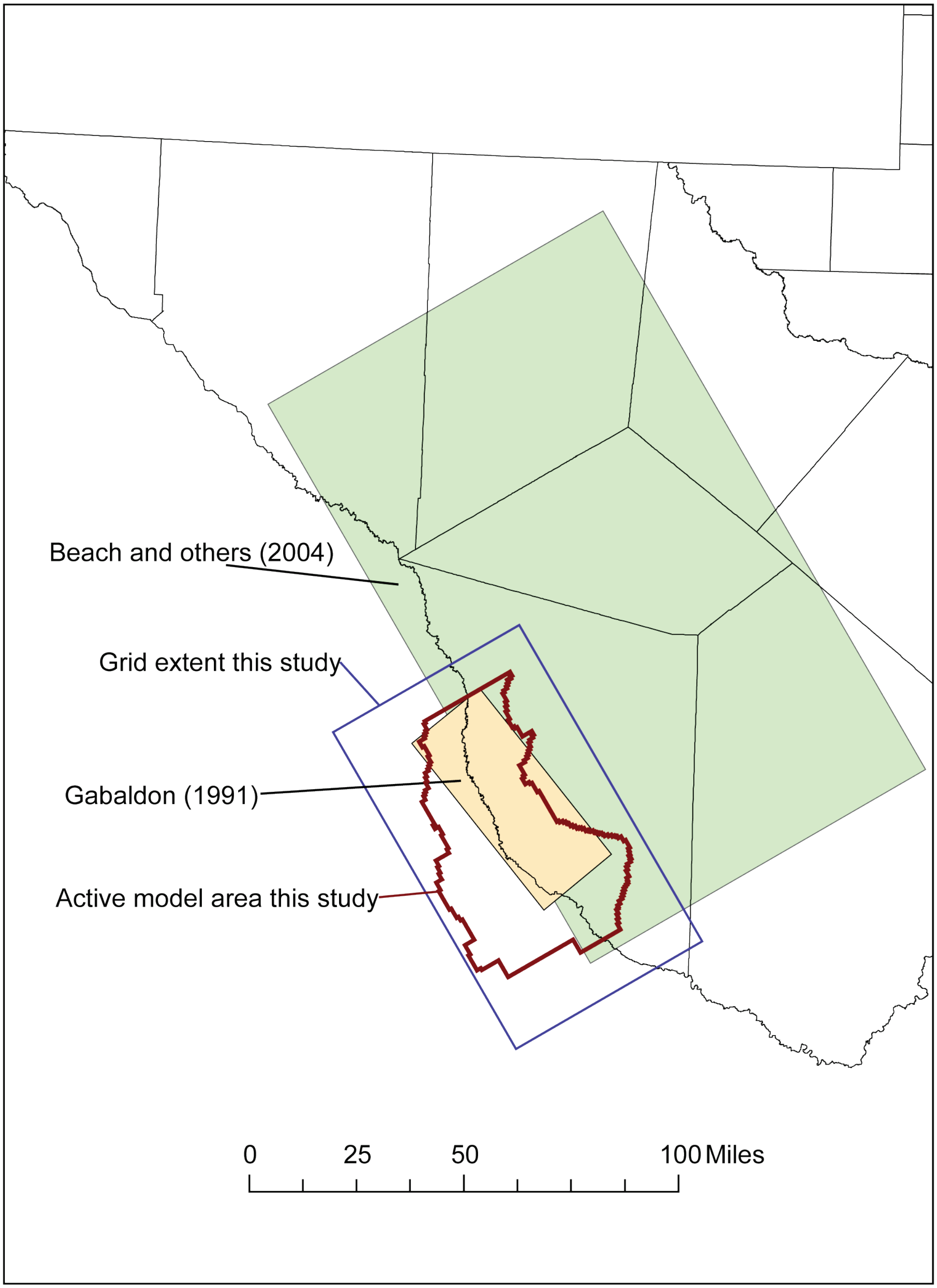



**Figure 3-1. Location of previous studies overlain with the present study.**

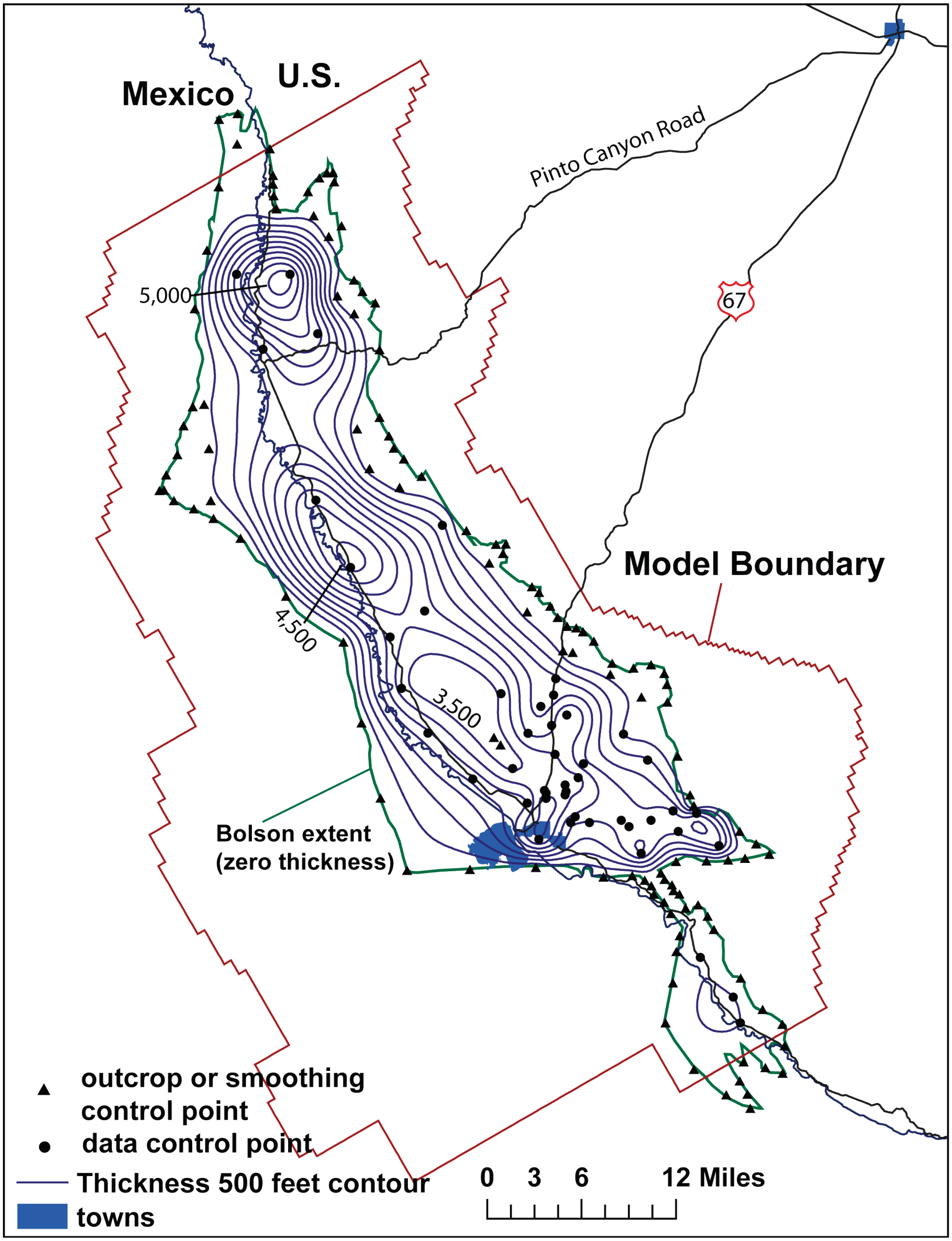



**Figure 4-1. Bolson thickness with control points.**

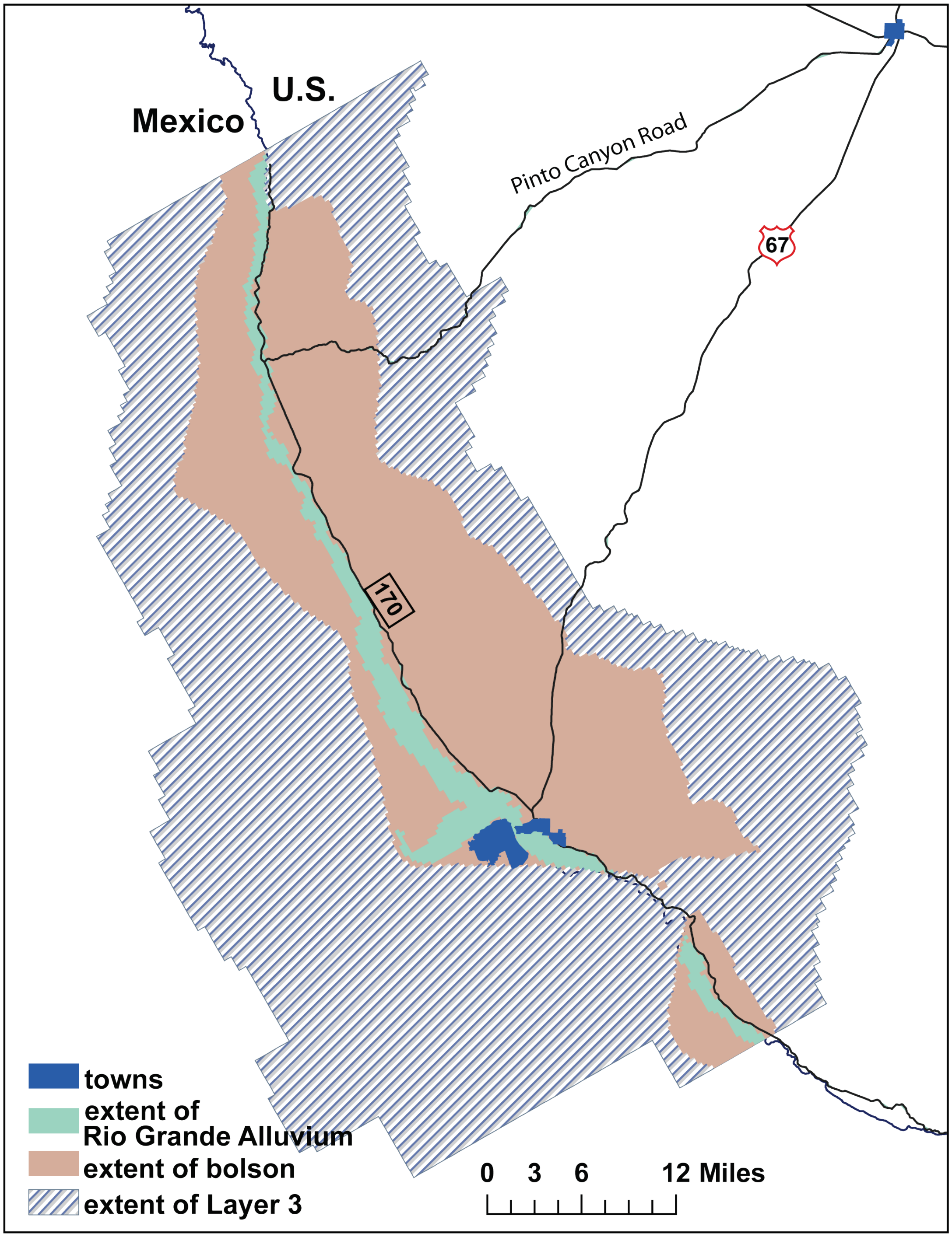



**Figure 4-2. Extent of Rio Grande Alluvium and Presidio-Redford Bolson deposits in model area.**

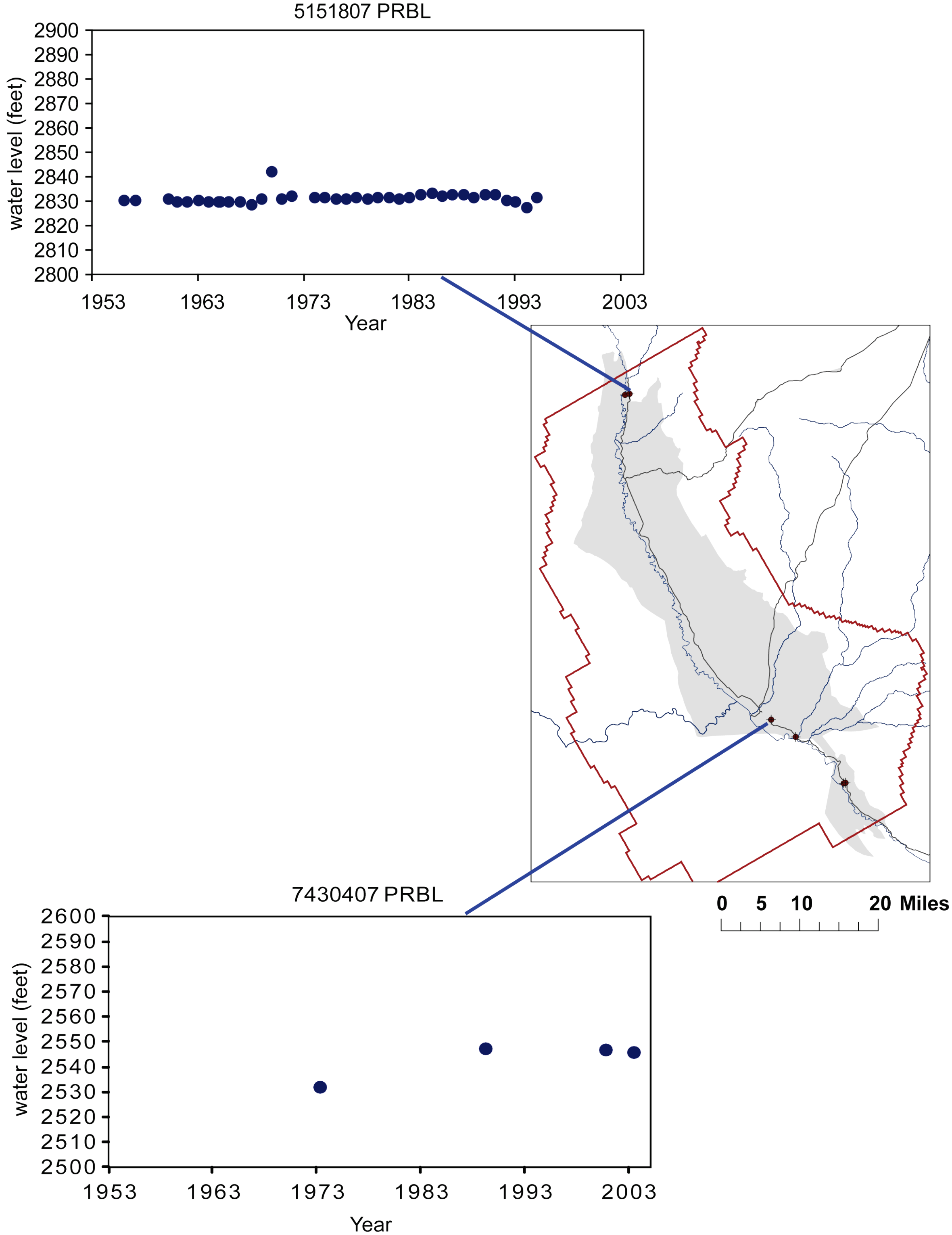



**Figure 4-3 Hydrographs for Presidio Bolson, state well numbers 5151807 and 7430407.**

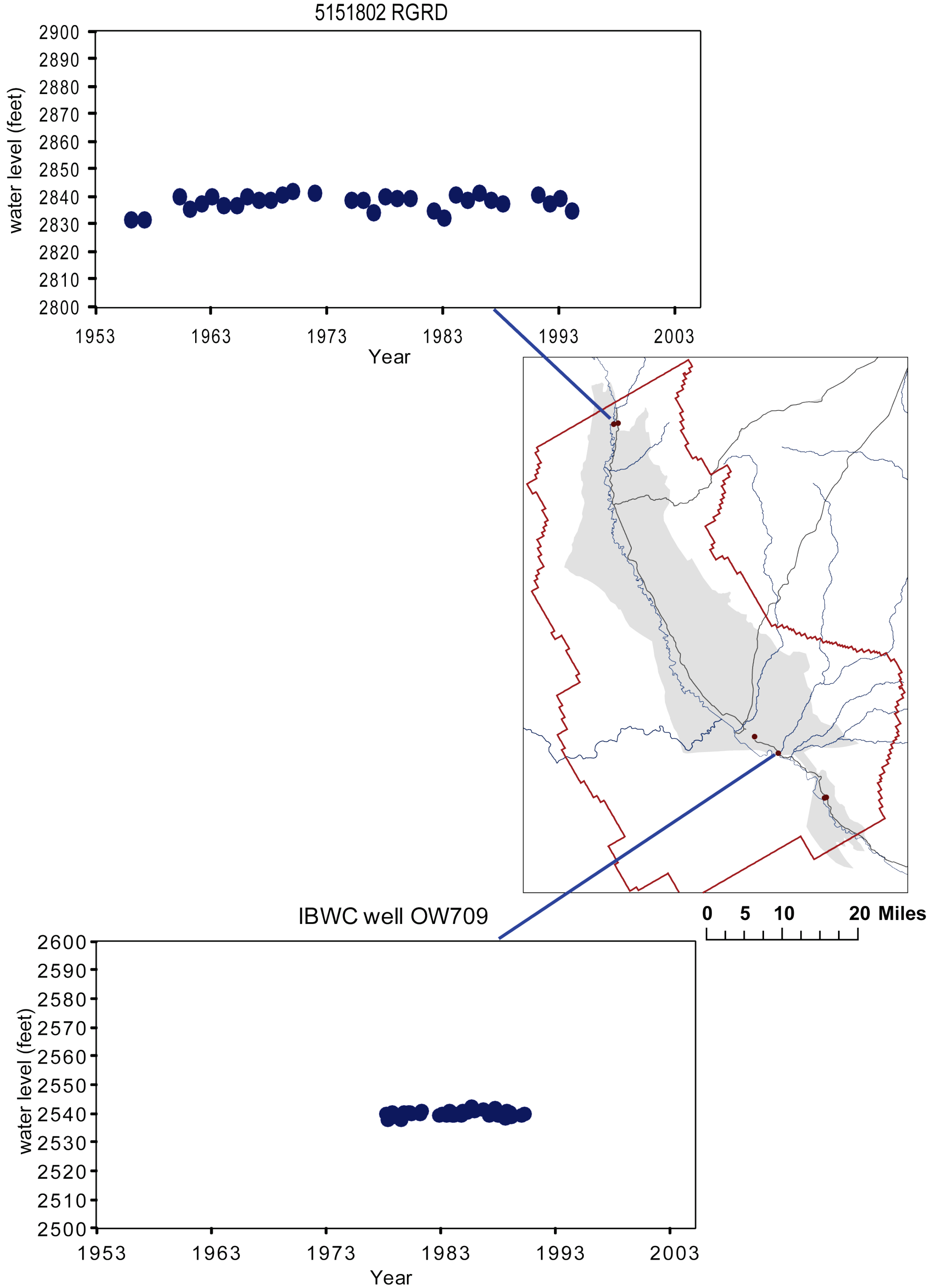



