Prepared in cooperation with the U.S. Army Corps of Engineers, New Mexico Interstate Stream Commission, Texas Commission on Environmental Quality, and Texas Water Development Board

Pecos River Basin Salinity Assessment, Santa Rosa Lake, New Mexico, to the Confluence of the Pecos River and the Rio Grande, Texas, 2015

Scientific Investigations Report 2019–5071

U.S. Department of the Interior
U.S. Geological Survey

Background, Pecos River above Santa Rosa Dam, New Mexico, upstream view. Photograph by Daniel Sinclair, U.S. Geological Survey, February 2015.

Front cover:

Top, Lea Lake at Bottomless Lakes State Park, New Mexico. Photograph by Johnathan Bumgarner, U.S. Geological Survey, October 2011.

Left, Pecos River at Independence Creek, Texas, downstream view. Photograph by Johnathan Bumgarner, U.S. Geological Survey, January 2012.

Right, Pecos River at Old Crane Road bridge, Texas, downstream view. Photograph by Christopher Braun, U.S. Geological Survey, February 2015.

Back cover:

Left, Pecos River at Red Bluff Reservoir outflow, Texas, downstream view. Photograph by Johnathan Bumgarner, U.S. Geological Survey, October 2011.

Right, Bitter Lake National Wildlife Refuge south weir inflow, New Mexico, downstream view. Photograph by Daniel Sinclair, U.S. Geological Survey, February 2015.

Bottom, Pecos River near Malaga, New Mexico, downstream view. Photograph by Daniel Sinclair, U.S. Geological Survey, February 2015.

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By Natalie A. Houston, Jonathan V. Thomas, Patricia B. Ging, Andrew P. Teeple, Diana E. Pedraza, and David S. Wallace

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U.S. Department of the Interior
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Figures

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic inch (in^3)	16.39	cubic centimeter (cm^3)
cubic inch (in^3)	0.01639	cubic decimeter (dm^3)
cubic inch (in^3)	0.01639	liter (L)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
gallon per day per square mile [$(gal/d)/mi^2$]	0.001461	cubic meter per day per square kilometer [$(m^3/d)/km^2$]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per day per square mile [$(Mgal/d)/mi^2$]	1,461	cubic meter per day per square kilometer [$(m^3/d)/km^2$]
	Mass	
ton, short (2,000 lb)	0.9072	metric ton (t)
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year

International System of Units to U.S. customary units

Multiply	By	To obtain
	Volume	
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as

°F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as

°C = (°F – 32) / 1.8.

Datum

Vertical coordinate information is referenced to either the North American Vertical Datum of 1988 (NAVD 88) or the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C). Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter and micrograms per liter are units expressing the concentration of chemical constituents in solution as mass of solute (milligrams or micrograms) per unit volume (liter) of water.

Isotope Unit Explanation

Per mil (‰): A unit expressing the ratio of stable-isotope abundances of an element in a sample to those of a standard material. Per mil units are equivalent to parts per thousand. Stable-isotope ratios are computed as follows (Kendall and McDonnell, 1998):

$$\delta X = \{(R_{sample} - R_{standard})/R_{standard}\} \times 1{,}000$$

where

- δ is the “delta” notation,
- X is the heavier stable isotope, and
- R is ratio of the heavier, less abundant isotope to the lighter, stable isotope in a sample or standard.

The δ values for stable-isotope ratios discussed in this report for hydrogen and oxygen are referenced to the following standard materials:

Element	R	Standard identity and reference
Hydrogen	Hydrogen-2/hydrogen-1 (δD)	Vienna Standard Mean Ocean Water (VSMOW) (Fritz and Fontes, 1980)
Oxygen	Oxygen-18/oxygen-16 ($\delta^{18}O$)	Vienna Standard Mean Ocean Water (VSMOW) (Fritz and Fontes, 1980)

Results for measurements of stable isotopes of an element (with symbol δ) in water, solids, and dissolved constituents commonly are expressed as the relative difference in the ratio of the number of the less abundant isotope ($^{i}\delta$) to the number of the more abundant isotope of a sample with respect to a measurement standard.

Abbreviations

ASTERv2	Advanced Spaceborne Thermal Emission and Reflection Radiometer version 2
BLM	Bureau of Land Management
BLNWR	Bitter Lake National Wildlife Refuge
BRACS	Brackish Resource Aquifer Characterization System
NMED	New Mexico Environment Department
NWIS	National Water Information System
ppm	part per million
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board
USGS	U.S. Geological Survey

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Abstract

The elevated salinity of the Pecos River throughout much of its length is of paramount concern to water users and water managers. Dissolved-solids concentrations in the Pecos River exceed 3,000 milligrams per liter in many of its reaches in the study area, from Santa Rosa Lake, New Mexico, to the confluence of the Pecos River with the Rio Grande, Texas. The salinity of the Pecos River increases downstream and affects the availability of useable water in the Pecos River Basin. In this report, "salinity" and "dissolved-solids concentration" are considered synonymous; both terms are used to refer to the total ionic concentration of dissolved minerals in water. The sources of salinity in the Pecos River Basin are natural (geologic) and anthropogenic, including but not limited to groundwater discharge, springs, and irrigation return flows. Previous studies in the Pecos River Basin were project specific and designed to address salinity issues in specific parts of the basin; therefore, in 2015, the U.S. Geological Survey in cooperation with the U.S. Army Corps of Engineers, New Mexico Interstate Stream Commission, Texas Commission on Environmental Quality, and Texas Water Development Board assessed the major sources of salinity throughout the extent of the basin where elevated salinity in the Pecos River is well documented (that is, in the drainage area of the Pecos River from Santa Rosa Lake to the confluence of the Pecos River and the Rio Grande). The goal was to gain a better understanding of how specific areas might be contributing to the elevated salinity in the Pecos River and how salinity of the Pecos River has changed over time. This assessment includes a literature review and compilation of previously published salinity-related data, which guided the collection of additional water-quality samples and streamflow gain-loss measurements. Differences in water quality of surface-water and groundwater samples, streamflow measurements, and geophysical data were assessed to gain new insights regarding sources of salinity in the Pecos River Basin and a more detailed assessment of potential areas of elevated salinity in the basin. The datasets compiled for this assessment are available in a companion data release.

The literature review identified several potential sources of salinity inputs to the Pecos River in New Mexico and Texas. In New Mexico, sources of salinity inputs included sinkhole springs discharging into El Rito Creek, the Bitter Lake National Wildlife Refuge inflow to the Pecos River, inflow from the Rio Hondo, including the main channel and a restored channel at the Bitter Lake National Wildlife Refuge referred to as the "Rio Hondo spring channel," the outflow from Lea Lake at Bottomless Lakes State Park, and the Malaga Bend region of the Pecos River. In Texas, sources of salinity inputs included Salt Creek downstream from Red Bluff Reservoir and the area near the Horsehead Crossing ford on the Pecos River.

The compilation of historical water-quality data revealed a lack of consistent sampling of the same constituents at the same sites along the main stem of the Pecos River, which results in data gaps that hinder the ability to effectively analyze long-term changes in water quality that may help with the understanding of how salinity in the Pecos River has changed over time and identifying the sources of salinity in the Pecos River Basin. To help fill these data gaps, water-quality and streamflow data were collected in the study area in February 2015 by the U.S. Geological Survey. Historical water-quality data and newly collected data from February 2015 were evaluated for selected major-ion concentrations, dissolved-solids concentrations, and deuterium, oxygen, and strontium isotopes. Analysis of the data indicated several areas of increasing salinity in the Pecos River. Most notable increases were in two subreaches of the river, between Acme, N. Mex., and Artesia, N. Mex., and between Orla, Tex., and Grandfalls, Tex. Increasing sodium and chloride concentrations from Acme to Artesia coincided with changes in isotopic ratios within the Pecos River Basin. Changes in isotopic ratios in this reach indicate a likely inflow from an isotopically different source of water compared to the water in the main stem of the Pecos River, such as groundwater inflow, inflow from surface-water features distinct from the main stem of the Pecos River, or both. In the subreach between Orla and Grandfalls, an increase in dissolved-solids concentrations was observed along with a shift in isotope values, indicating that neither evaporative processes in Red Bluff Reservoir nor inflow from Salt Creek likely solely influences the salinity of the Pecos River in this subreach. The highest

dissolved-solids concentrations in the Pecos River Basin were measured downstream from Grandfalls, where dissolved-solids concentrations are greater than 16,000 milligrams per liter near Iraan, Tex. Changes in isotopic values (deuterium, oxygen, and strontium) indicate mixing of different waters at several areas along the main stem of the Pecos River. The spatial distribution of the areas of interest from the literature review and the water-quality data are available in the companion data release.