**Figure 4-4. Hydrographs for state well number 5151802 and IBWC well OW709, both Rio Grande Alluvium wells.**

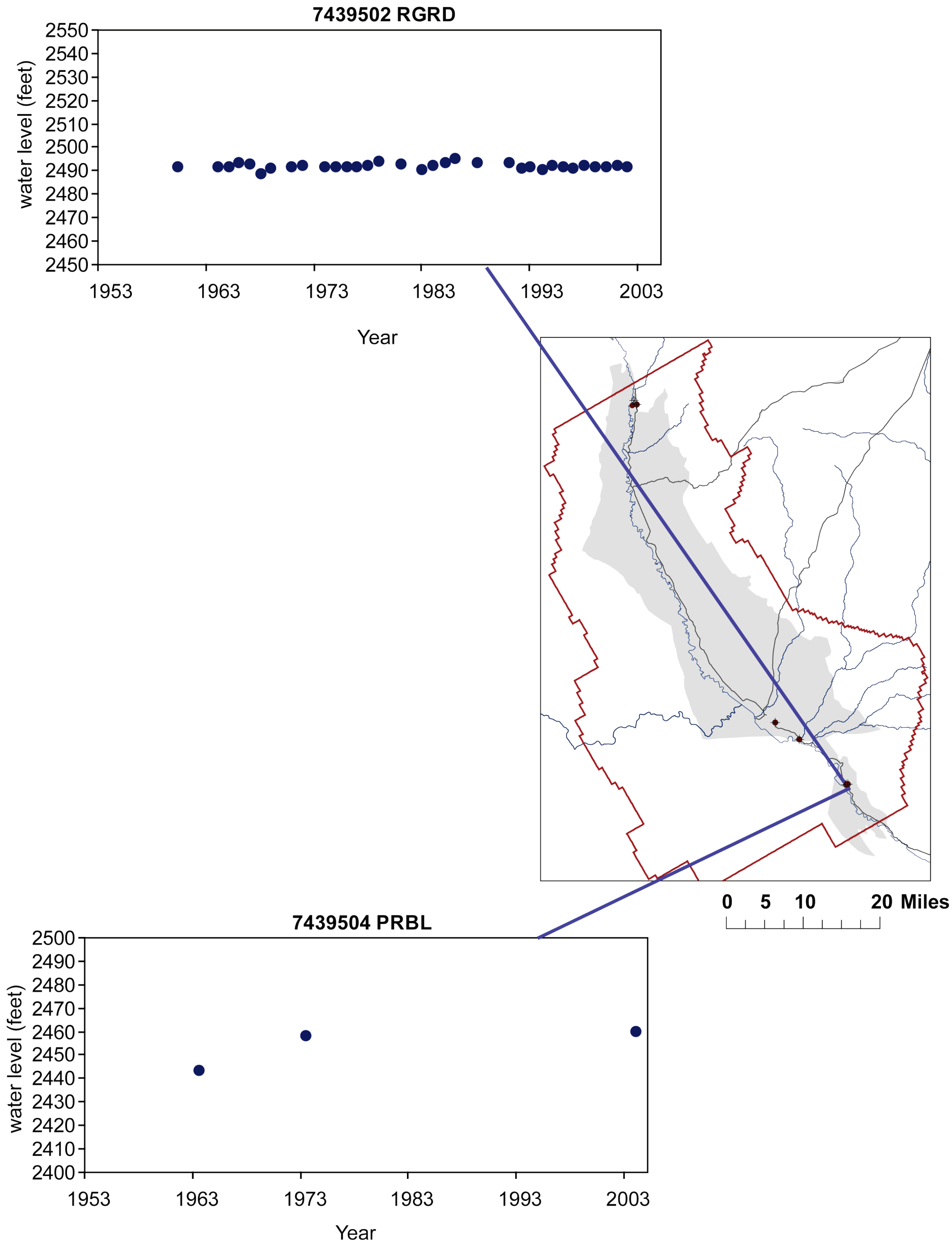



**Figure 4-5. Hydrographs for state well number 7439502 (Rio Grande Alluvium) and state well number 7439504 (Presidio Bolson).**

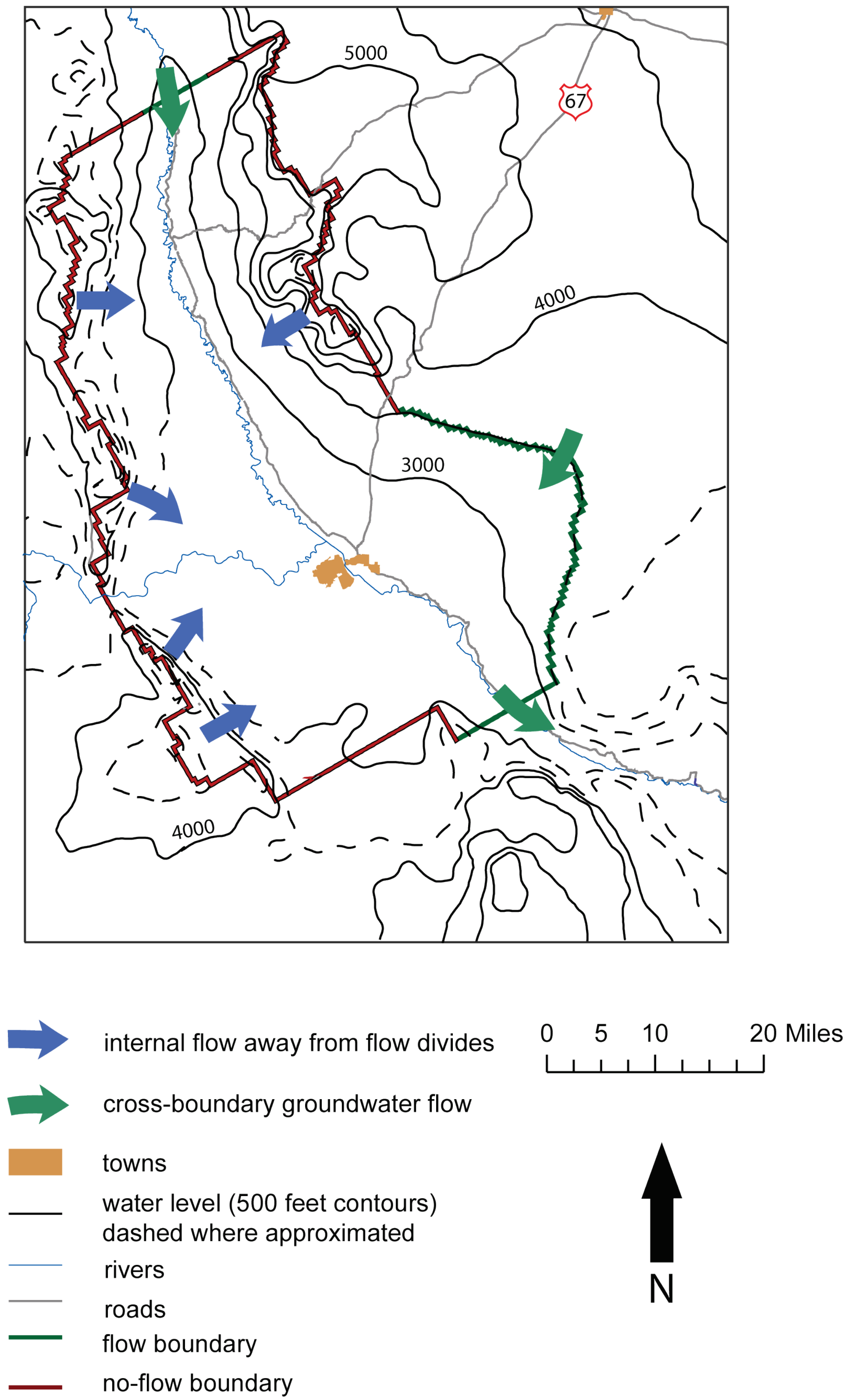



**Figure 4-6 Water Level Map**

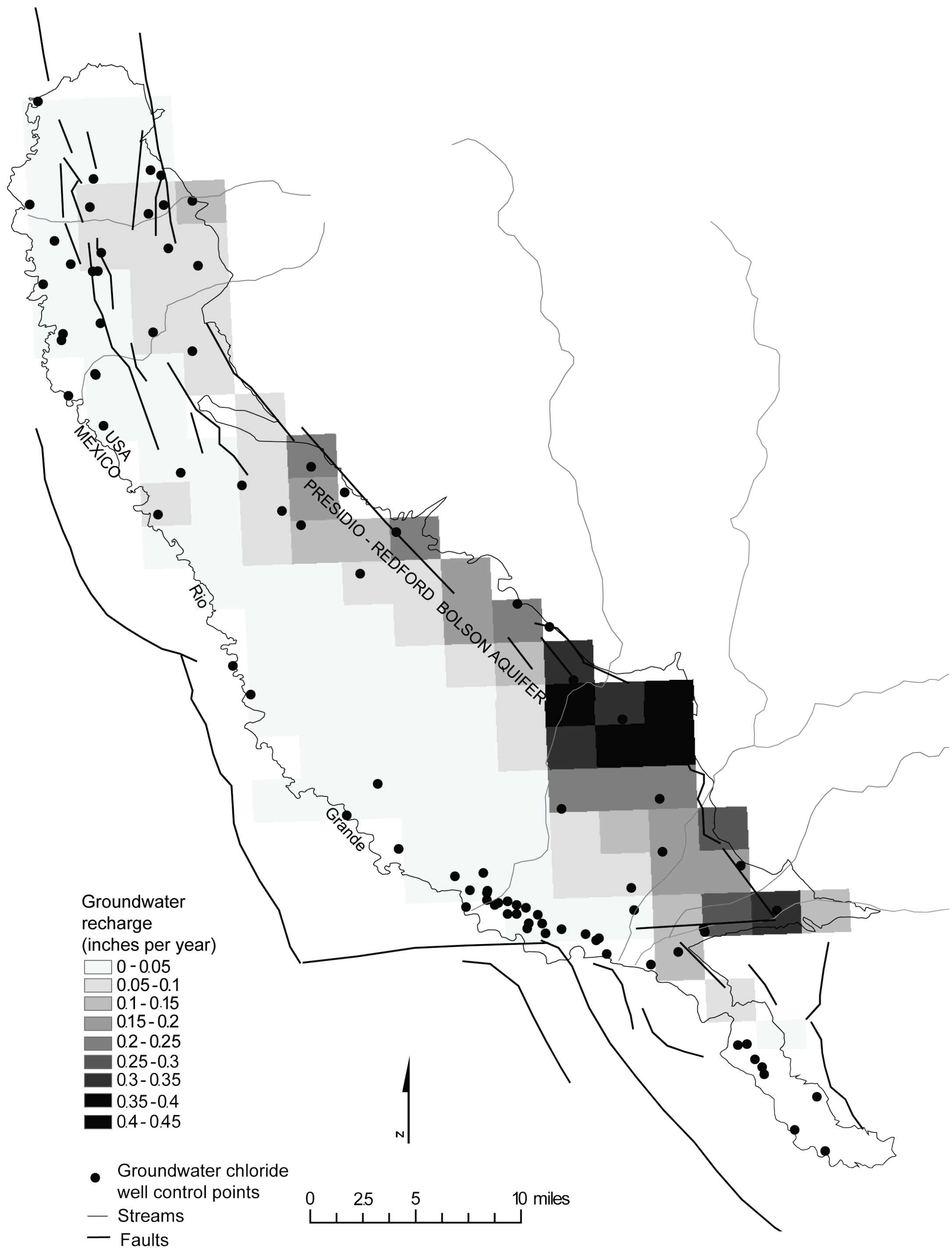



**Figure 4-7 Estimated groundwater recharge in the Presidio-Redford Bolson and the Rio Grande Alluvium aquifers using chloride mass balance method (from Chowdhury and Wade, in prep).**