Introduction

The Pecos River flows 926 miles south-southeast through eastern New Mexico and western Texas to its confluence with the Rio Grande at Amistad Reservoir near Del Rio, Tex. (fig. 1*A* and *B*). The Pecos River Basin covers approximately 44,000 square miles and ranges in elevation from more than 12,000 feet above the North American Vertical Datum of 1988 (NAVD 88) at the headwaters of the river to approximately 1,100 feet at its confluence with the Rio Grande. The headwaters of the Pecos River, although not part of this study, are located north of Pecos, N. Mex., on the western slope of the Sangre de Cristo Mountains in San Miguel and Mora Counties. The Sangre de Cristo, Sacramento, Guadalupe, Delaware, Apache, and Glass Mountains rim the basin along the western side. The basin also includes the Capitan Mountains near Rio Bonito, N. Mex., and the Davis Mountains near Fort Davis, Tex. Much of the northeastern side of the basin is rimmed by the Llano Estacado. The Pecos River provides inflows to Amistad Reservoir, which is an international water resource managed jointly by the governments of the United States and Mexico through the International Boundary and Water Commission (Texas Water Development Board, 2016c). Although the Pecos River is not directly used as a drinking water source, Amistad Reservoir is used as a drinking water source (Safe Drinking Water Information System, 2017a, b). The Pecos River also is an important source of water for irrigation, livestock, wildlife habitat, and recreation (Texas State Soil and Water Conservation Board, 2009). The flow of the river has decreased because of growing demands for water, construction of reservoirs, reservoir management practices, and increasing climate variability (Yuan and others, 2007).

The elevated salinity of the Pecos River throughout much of its length is of paramount concern to water users and water managers. Dissolved-solids concentrations in the Pecos River exceed 3,000 milligrams per liter (mg/L) in many of its reaches in the study area, from Santa Rosa Lake, N. Mex., to the confluence of the Pecos River with the Rio Grande, Tex. (Miyamoto and others, 2006) (fig. 1*A* and *B*). In this report, “salinity” and “dissolved-solids concentrations” are considered synonymous; both terms are used to refer to the total ionic concentration of dissolved minerals in water (Winslow and Kister, 1956; Calfed Bay-Delta Program, 2007). There are two main processes that increase salinity in river systems such as the Pecos River. The first process is the addition of dissolved solids from an external source by the discharge of saline groundwater and irrigation return flows. The second process is the removal of fresher water by diversion for irrigation or by evapotranspiration resulting in the increase of dissolved solids because less water is available for dilution. Sources of salinity from both types of processes can be either natural or anthropogenic (Anning and others, 2007). This report is primarily focused on identifying and documenting areas where there are additions of dissolved solids to the Pecos River from external sources.

The sources of salinity in the Pecos River Basin are typically salts such as sodium chloride and calcium sulfate; throughout the course of the Pecos River in New Mexico and Texas, the salinity of the river primarily increases because of the discharge of saline groundwater and irrigation return flows (see for example Summers, 1972; Texas Water Development Board, 1972; Hoagstrom, 2009; Meyer and others, 2012). As a result, the dissolved-solids concentration of water entering Texas averages about 6,000 mg/L, whereas downstream, at Girvin, Tex., the dissolved-solids concentration averages about 12,000 mg/L (Miyamoto and others, 2006, 2008). Winslow and Kister (1956) defined water with a dissolved-solids concentration less than 1,000 parts per million (ppm, equivalent to milligrams per liter) as freshwater and defined saline water as water that contains greater than 1,000 mg/L of dissolved solids. Saline water is used in lieu of freshwater for many purposes in the Pecos River Basin (see for example Mourant and Shomaker, 1970; Miyamoto and others, 2006, 2008). Water is defined as slightly saline when the dissolved-solids concentration ranges from 1,000 to 3,000 mg/L (Winslow and Kister, 1956). Water is defined by Winslow and Kister (1956) as moderately saline, very saline, and brine when the dissolved-solids concentrations range from 3,000 to 10,000 mg/L, range from 10,000 to 35,000 mg/L, and are greater than 35,000 mg/L, respectively. Winslow and Kister (1956) stated that water that contains a dissolved-solids concentration of less than 3,000 mg/L is suitable for irrigation. Higher saline water (greater than 3,000 mg/L) affects the availability of useable water for agriculture, livestock, and recreation (Anning and others, 2007). Many researchers have documented high salinity in the Pecos River Basin (hereinafter referred to as the “basin”). Although studies have been done to help identify and document the sources of salinity to the basin, the need to better understand the sources of salinity remains (Miyamoto and others, 2006; Yuan and others, 2007; Hoagstrom, 2009; Gregory and others, 2014).

Along the Pecos River, five major dams control the flow of the water: Santa Rosa, Sumner, Brantley, and Avalon Dams in New Mexico and Red Bluff Dam in Texas (fig. 1*A* and *B*). Apportionment of water resources of the Pecos River is governed by the Pecos River Compact, which was signed by New Mexico and Texas in 1948. Among its goals, the compact provides for the equitable division of the use of the Pecos River waters and promotes comity between the two States (U.S. Congress, 1949). The Pecos River Compact created the Pecos River Commission and requires the State of New Mexico to deliver a certain quantity of water to Texas each year (Kraai, 1993). As a result of a U.S. Supreme Court Amended Decree in 1988, a river master was appointed to oversee the accounting of deliveries according to a specific set of accounting rules (Thorson, 2003). Essentially, New Mexico is required to deliver to Texas approximately 45 percent of the water that flows past Sumner Dam plus a percentage of any flood water between Sumner Dam and the Texas State line (Thorson, 2003) based on a 3-year average and indexed to flows representing 1947 watershed conditions.

To help fulfill its Pecos River Compact obligations, the State of New Mexico entered into the Carlsbad Project Settlement Agreement between the Bureau of Reclamation, Pecos Valley Artesian Conservancy District, and Carlsbad Irrigation District. The settlement allowed the State of New Mexico to purchase water rights, retire irrigated farmland, and construct augmentation well fields (Thorson, 2003; Elhassan and others, 2006). During years when there is a shortfall in precipitation and snowmelt runoff, New Mexico may need to pump water from the wells in the augmentation well fields and deliver it to the Pecos River through a system of pipes, although as of 2017 no water had been pumped from these wells to fulfill the compact. There is no language in the Pecos River Compact limiting the salinity of water delivered to Texas from New Mexico (Miyamoto and others, 2006; Reimus and others, 2012). The compact does provide for construction of works for water salvage, more efficient water use, and flood protection. Water salvage has been interpreted to include water recovered for beneficial uses by improving the water quality. Therefore, improving the water quality in the basin also is a priority of the Pecos River Commission (U.S. Congress, 1949).

Past studies have been completed in the basin by many local, State, and Federal agencies to gain a better understanding of where salinity increases or to assess other water-quality issues. However, most of these studies were project specific and designed to address salinity issues in specific parts of the basin. In 2015, the U.S. Geological Survey (USGS) in cooperation with the U.S. Army Corps of Engineers, New Mexico Interstate Stream Commission, Texas Commission on Environmental Quality, and Texas Water Development Board completed an assessment of the major sources of salinity to the Pecos River in the reaches from Santa Rosa Lake to the confluence of the Pecos River with the Rio Grande.

Purpose and Scope

The purpose of this report is to identify the sources of salinity in the study area (the part of the basin from Santa Rosa Lake to the confluence of the Pecos River and the Rio Grande). The Pecos River in the study area was divided into four reaches, and the changes in salinity were evaluated by subreach using a combination of methods including an extensive literature review, compilation of geophysical data and existing water-quality data from multiple agencies, and the collection of water-quality data at 26 sites in February 2015. Differences in the water quality of surface-water and groundwater samples and streamflow measurements were assessed to gain insights regarding sources of salinity including locations where saline groundwater might be upwelling or discharging into the Pecos River in the study area. The concentrations of salinity-related constituents and selected isotopes are described; some of the historical and all of the newly collected data are summarized, and areas where saline groundwater likely enters the Pecos River in the study area are also described. Selected isotopes were measured to aid in identifying sources, ages, and movement of saline groundwater. The chemical properties of water are described in context of the geologic setting of the study area.

To aid in the understanding of how the underlying geology may contribute to the salinity of the Pecos River in the study area, the horizontal extent of and depth to the base of the geologic units that underlie the study area were mapped. All of the data compiled for this study are available in a companion data release (Houston and others, 2019).

Description of the Study Area

The study area is defined by the Pecos River Basin extent from Santa Rosa Lake, N. Mex., to the confluence of the Pecos River with the Rio Grande, upstream from Amistad Reservoir (fig. 1*A* and *B*). Compared to the rest of the basin, the upper part of the basin from the headwaters to Santa Rosa Lake contains relatively low concentrations of dissolved solids and was not included in this study (U.S. Geological Survey, 2017b). Multiple tributaries empty into the Pecos River in the study area, and most of these tributaries flow into the Pecos River from the west. The major tributaries that empty into the Pecos River from the west include (from north to south) the Rio Hondo, Rio Felix, Rio Peñasco, North and South Seven Rivers, and Black River in New Mexico and the Delaware River, Salt Creek, and Independence Creek in Texas. The major tributaries that empty into the Pecos River from the east include Taiban Creek, near Fort Sumner, N. Mex., and Live Oak Creek near Sheffield, Tex.