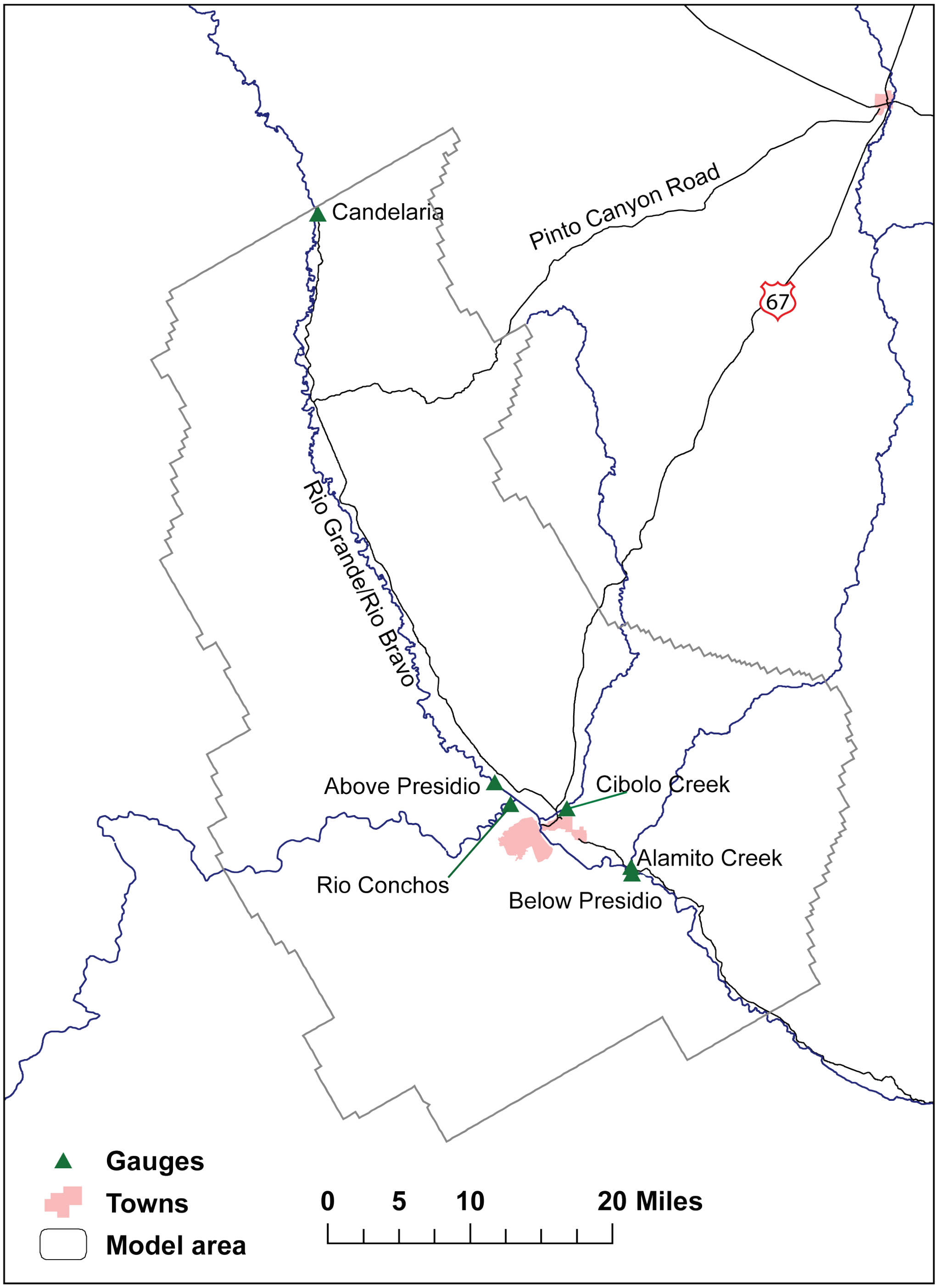
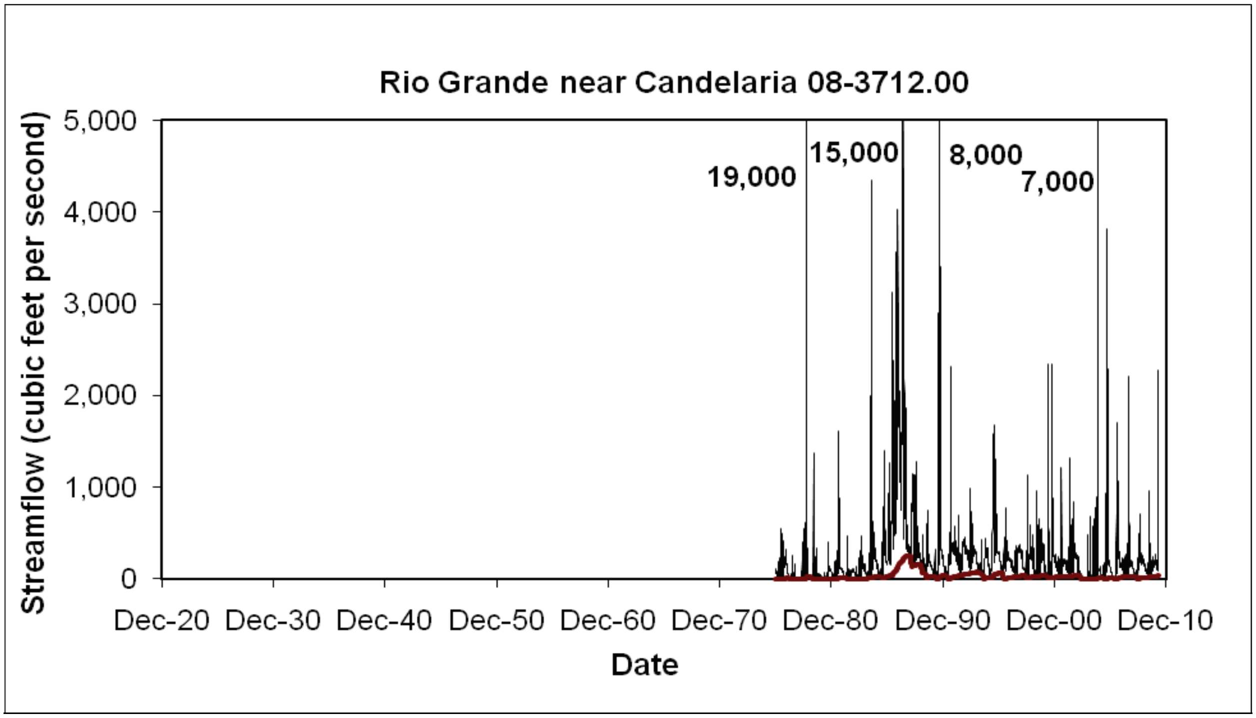



**Figure 4-8. Location of stream gauges.**



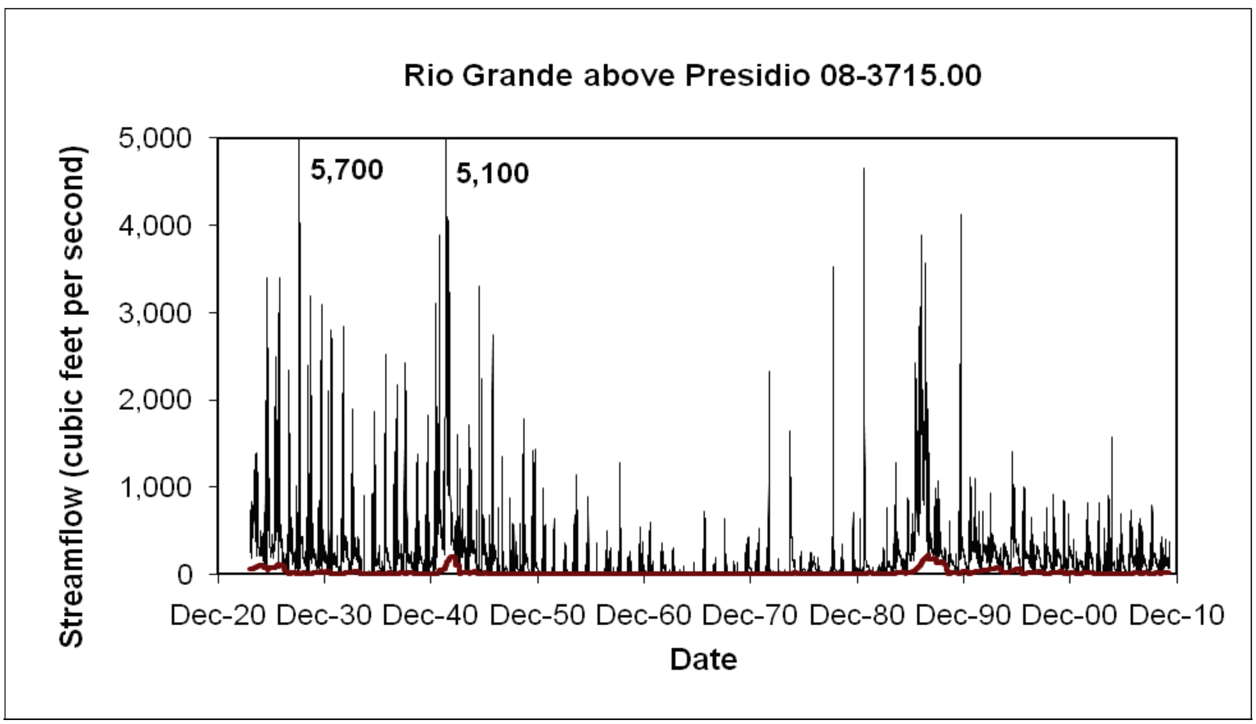




**Figure 4-9. Stream flow hydrographs for Candelaria and gauge above Presidio (IBWC, 2011). Base flow estimates are shown in with thick red line at the base.**

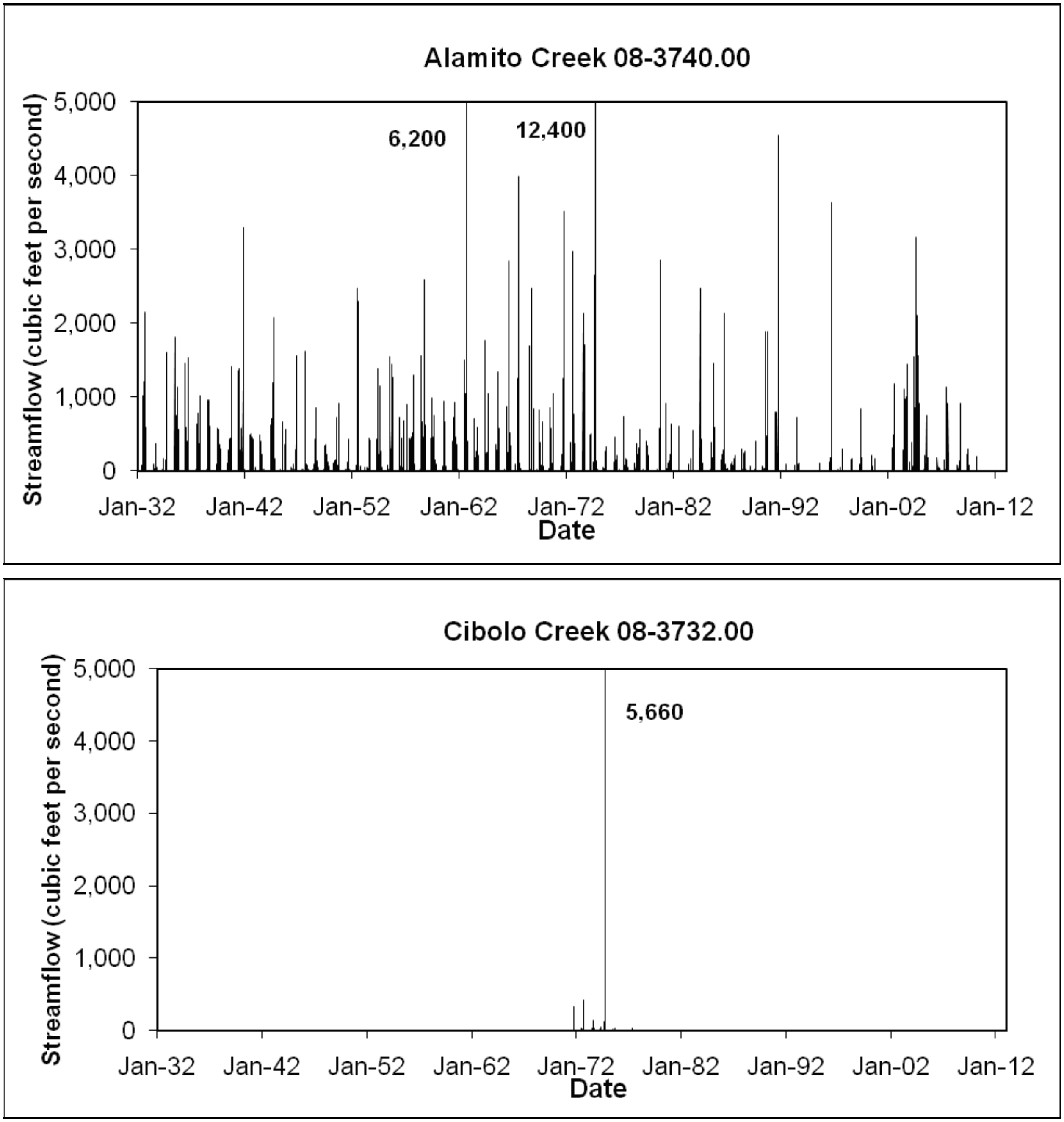
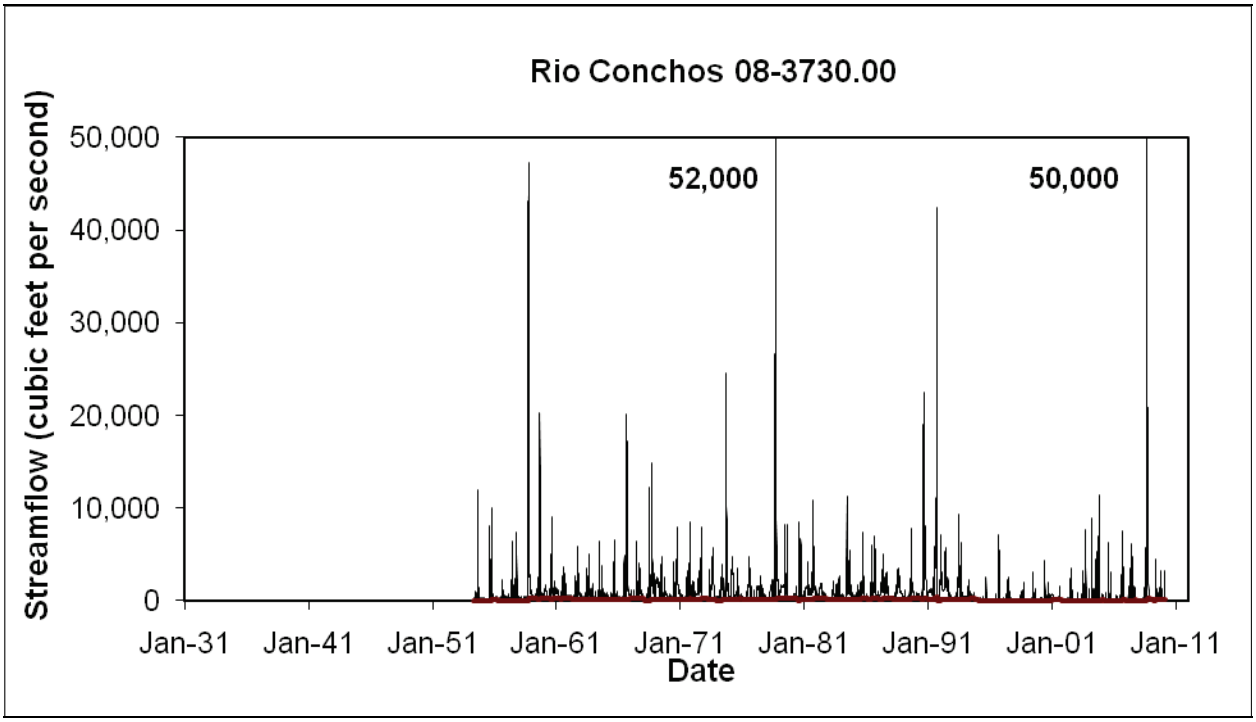