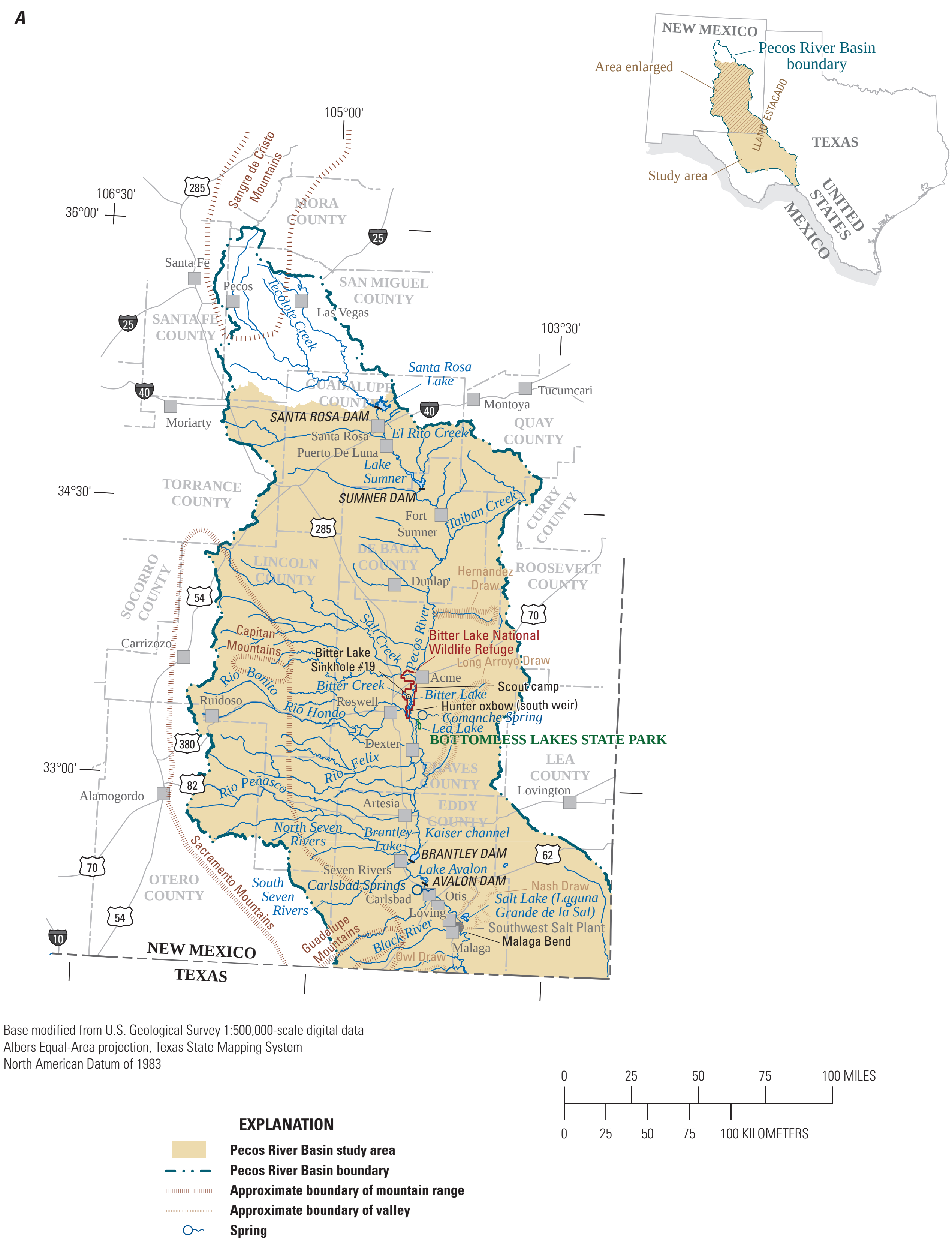

Figure 1. *A*, Pecos River Basin study area in New Mexico and *B*, Pecos River Basin study area in Texas.

Figure 1. *A*, Pecos River Basin study area in New Mexico and *B*, Pecos River Basin study area in Texas.—Continued

Geologic and Hydrogeologic Setting

Much of the basin is a karstic landscape, and the rocks that underlie the basin are soluble. Solution-enlarged fractures in karst terrane facilitate the movement of water and chemical interactions between the minerals in the rocks and the water moving through the rocks (rock-water interactions) that can change the chemical composition of groundwater (Warren, 2005; Stafford and others, 2009). Rock-water interactions in karst terrane also promote the formation of sinkholes, caves, and other karst features (Maclay, 1995; Ferrill and others, 2004; Musgrove and others, 2009). The basin contains numerous solution-enlarged fractures that have resulted in the formation of sinkholes, caves, and other karst features. Depending on the depth of these karst features, connectivity to the groundwater system, and the potential upwelling of older, more saline groundwater, these features may provide pathways for saline water to make its way to the Pecos River. Sedimentary rocks from the Pennsylvanian, Permian, Triassic, Cretaceous, Tertiary, and Quaternary (alluvium) Periods are commonly present in the subsurface, and many are exposed at the surface in the study area (Texas Water Development Board, 1972). This study focuses on the soluble subsurface rocks deposited from the Permian to the Quaternary Period. Thomas (1963, p. G-3) wrote, “soluble rocks are of critical importance in the hydrology of the Pecos River Basin, especially in the parts that lie in New Mexico. Strata of limestone, anhydrite and gypsum, halite [the mineral form of sodium chloride], and other evaporites (including the valuable mineral sylvite) were deposited about 200 million years ago during the Permian Period.”

Much of the southern part of the study area is in the Permian Basin (fig. 2), which is a sedimentary basin formed during the early Paleozoic Era and filled during the middle Paleozoic Era (Hills, 1972). During the Permian Period, parts of eastern New Mexico and western Texas (including the study area) were covered by a shallow ocean or sea with restricted circulation, and marine sandstone, limestone, and shale were deposited in the Permian Basin. In the later part of the Permian Period, the Permian Basin became isolated, and the sedimentary deposits changed to gypsum, anhydrite, halite, and associated salts including potash (Hills, 1972). These evaporite deposits can contribute large amounts of natural salt that increase salinity to parts of the Pecos River and its tributaries (Thomas, 1963).

Several geologic structures in the study area formed during the Paleozoic Era (fig. 2). The Central Basin Platform is a structural high in the northern part of Pecos County that divided the Permian Basin into the Delaware Basin to the west and the Midland Basin to the east (Hills, 1972; Ashworth, 1990; Land, 2003; Meyer and others, 2012). The Val Verde Basin was separated from the Delaware Basin by the development of the Capitan Reef during the Permian Period (Hills, 1972; Small and Ozuna, 1993). The Delaware Basin contains complex karstic terrain that formed because of the differential dissolution of evaporite units found in the Castile, Salado, and Rustler Formations (Warren, 2005). The Roswell Basin is in an area called the northwest shelf, north of the Capitan Reef (Land, 2003). Havenor (1996, 2003) described the Roswell Basin as a series of en echelon subbasins. Gross (1982) stated that these en echelon subbasins (or more precisely, the fault blocks that bound these en echelon subbasins) control groundwater flow in the Roswell Basin.

Dissolution of Permian-age evaporite deposits that began at the time of deposition and continued through the Cretaceous Period caused the Permian-age beds to collapse and form a north-south depositional trough called the Belding-Coyanosa Trough (fig. 2) (Armstrong and McMillion, 1961; Boghici, 1997). By the Triassic Period, the sea retreated, which led to a sequence of nondeposition (evidenced by nondepositional unconformities) (Tomkeieff, 1962), erosion, and then deposition of fluvial and deltaic sediments. During the Jurassic Period, the region of western Texas and eastern New Mexico that includes the study area was above sea level, erosion was the dominant process, and the land surface was tilted to the southeast (Barker and Ardis, 1996). Small remnants of Jurassic-age rocks are present approximately 30 miles southeast of Santa Rosa, N. Mex., near the boundary of the basin (Summers, 1972; Bachman, 1984), but the minor extent of the Jurassic-age rocks was not included in the depictions of the geology and hydrogeology for the study area (figs. 3 and 4). During the Cretaceous Period, sea level once again rose, and the deposition of continental sediments changed to the deposition of shallow marine sediments (Barker and Ardis, 1996). Although absent from a large part of the study area in New Mexico, Cretaceous rocks are present in the same part of the study area in New Mexico where Jurassic-age rocks are found (Summers, 1972; Bachman, 1984). Cretaceous deposition occurred primarily in Texas and included the filling of the structural troughs that began forming in the Permian and Triassic Periods.

Tertiary Period volcanism deposited extrusive igneous rocks following the Cretaceous marine deposition (George and others, 2011). Continental sediments of sand and gravel were deposited during the Tertiary and Quaternary Periods (Texas Water Development Board, 1972).

During the Cenozoic Era, two depositional troughs that roughly trend north to south formed in the central and western parts of the study area because of the continued dissolution of the Permian-age evaporite deposits and collapse of the overlying sediments (Armstrong and McMillion, 1961; Meyer and others, 2012). These troughs subsequently filled with Cenozoic-age alluvium and are known as the Monument Draw (central) and Pecos (western) Troughs (fig. 2). In this report the term “Monument Draw Trough” is used to represent both the Cenozoic-age Monument Draw and Permian- to Cretaceous-age Belding-Coyanosa Troughs (fig. 2) because the spatial extents and separation of these structural features are not well defined.