**Figure 4-10. Streamflow hydrographs for Alamito Creek and Cibolo Creek (IBWC, 2011 and USGS, 2006).**



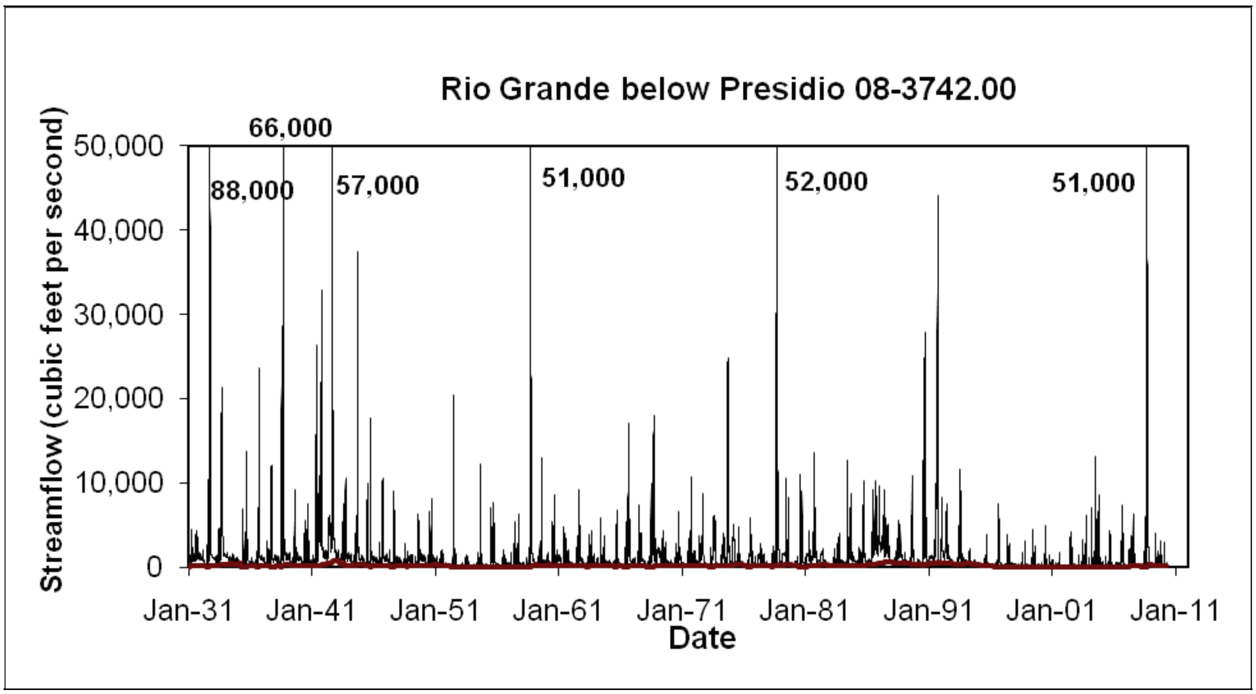




**Figure 4-11. Streamflow hydrographs for the Rio Conchos and the gauge below Presidio (IBWC, 2011). Base flow estimates are shown in with thick red line at the base.**

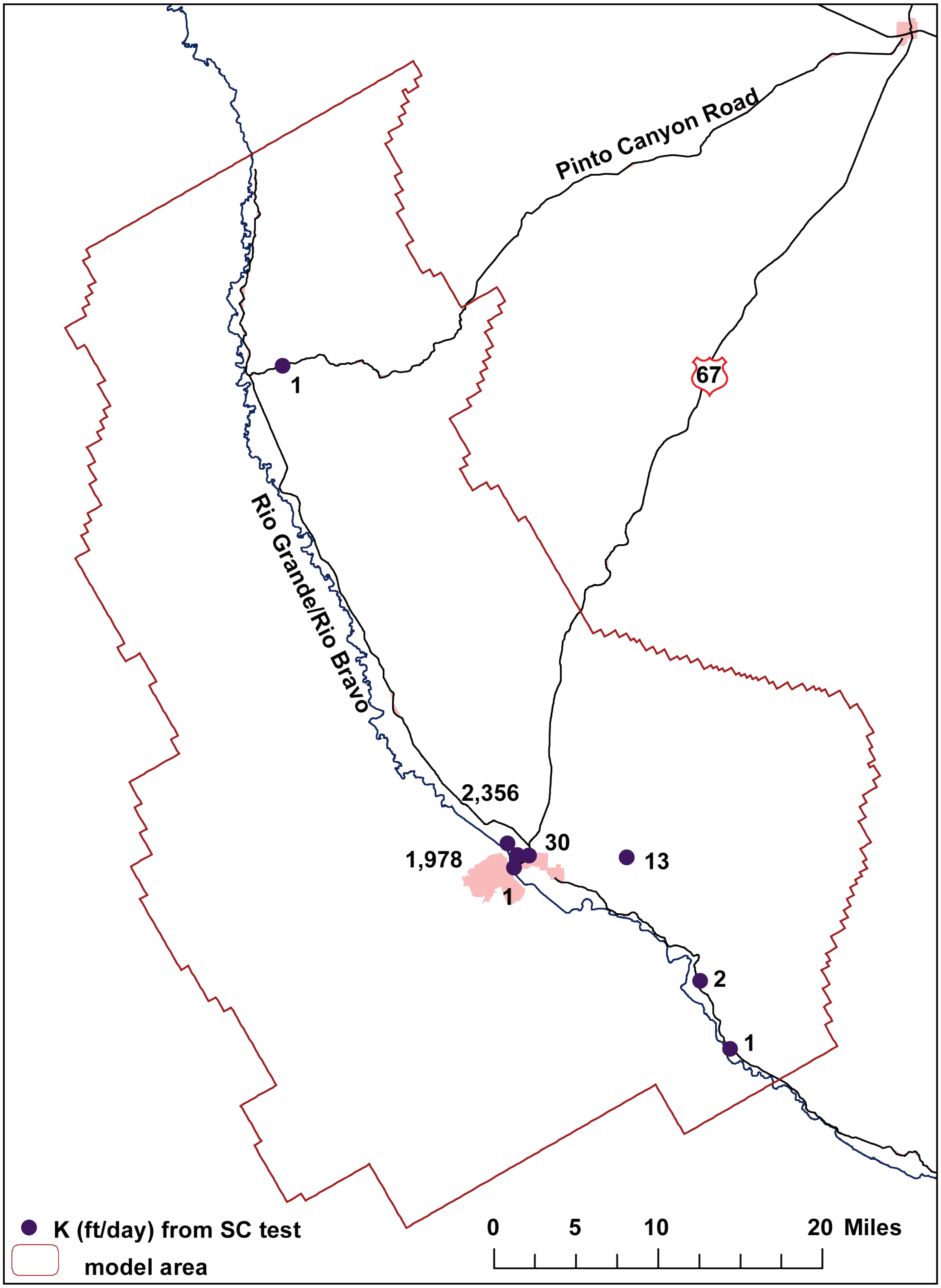



**Figure 4-12. Location of specific capacity measurements and estimates of hydraulic conductivity.**

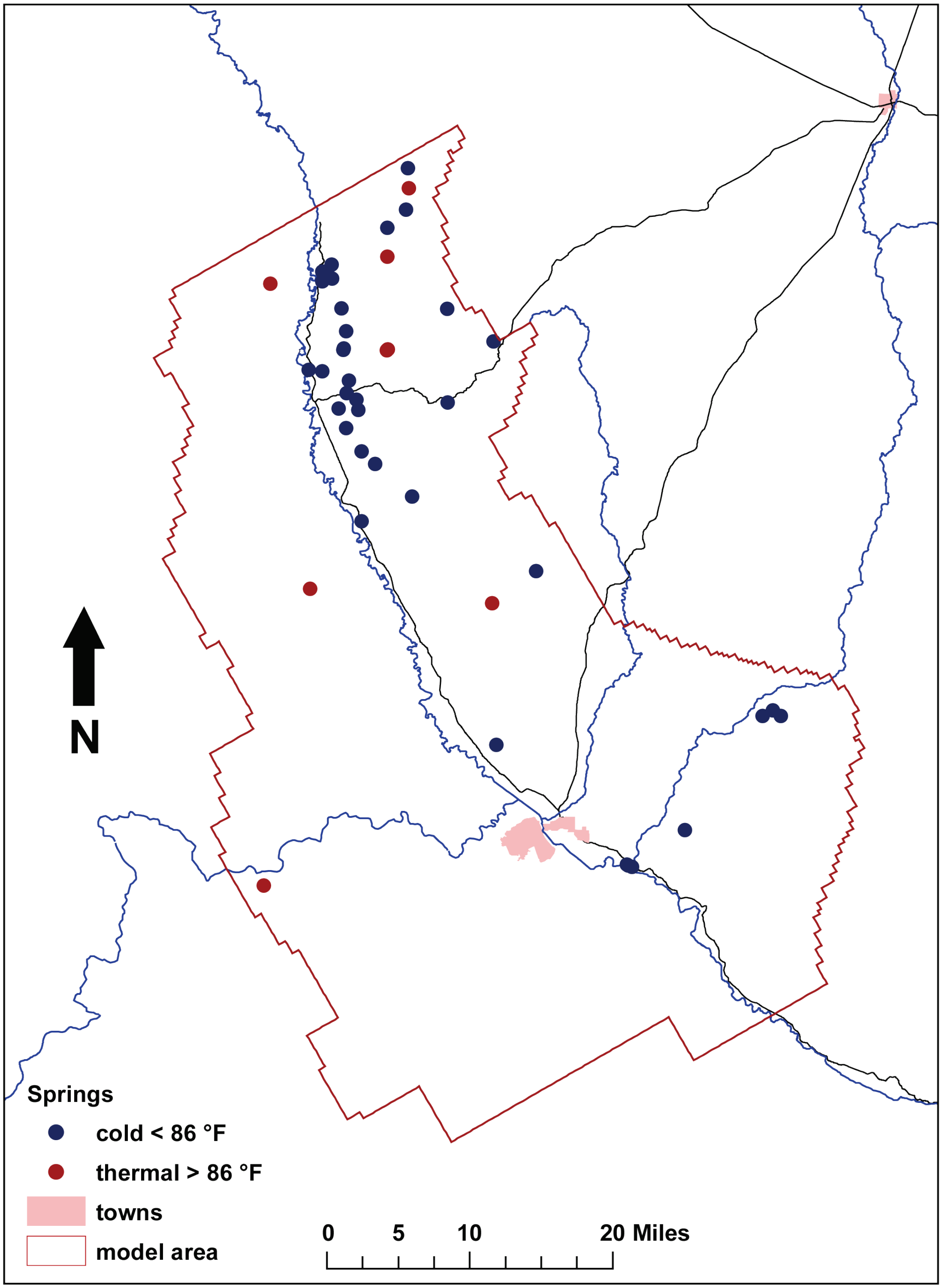



**Figure 4-13. Location of springs in the study area.**

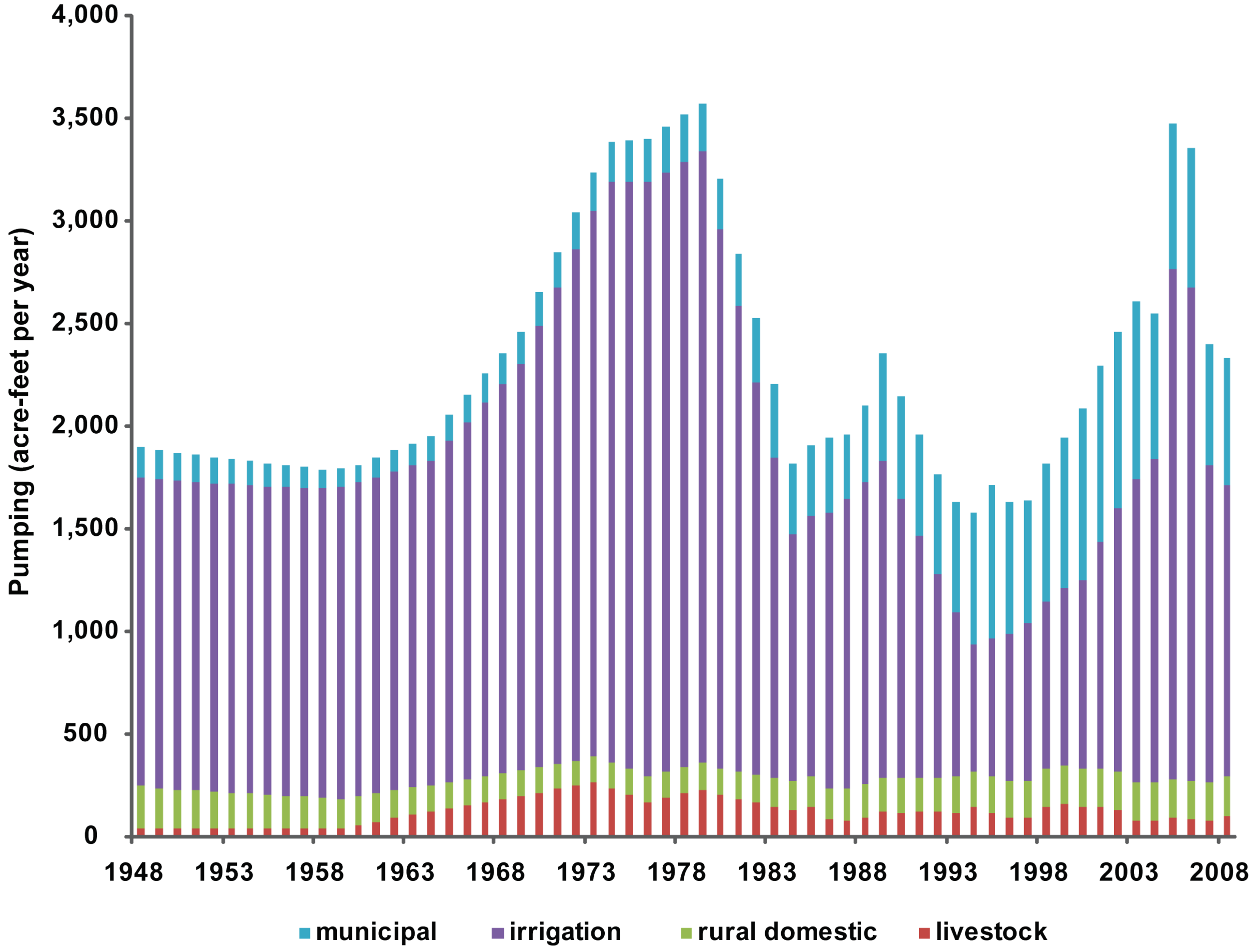



**Figure 4-14. Estimated groundwater use in U.S. portion of study area. Pumping amounts for years not listed in Tables 4-6 and 4-7 are interpolated or extrapolated from values in the tables and other information such as population. See text for details.**