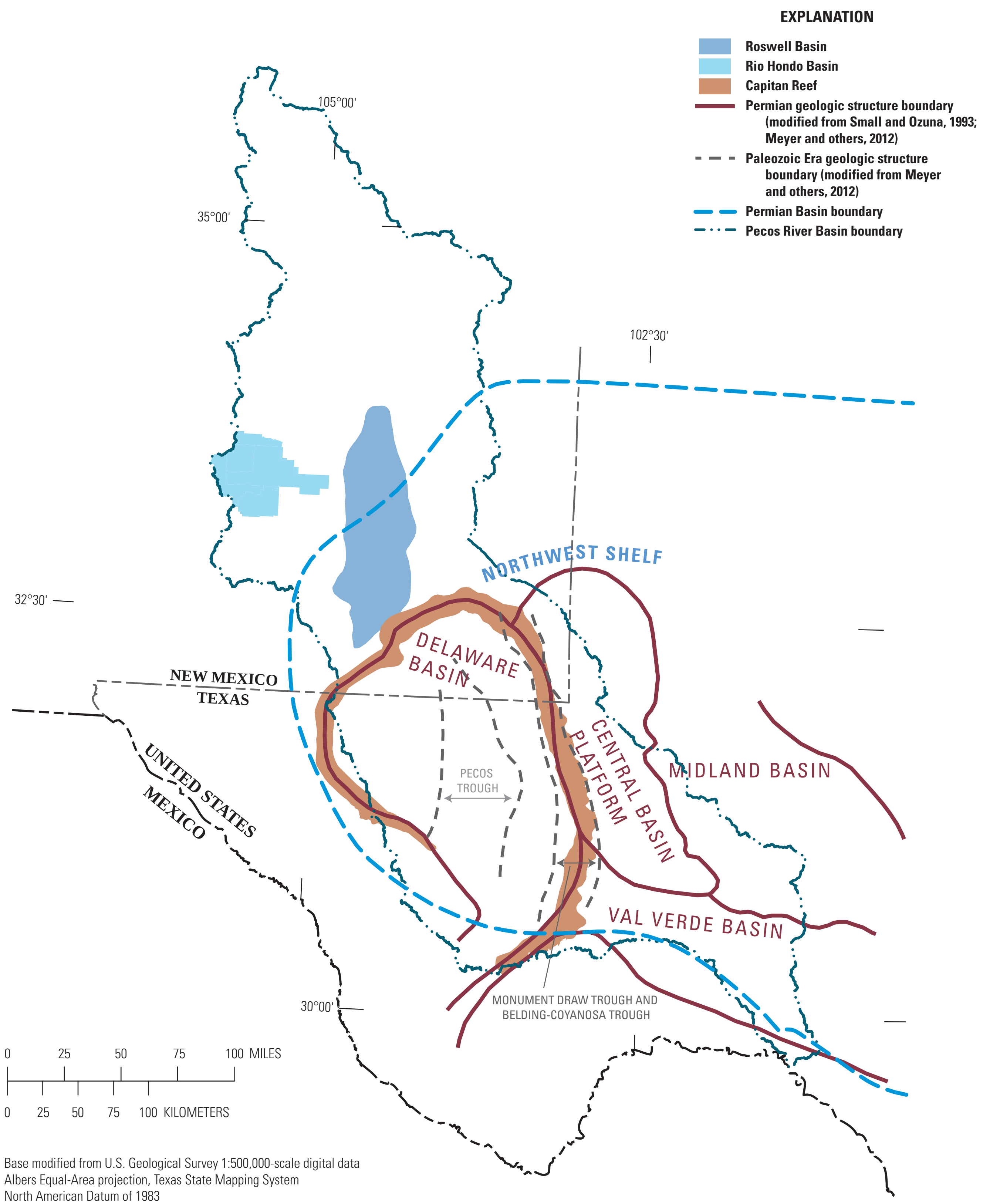

Figure 2. Generalized boundaries of geologic structural features in the Pecos River Basin, New Mexico and Texas.