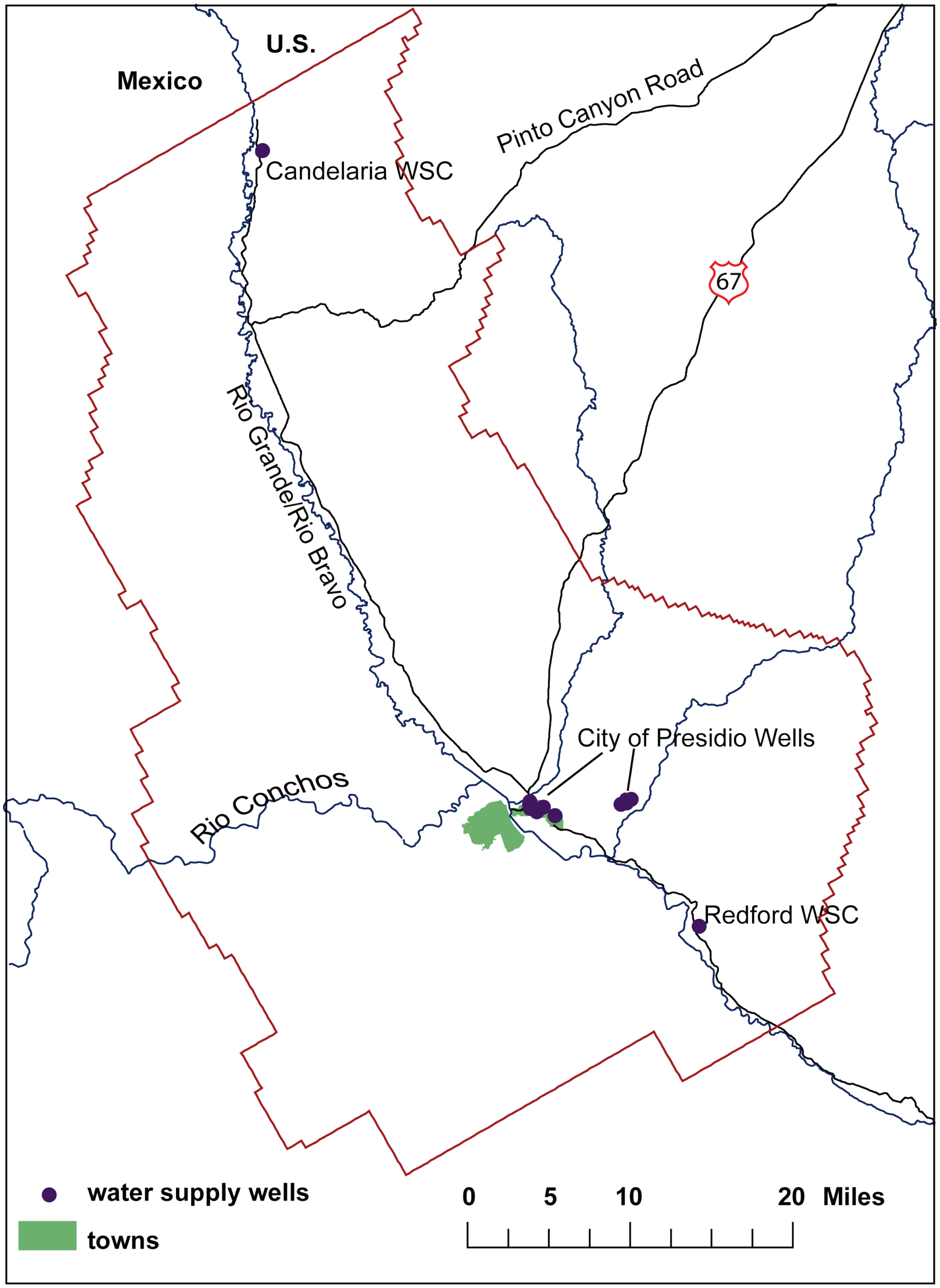



**Figure 4-15. Location of public water supply wells in study area.**

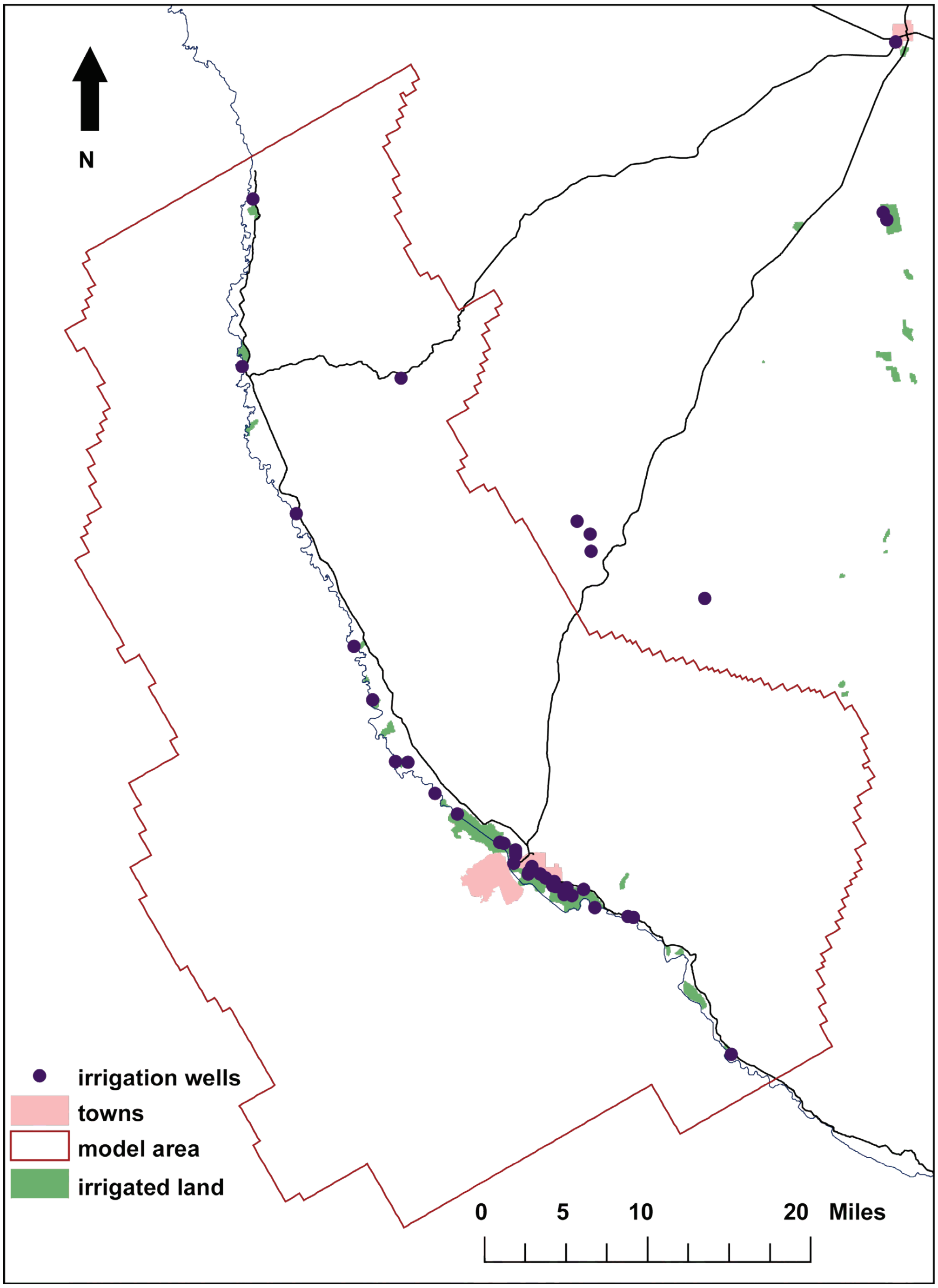



**Figure 4-16. Location of irrigation wells overlaid on irrigated land coverage.**

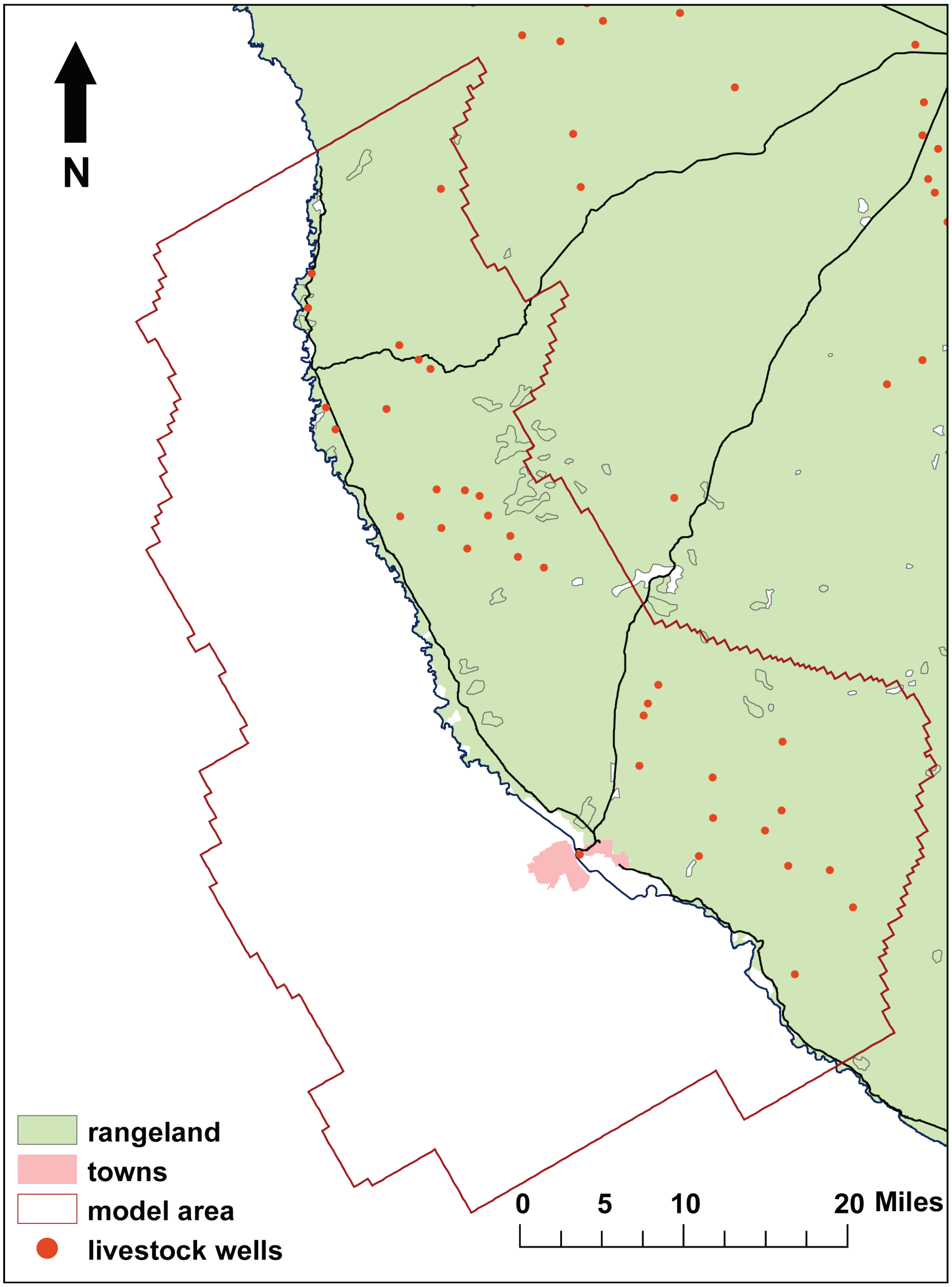



**Figure 4-17. Rangeland areas from land use coverage shown with livestock wells.**

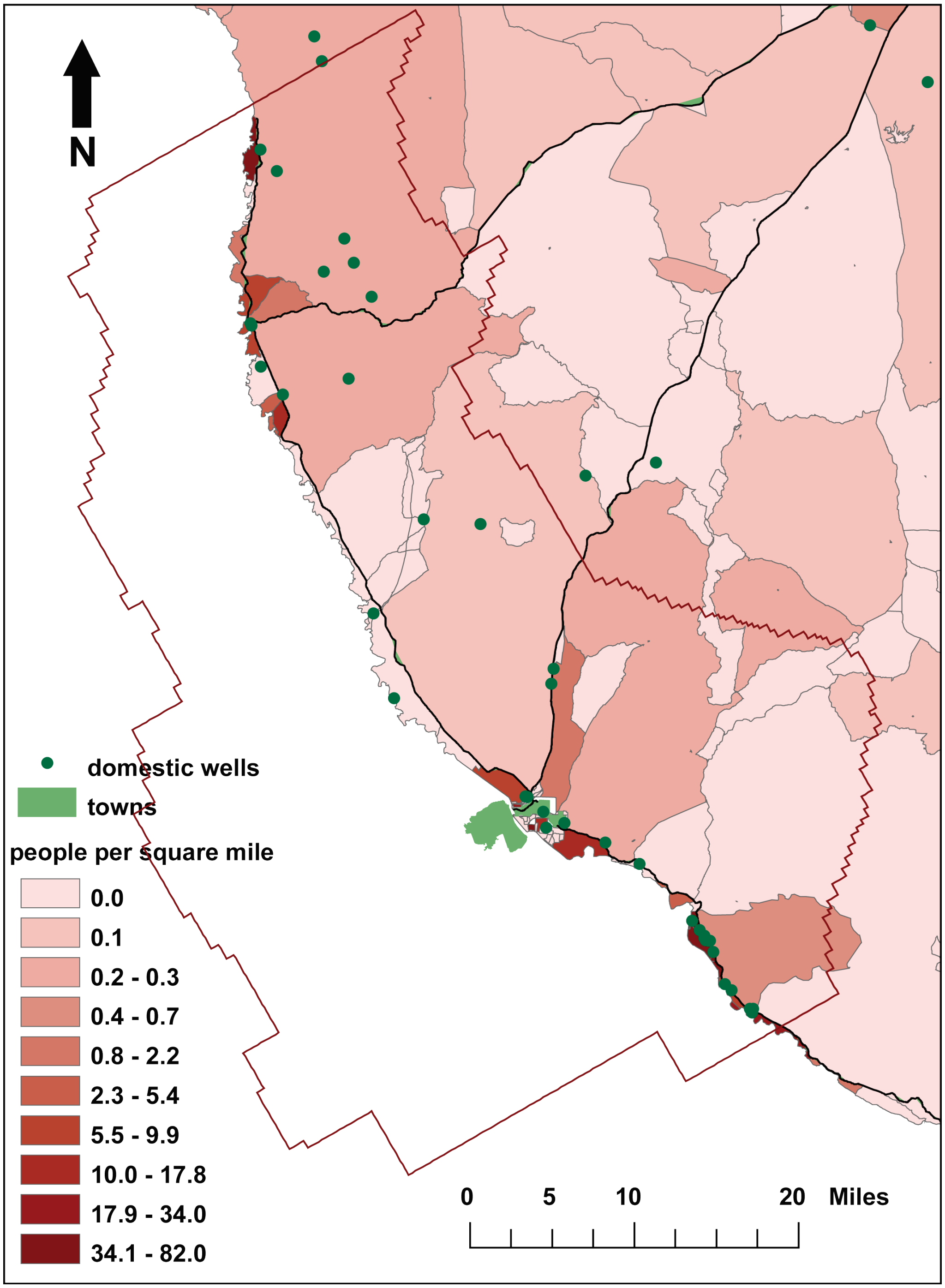



**Figure 4-18. Domestic well locations overlaid on census block coverage.**

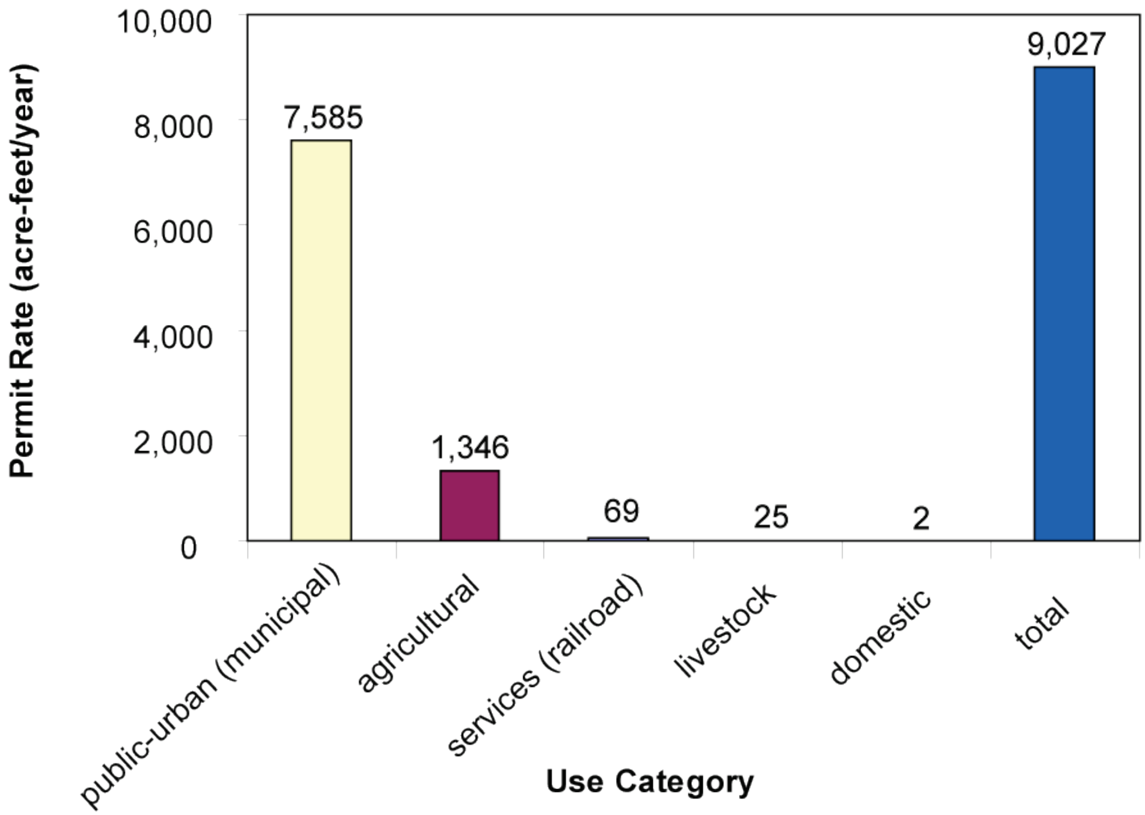



**Figure 4-19. Permitted groundwater use totals for Ojinaga area of Mexico from CNA database (2007).**

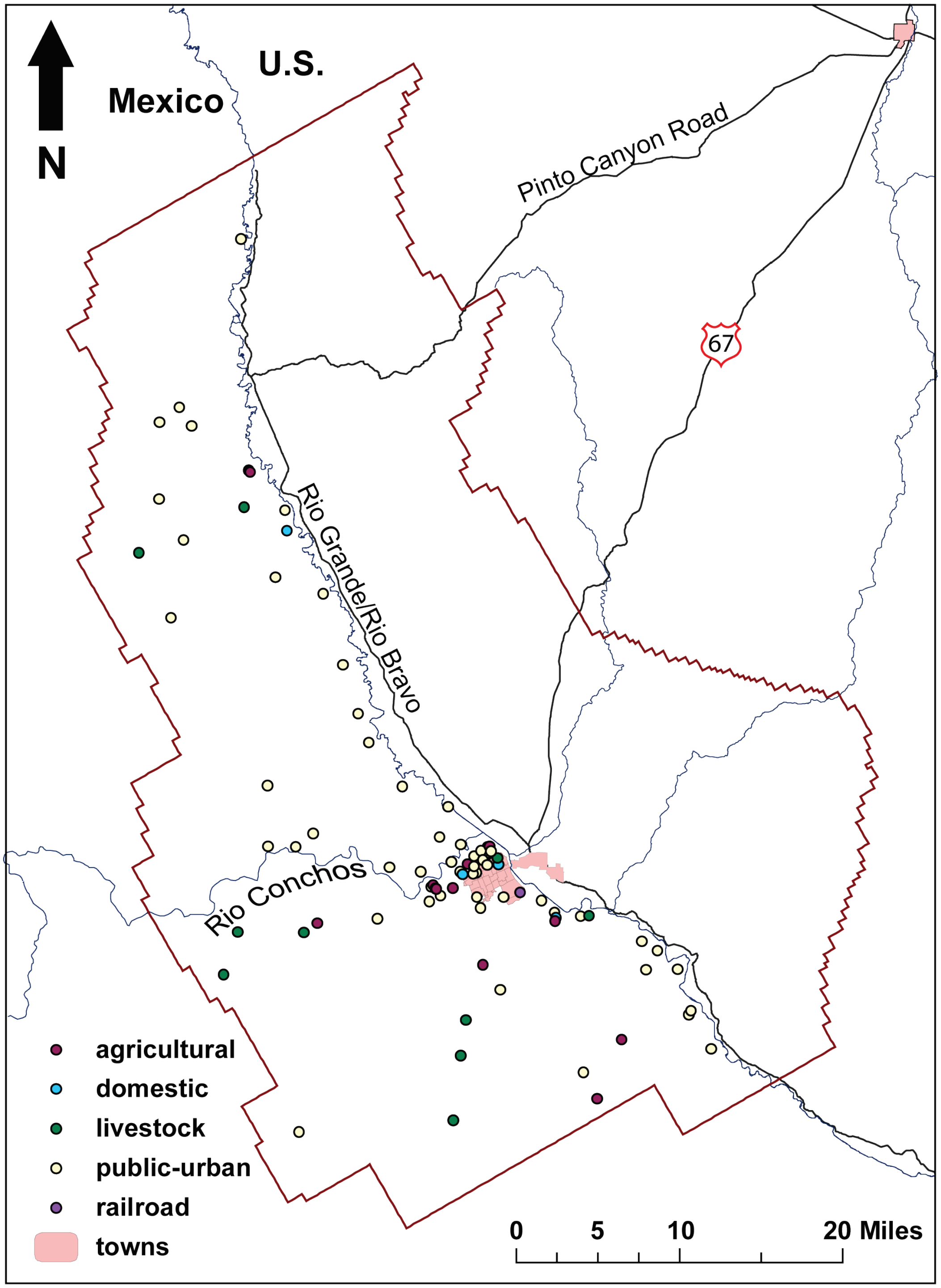



**Figure 4-20. Permit locations from CNA database (2008) in model area.**

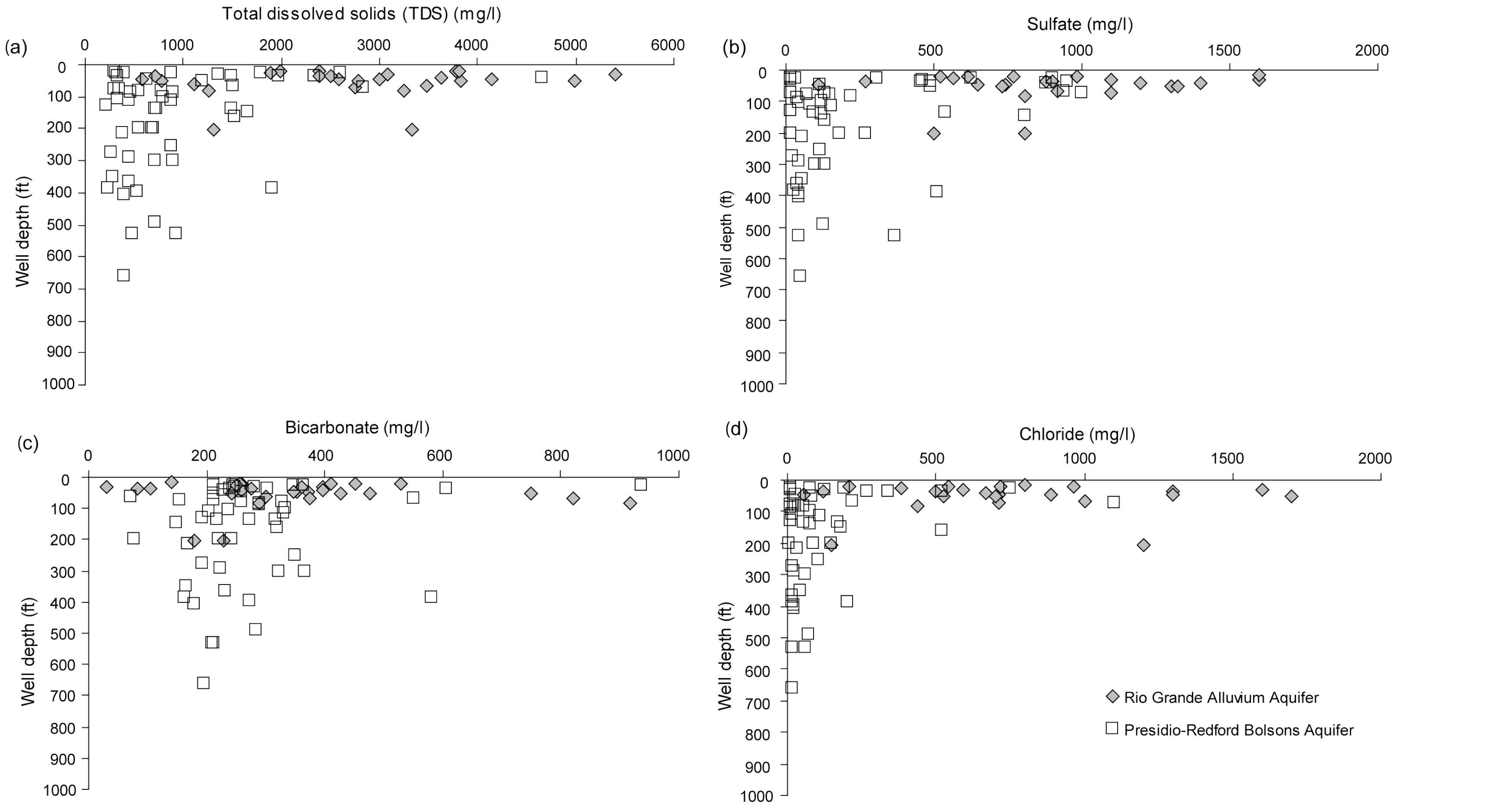



**Figure 4-21. Plots of various chemical parameters to show changes in their concentrations with depth (a) total dissolved solids, (b) sulfate, (c) bicarbonate, and (d) chloride.**

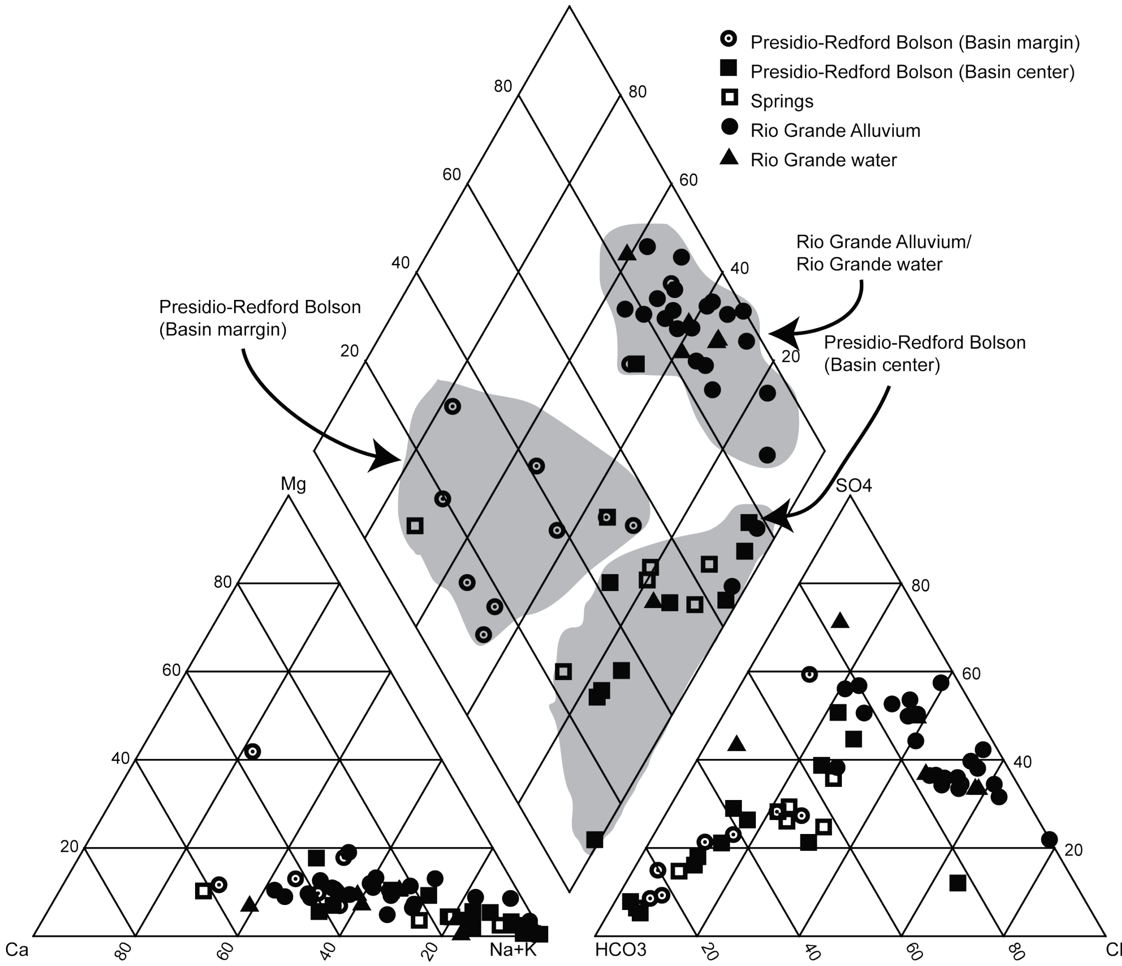



**Figure 4-22. Piper diagram of the groundwater from the Presidio-Redford Bolson and Rio Grande Alluvium aquifers and surface water from the Rio Grande (from Chowdhury and others, 2008).**

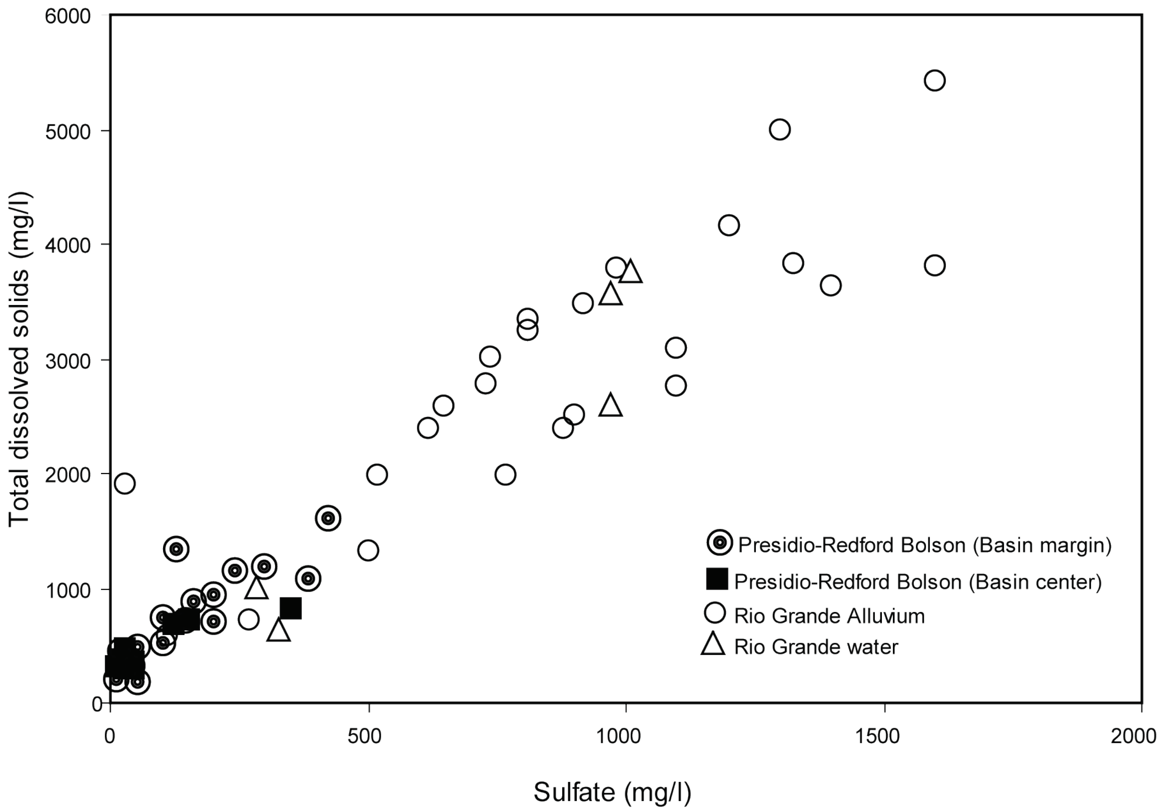



**Figure 4-23. A plot of total dissolved solids versus sulfate in the groundwater from the Presidio-Redford Bolson Aquifer, Rio Grande Alluvium Aquifer, and surface water from the Rio Grande (from Chowdhury and others, 2008).**

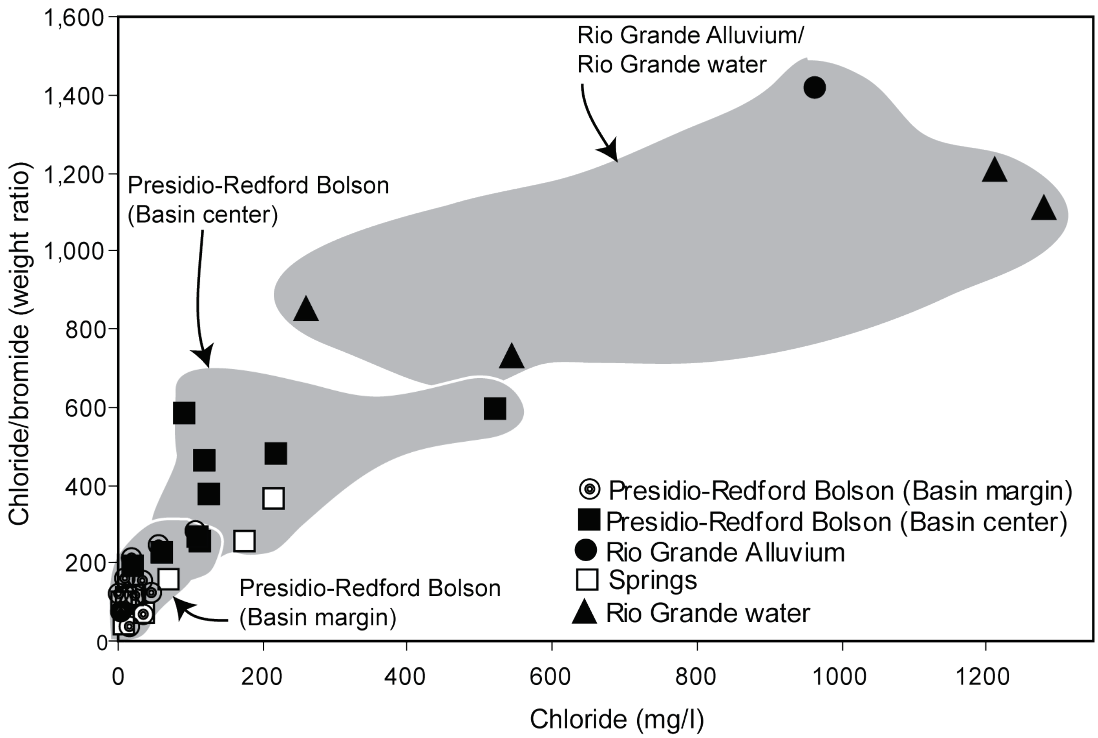



**Figure 4-24. Plot of chloride/bromide ratios versus chloride from the Presidio-Redford Bolson Aquifer, Rio Grande Alluvium Aquifer, and surface water from the Rio Grande. Note increase in the ratios from the basin margins to the Rio Grande (Chowdhury and others, 2008).**

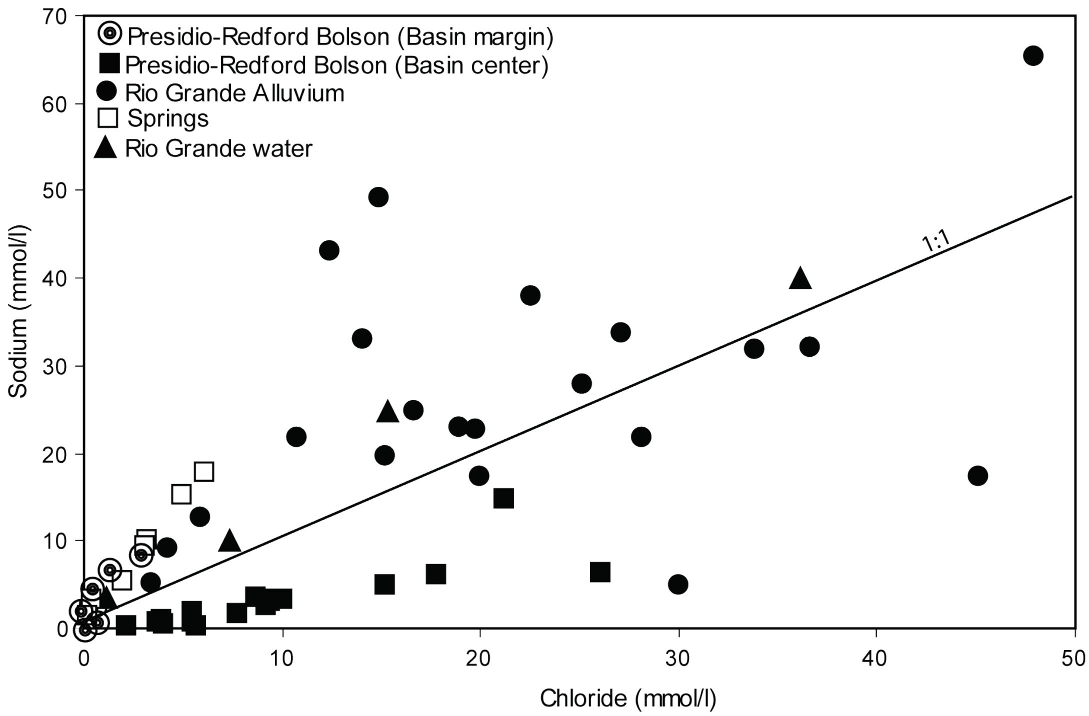



**Figure 4-25. Plot of sodium versus chloride of groundwater from the Presidio-Redford Bolson Aquifer, Rio Grande Alluvium Aquifer, and surface water from the Rio Grande.**

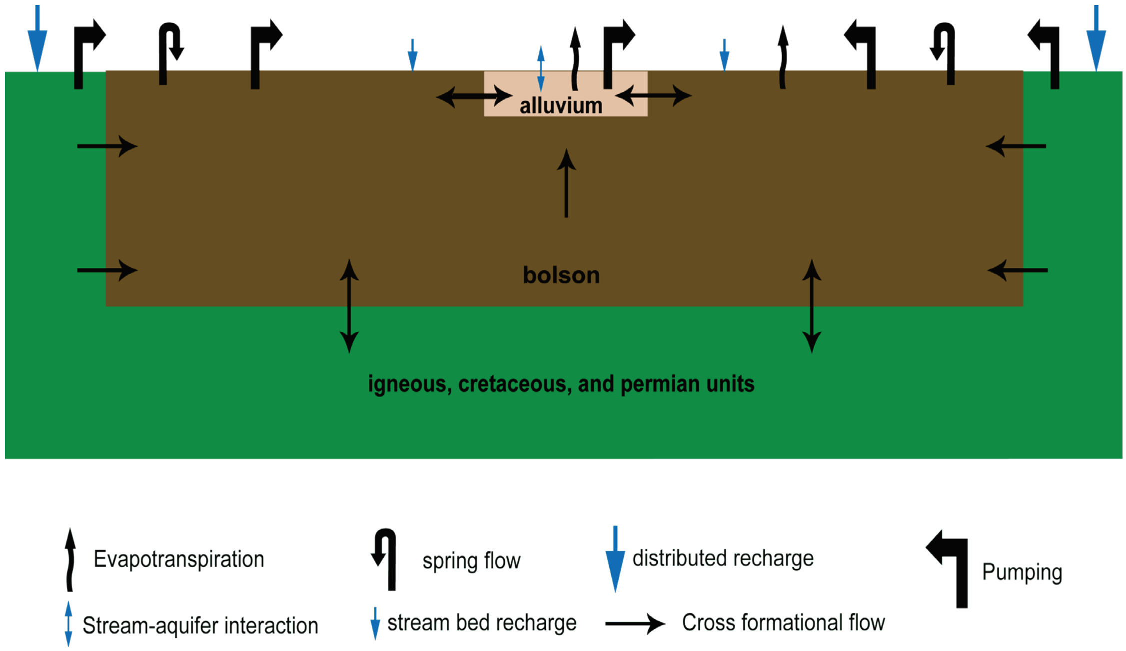



**Figure 5-1. Diagram of conceptual model of groundwater flow system for the Presidio and Redford Bolsons.**

# Appendix A
## Estimates of annual baseflow

**Table A.1 Annual estimates of baseflow based on gauge data (IBWC, 2006) and analysis discussed in Section 4.5. Entries of "na" mean data was not available.**

| Year | Candelaria | | Above Presidio | | Rio Conchos | | Below Presidio | |
|---|---|---|---|---|---|---|---|---|
| | cubic feet per second | Acre feet per year | cubic feet per second | Acre feet per year | cubic feet per second | Acre feet per year | cubic feet per second | Acre feet per year |
| 1924 | na | na | 80 | 57,824 | na | na | na | na |
| 1925 | na | na | 83 | 60,384 | na | na | na | na |
| 1926 | na | na | 94 | 68,344 | na | na | na | na |
| 1927 | na | na | 37 | 27,151 | na | na | na | na |
| 1928 | na | na | 13 | 9,692 | na | na | na | na |
| 1929 | na | na | 10 | 7,205 | na | na | na | na |
| 1930 | na | na | 23 | 16,680 | na | na | na | na |
| 1931 | na | na | 16 | 11,703 | na | na | 119 | 86,516 |
| 1932 | na | na | 7 | 5,233 | na | na | 152 | 110,405 |
| 1933 | na | na | 25 | 17,957 | na | na | 259 | 187,534 |
| 1934 | na | na | 12 | 8,429 | na | na | 381 | 276,159 |
| 1935 | na | na | 4 | 2,779 | na | na | 134 | 97,251 |
| 1936 | na | na | 7 | 5,392 | na | na | 90 | 65,055 |
| 1937 | na | na | 6 | 4,581 | na | na | 92 | 66,705 |
| 1938 | na | na | 16 | 11,393 | na | na | 161 | 116,712 |
| 1939 | na | na | 9 | 6,735 | na | na | 205 | 148,270 |
| 1940 | na | na | 5 | 3,667 | na | na | 147 | 106,640 |
| 1941 | na | na | 21 | 15,053 | na | na | 197 | 142,697 |
| 1942 | na | na | 130 | 93,841 | na | na | 539 | 390,247 |
| 1943 | na | na | 93 | 67,670 | na | na | 425 | 308,093 |
| 1944 | na | na | 23 | 16,331 | na | na | 230 | 166,908 |
| 1945 | na | na | 17 | 11,967 | na | na | 159 | 115,370 |
| 1946 | na | na | 8 | 5,916 | na | na | 124 | 89,511 |
| 1947 | na | na | 4 | 2,805 | na | na | 114 | 82,862 |
| 1948 | na | na | 1 | 483 | na | na | 119 | 86,111 |
| 1949 | na | na | 3 | 2,248 | na | na | 123 | 89,165 |
| 1950 | na | na | 3 | 2,423 | na | na | 200 | 144,915 |
| 1951 | na | na | 1 | 703 | na | na | 201 | 145,290 |
| 1952 | na | na | 0 | 32 | na | na | 60 | 43,722 |
| 1953 | na | na | 0 | 26 | na | na | 13 | 9,074 |
| 1954 | na | na | 0 | 294 | 12 | 8,810 | 14 | 10,241 |
| 1955 | na | na | 0 | 91 | 23 | 16,804 | 27 | 19,331 |
| 1956 | na | na | 0 | 3 | 28 | 20,278 | 30 | 21,892 |
| 1957 | na | na | 0 | 8 | 21 | 15,128 | 17 | 12,460 |
| 1958 | na | na | 1 | 402 | 64 | 46,078 | 63 | 45,853 |
| 1959 | na | na | 0 | 14 | 194 | 140,392 | 211 | 152,621 |
| 1960 | na | na | 0 | 277 | 190 | 137,763 | 194 | 140,583 |
| 1961 | na | na | 0 | 258 | 192 | 138,808 | 184 | 133,532 |
| 1962 | na | na | 1 | 641 | 133 | 96,597 | 132 | 95,777 |
| 1963 | na | na | 1 | 434 | 108 | 78,216 | 107 | 77,185 |
| 1964 | na | na | 0 | 1 | 128 | 92,969 | 130 | 94,512 |
| 1965 | na | na | 0 | 3 | 121 | 87,921 | 115 | 83,503 |
| 1966 | na | na | 1 | 528 | 104 | 75,386 | 83 | 60,211 |
| 1967 | na | na | 0 | 8 | 193 | 139,886 | 171 | 123,721 |

| Year | Candelaria | | Above Presidio | | Rio Conchos | | Below Presidio | |
|---|---|---|---|---|---|---|---|---|
| | cubic feet per second | Acre feet per year | cubic feet per second | Acre feet per year | cubic feet per second | Acre feet per year | cubic feet per second | Acre feet per year |
| 1968 | na | na | 0 | 65 | 80 | 57,971 | 78 | 56,337 |
| 1969 | na | na | 0 | 8 | 136 | 98,387 | 159 | 115,356 |
| 1970 | na | na | 1 | 908 | 133 | 96,275 | 139 | 101,034 |
| 1971 | na | na | 1 | 773 | 149 | 107,587 | 161 | 116,676 |
| 1972 | na | na | 3 | 2,037 | 155 | 112,177 | 160 | 115,580 |
| 1973 | na | na | 2 | 1,246 | 95 | 68,626 | 115 | 83,174 |
| 1974 | na | na | 3 | 1,939 | 63 | 45,901 | 156 | 113,168 |
| 1975 | na | na | 5 | 3,625 | 153 | 110,522 | 258 | 187,017 |
| 1976 | 3 | 1,905 | 2 | 1,589 | 74 | 53,440 | 102 | 73,584 |
| 1977 | 2 | 1,572 | 4 | 2,892 | 104 | 75,452 | 146 | 106,059 |
| 1978 | 7 | 5,311 | 2 | 1,267 | 137 | 99,088 | 140 | 101,650 |
| 1979 | 6 | 4,562 | 4 | 2,964 | 262 | 189,951 | 248 | 179,459 |
| 1980 | 1 | 596 | 1 | 640 | 109 | 79,235 | 118 | 85,166 |
| 1981 | 5 | 3,339 | 7 | 5,086 | 121 | 87,725 | 136 | 98,733 |
| 1982 | 5 | 3,272 | 9 | 6,386 | 194 | 140,464 | 226 | 163,559 |
| 1983 | 2 | 1,425 | 3 | 2,338 | 72 | 52,342 | 125 | 90,670 |
| 1984 | 12 | 8,398 | 12 | 8,933 | 121 | 87,473 | 144 | 104,393 |
| 1985 | 19 | 13,750 | 21 | 15,274 | 177 | 128,588 | 205 | 148,276 |
| 1986 | 60 | 43,202 | 59 | 42,576 | 204 | 147,930 | 305 | 220,999 |
| 1987 | 216 | 156,208 | 179 | 130,040 | 197 | 142,889 | 538 | 389,944 |
| 1988 | 164 | 119,168 | 155 | 112,496 | 149 | 107,801 | 459 | 332,551 |
| 1989 | 51 | 36,888 | 61 | 43,858 | 175 | 126,824 | 366 | 265,087 |
| 1990 | 20 | 14,464 | 19 | 13,555 | 179 | 129,364 | 295 | 213,574 |
| 1991 | 21 | 15,183 | 23 | 16,714 | 160 | 115,697 | 450 | 326,027 |
| 1992 | 36 | 25,930 | 38 | 27,313 | 117 | 85,065 | 477 | 345,790 |
| 1993 | 61 | 44,105 | 59 | 43,079 | 139 | 101,045 | 364 | 263,870 |
| 1994 | 42 | 30,413 | 46 | 33,202 | 158 | 114,624 | 362 | 262,586 |
| 1995 | 33 | 23,725 | 39 | 28,295 | 21 | 15,043 | 177 | 127,982 |
| 1996 | 29 | 21,070 | 30 | 21,820 | 10 | 6,883 | 69 | 50,258 |
| 1997 | 21 | 15,099 | 22 | 16,197 | 14 | 9,795 | 62 | 44,975 |
| 1998 | 24 | 17,666 | 20 | 14,209 | 17 | 12,181 | 48 | 34,808 |
| 1999 | 29 | 21,110 | 19 | 13,820 | 19 | 13,483 | 34 | 24,489 |
| 2000 | 22 | 15,780 | 19 | 13,891 | 29 | 21,155 | 50 | 35,911 |
| 2001 | 22 | 15,727 | 13 | 9,774 | 36 | 26,426 | 50 | 36,057 |
| 2002 | 32 | 22,900 | 17 | 11,970 | 11 | 8,315 | 34 | 24,463 |
| 2003 | 29 | 21,021 | 7 | 5,336 | 12 | 9,024 | 16 | 11,939 |
| 2004 | na | na | 3 | 1,833 | 20 | 14,579 | 21 | 15,245 |
| 2005 | na | na | na | na | 31 | 22,646 | 35 | 25,410 |
| average | 35 | 25,135 | 21 | 14,883 | 107 | 77,250 | 170 | 123,180 |

# Appendix B: Comments and responses to the conceptual model report including questions and answers from the Second Stakeholder Advisory Forum for the Presidio-Redford Bolson Aquifer GAM held at the Presidio Activity Center on March 15, 2011

Comment 1. Can you provide a map showing the study area locations for each of the recharge estimate studies [Gates and others (1980), LBG-Guyton and Associates (2001), Gabaldon (1991), and Chowdhury and Wade, (in preparation)] that you reference in your presentation? And can you place them all on one map?

*Response 1. We have added Figure 4-7 which shows the estimates of recharge rates from Chowdhury and Wade (in prep). The other three references do not provide maps explicitly showing the location of the areas used to estimate recharge. Generally the study area for the references is the Presidio Bolson outcrop, and in at least one case, also the surrounding highland drainage areas. The Gates and others reference provides no specific information on the area used to estimate the recharge. For the LBG-Guyton and Associates reference the recharge area corresponds approximately to the outcrop of layer 3 shown in Figure 4-2. For the Gabaldon reference the recharge area corresponds to either the outcrop of layer 2 or the intersection between layer 2 and 3 outcrops (approximately the mountain front) depending on the version of the model.*

Comment 2. How old are the pumping estimates for the Mexico permits shown in your presentation?

*Response 2. The information was downloaded from the* Comisión National del Agua (CNA) website in early 2008.

Comment 3. The pumping estimates for Mexico are too low. There has been a recent increase in irrigation use derived from groundwater sources in Ojinaga, Mexico.

*Response 3. Our estimates of pumping locations and amounts for Mexico are meant as approximations only to represent historical use from 1946 through 2008. Historical use is likely to be less than the permitted amount and future use may be greater because of new permits. When we calibrate the model to historical water levels we will adjust our approximate estimates within 50 percent of permit values scaled to population to account for the uncertainty. Future predictive modeling will need to include additional information to account for possible new permits.*

Comment 4. Are groundwater sources permitted in Mexico? Because 2-300 new irrigation wells have been added in Ojinaga, Mexico to supply water to approximately 40,000 acres of crops.

*Response 4. Yes, water use is permitted in Mexico by the Comisión Nacional del Agua (CONAGUA). When the model is used for future predictions we will try to locate more recent land use coverages for Mexico within the project study area, and will look for additional sources of information that may be available for estimating permitted quantities for Ojinaga, Mexico.*

Comment 5. In your presentation, you show that there is no cross-flow with Mexico [slide showing groundwater flow directions and proposed model boundaries- Figure 4-6 of the report]. Is this correct?

*Response 5. The flow directions on Figure 4-6 are meant to represent historical flow directions and the model boundaries are based on surface water divides determined from topographic maps. We are assuming that the groundwater divides historically coincide with surface water divides and that under natural conditions groundwater moved from the mountain peaks to the center of the valley. The model will allow groundwater flow directions within the model to reverse across the center of the Rio Grande Valley if future pumping induces gradients across the valley.*

Comment 6. Is layer 3 in the model [igneous Aquifer and Permian and Cretaceous rocks] saturated throughout?

*Response 6. Yes, layer 3 is saturated throughout, but permeability is low so it is generally not considered a highly productive resource. Because of the low permeability for layer 3, cross-flow with layer 2 will generally only occur if a pumping well is placed in layer 3.*

Comment 7. How deep is the bottom of layer 3?

*Response 7. Most of the action occurs in the shallower portions, but the base of layer 3 is 2,500 feet below sea level over most of the model area. On the eastern side towards the topographic divide the base of layer 3 slopes upward to be consistent with the base of layer 3 in the groundwater availability model for the West Texas Bolsons (Wild Horse Flat, Michigan Flat, Ryan Flat, and Lobo Flat) and Igneous aquifers. The thickest portion of the bolson [layer 2] is approximately 5,000 feet.*

Comment 8. You show pumping estimates for Mexico and the United States, can you include pumping from the Shafter Silver Mine in your model? They resumed mining activities which will include dewatering the mine which is submerged.

*Response 8. The pumping estimates included in the model represent historical pre-2008 pumping and our information indicates that the Shafter Silver Mine well is located just outside the model boundary. The effects on water levels near the boundary due to pumping associated with mining activities in Shafter can be evaluated using the existing groundwater availability model for the Igneous and parts of the West Texas Bolsons aquifers.*

Comment 9. You mention using a lag time for recharge of approximately 30 years in the groundwater flow model. I have been monitoring rainfall for the past 5 years at my property, which is located within the mountains. Rainfall has been showing a declining trend over the past 5 years. In fact, rainfall amounts have been relatively lower in the mountains than in the valleys for the past 5 years. Rainfall is also highly variable throughout the study area. How does that fit into the model?

*Response 9. A 5-year trend is a relatively shorter time frame, we are aiming for capturing long-term conditions which may be more representative of average conditions. There is data on a relatively tighter scale known as Parameter-elevation Regressions on Independent Slopes Model [PRISM] that captures more of the spatial variability in rainfall than is shown among the 3 rainfall gages in the United States that are used in this presentation. The general conceptualization is that rainfall amounts are higher in the mountains relative to the valley.*

Comment 10. Are you using any of the information available from the Texas Natural Resources Information System [TNRIS]?

*Response 10. Yes, the Texas Natural Resources Information System [TNRIS] is a division of the Texas Water Development Board and we have used their geographic information for such things as rivers, county boundaries and cities and roads*

Comment 11. Are you using the State Soil Geographic Database [STATSGO] or the Soil Survey Geographic Database [SSURGO]?

*Response 11. No, we are not using the State Soil Geographic Database [STATSGO] or the Soil Survey Geographic Database [SSURGO] at this time. They provide detailed information at a scale that will not be replicated in the regional to sub-regional groundwater flow model under* *development. We are attempting to simulate general conditions and aquifer properties over a broader area, or at a larger scale.*

Comment 12. Are you using topographic data from the Texas Natural Resources Information System [TNRIS]? And if so, can you cite the reference and year?

*Response 12. The elevation data is the 1-second DEM (approximately 30-meters resolution) from the United States Geological Survey. This reference has been added to the report.*

Comment 13. Are you using any of the data available from the Instituto Nacional de Estadistica Geografia e Informatica [INEGI]? They may have more accurate data with respect to digital elevation models, vegetation, and land use for Mexico.

*Response 13. Yes, we have used information from surface and subsurface hydrology maps as well as geology maps from the Instituto Nacional de Estadistica Geografia e Informatica [INEGI].*

Comment 14. I'm curious why you are using/referencing vegetative cover from Pennsylvania State University in your presentation?

*Response 14. We are using the vegetative imagery from Pennsylvania State University for informative purposes, such as this presentation, as it shows vegetative cover for the United States and Mexico. We are not using the vegetative imagery from Pennsylvania State University in the groundwater flow model.*

Comment 15. Who have you coordinated with in the past that is from the International Boundary and Water Commission [IBWC]?

*Response 15. Mr. Rong Kuo.*

Comment 16. Can you provide us with a copy of your presentation in color?

*Response 16. Yes. It is available upon request.*

Comment 17. We found that there were portions of the Edwards-Trinity (Plateau) Aquifer that did not receive recharge when the percentage of annual recharge dropped below 10 percent. I would be interested in knowing at what percentage this occurs for this project site.

*Response 17. I would expect it is high for this project site, and will provide estimates when they become available.*

*Follow-up 17. As part of model calibration we will estimate the minimum annual precipitation that allows recharge.*

Comment 18. How deep is the bolson well that you show in close proximity to the alluvium well in your presentation, and do we know if it is a bolson well?

*Response 18. It is difficult to estimate how deep the bolson well is at this time without looking at the database, but it was originally identified as a bolson well based on its location and depth. (See Response to Comment 21 below).*

Comment 19. How deep are all the wells that you show in the presentation?

*Response 19. It is difficult to estimate at this time without looking at the database, but we can provide that information at a later date. (See Response to Comment 21 below).*

Comment 20. I believe you have done some groundwater sampling in this area. Can you identify the layers that the wells are located in based on your water quality analyses?

*Response 20. Yes, we have collected samples, but we do not analyze them internally. The collected samples are shipped to a laboratory which analyzes them and provides us with the results. You are correct; there is a difference in the water quality among the layers. Water samples collected from wells penetrating the bolson aquifer are generally fresher than samples collected from wells penetrating the alluvium aquifer. (See Response to Comment 21 below).*

Comment 21. Can you provide us with the well depths for all the wells shown in your presentation, especially for the bolson well and the alluvium well that are located next to each other?

*Response 21. Yes, we can provide the requested data.*

*Follow-up 18, 19 and 21. First pair of Presidio Bolson hydrographs – 5151807 well is 84 feet deep, 7430407 well is 84 feet deep; Second pair of Rio Grande Alluvium hydrographs – 5151802 well is 45 feet deep, IBWC well OW709 (7430820) no data for well depth at this time; third pair of hydrographs – 7439502 (Rio Grande Alluvium) well is 11 feet deep, 7439504 (Presidio Bolson) well is 214 feet deep. A screen shot for two wells from the TWDB WIID is shown on the following page.*

Comment 22. How deep are the city wells?

*Response 22. Several hundred feet, I believe that they are approximately 200 feet deep, but I will check our database and provide this information at a later date.*

*Follow-up 22. City of Presidio wells range in depth from 34 feet (drilled in 1929) to 537 feet (drilled in 2001).*

Comment 23. It appears that there is concern over groundwater pumping, has anyone looked at the laws or treaties for pumping groundwater between the United States and Mexico?

*Response 23. Our primary area of interest involves pumping in the United States. At this time, we are not aware of any international treaties associated with groundwater pumping for the project area.*

*Follow-up 23. We have reviewed the IBWC website and verified that there are no treaties regarding groundwater use in the study area. We plan to use the best available information on groundwater use in the model and if better information becomes available we will update the pumping information in the model.*

Comment 24. Are there any known artesian wells in this area?

*Response 24. There are 1 to 2 known artesian wells in the project area, but as I recall they are located in the Chinati Mountains.*

Comment 25. Page 6: What has been the historic evolution of population on the Mexican side? National Institute and Statistics, Geography, and Informatic (INEGI) could be a very good source to find out about it. (Section Study area)

*Response 25. We consulted the INEGI website and were able to locate the 2010 population of Ojinaga which we have added to the text. We were not able to easily locate historical population information on the website.*

Comment 26. Page 9: The Mexican Institute of Water Technology (IMTA) recently developed an study to investigate the current situation of Chihuaha State's Aquifers. Perhaps this would help you to understand more the Presidio aquifer in the Mexican side (End of Page)

*Response 26. Because of the short time frame to complete this report we have not yet had a chance to review the IMTA's report. However, we appreciate the information and we will review the report for future updates to the model.*

Comment 27 Page 12: Why not to use instead 10-meter DEM? (Section Top of Model)What was the criteria to select this number? (Section Base of Model)

*Response 27. The model grid cells are one quarter mile square. Therefore the 30 meter DEM should be of sufficient resolution. The base of the model was selected to be deep enough to ensure that pumping from deep wells can be included in the model without excessive drawdown resulting from proximity to a no-flow boundary. The base was also selected to be consistent with the base of the groundwater availability model for the West Texas Bolsons (Wild Horse Flat, Michigan Flat, Ryan Flat, and Lobo Flat) and Igneous aquifers*

Comment 28. Is that also applicable for wells located in the most important towns such as Ojinaga and Presidio? What are the implications of error associated with the implementation of this regression equation? (Section Water Levels and Regional Groundwater flow)

*Response 28. We agree with the reviewer that depth to water values near pumping centers are not very useful for regressing water level based on elevation; however, most of the water level data for the area were collected prior to any significant development. The water level information from the regression were used to create the map shown in Figure 4-6 but will not be used for model calibration.*

Comment 29. Page 15: Verify that you are not missing the complete name of the University: Universidad Nacional Autonoma de Mexico (Section Recharge)

*Response 29. We thank the reviewer for noticing this error and we have made the correction on page 15 and in the reference section.*

Comment 30 Page 16: How does a gaining and losing stream affect the estimation of baseflow separation? (Section Rivers and Streams)

*Response 30. The estimates of baseflow in this section assume a gaining stream and the Rio Grande is likely to be both gaining and losing through the model increasing the uncertainty of the baseflow estimates.*

Comment 31 Page 18: Please review this equation, it seems it is missing the Storativity (S) term. By the way, there is a caveat with using this equation in that S terms needs to be known, which is not always the case. What are the advantages of using this equations vs using empirical well known approaches such as : T = 2000(Q/sw) confined aquifer T = 1500(Q/sw) unconfined aquifer (Section Hydraulic Properties, Equation 3)

*Response 31. We appreciate the reviewer noting this typo in equation 3 and it has been corrected on page 18. The equation was correctly used for the calculations to estimate the transmissivity values, the error was only in the text. To use the equation we assumed values of storativity of 0.06 for the bolson and 0.18 for the Rio Grande alluvium.*

Comment 32. Page 26: This is not necessarily correct. It should be remembered that most of the time the average water consumption per capita in US is far greater than in Mexico. Ciudad Juarez and El Paso TX are a very good example of it. (Section Groundwater pumping)

*Response 32.We agree in general water consumption per capita in the United States is generally far greater than in Mexico. However, the difference between per capita use in Presidio, Texas and in Ojinaga, Mexico may be less extreme than the difference between per capita use in Ciudad Juarez compared with El Paso Texas. We also clarified in the text on page 26 that the total amount of permitted use in Mexico is approximately 9,000 acre-feet per year rather than total amount of actual use. Also please see our response to comment 3 above.*

Comment 33. Page 35: Permitted use is very different from actual use (which tends to be smaller). Please get in touch with CNA to define a more realistic water consumption in the region. (Section Conceptual model of groundwater flow in the aquifer)

*Response 33. Please see our response to comment 3 above.*

Comment 34. Page 59: Incorporate name of cities and towns. Include the aquifer's boundary. (Figure 2-18).

*Response 34. The figure is meant to show the regional geology and structure. Additional geographic details can be found in Figure 2-1.*

Comment 35. Page 69: Incorporate the location of the most important towns? (Figure

4-5).

*Response 35. The map is too small to include additional text. The town locations are shown in Figure 2-1.*

Comment 36. Page 74: Update hydrographs up to 2010. (Figure 4-10).

*Response 36. We have updated the streamflow hydrographs with data through 2010 in Figures 4-9, 4-10, and 4-11.*