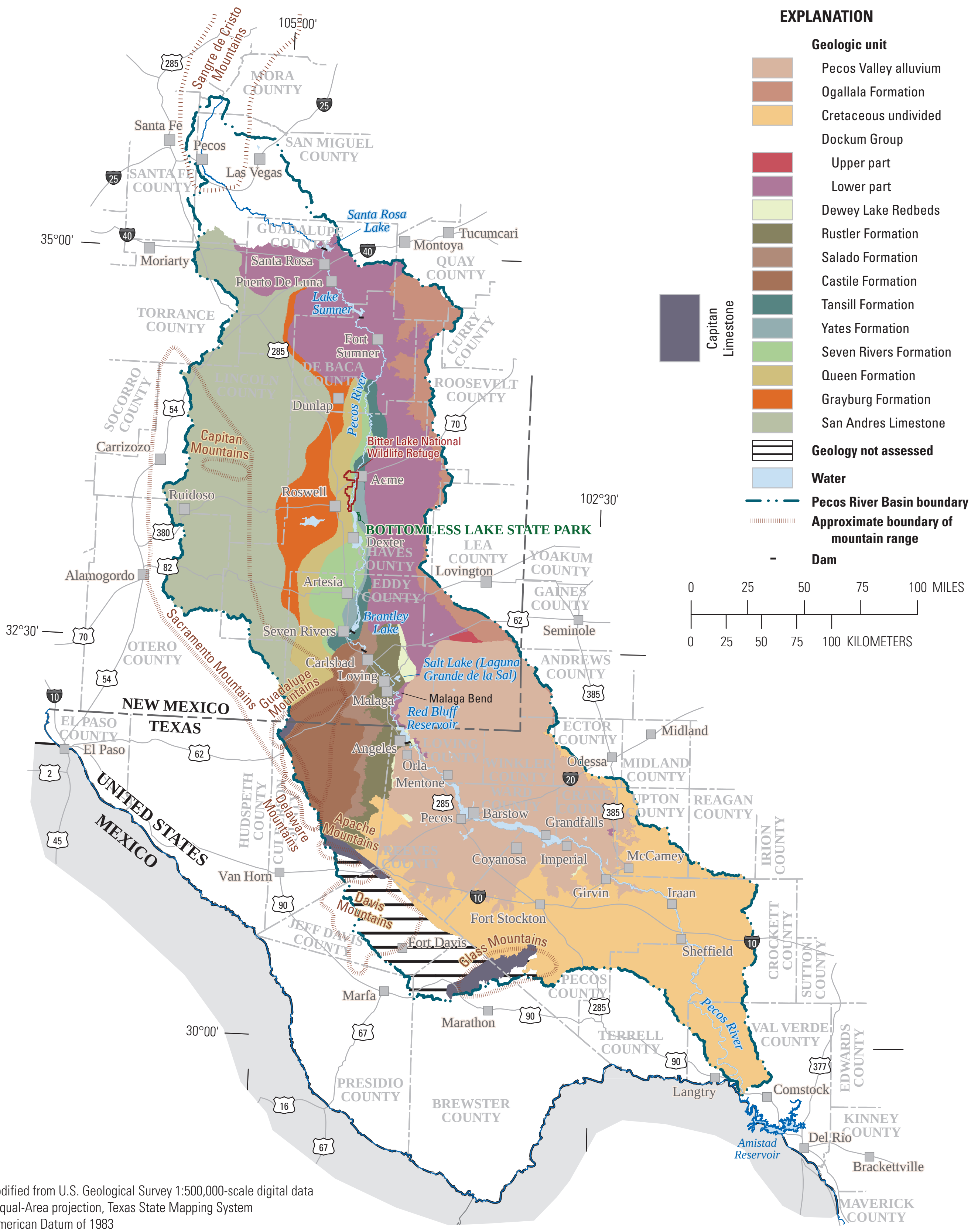

Figure 3. Geologic extents of the uppermost (top) geologic units of interest (and their hydrogeologic-unit equivalents) in the Pecos River Basin, New Mexico and Texas.

Modified from Robson and Banta (1995), New Mexico Interstate Stream Commission and New Mexico Office of the State Engineer (2002), and Pearson and others (2012)

Era	Period[1]	Series or group		Mapped geologic unit[2]	Aquifer name or hydrogeologic unit description (where present)		
					New Mexico		Texas
Cenozoic	Quaternary and Early Tertiary	Miocene		Pecos Valley alluvium	Pecos River Basin alluvial aquifer		Pecos Valley aquifer
Cenozoic	Tertiary	Late Miocene to Pliocene		Ogallala Formation	High Plains aquifer		*
Mesozoic	Cretaceous	Gulfian Series	Terlingua Group	Cretaceous undivided	*		**
Mesozoic	Cretaceous	Comanchean Series[3]	Washita Group	Cretaceous undivided	*		Edwards-Trinity aquifer system
Mesozoic	Cretaceous	Comanchean Series[3]	Fredericksburg Group	Cretaceous undivided	*		Edwards-Trinity aquifer system
Mesozoic	Cretaceous	Comanchean Series[3]	Trinity Group	Cretaceous undivided	*		Edwards-Trinity aquifer system
Mesozoic	Triassic	Dockum Group		Upper part of the Dockum Group	Sandstone and shale aquifer		Dockum aquifer
Mesozoic	Triassic	Dockum Group		Lower part of the Dockum Group	Sandstone and shale aquifer		Dockum aquifer
Paleozoic	Permian	Ochoan Series		Dewey Lake Redbeds	**		**
Paleozoic	Permian	Ochoan Series		Rustler Formation[4]	Limestone, sandstone, and shale aquifers		Rustler aquifer
Paleozoic	Permian	Ochoan Series		Salado Formation	**		**
Paleozoic	Permian	Ochoan Series		Castile Formation	**		**
Paleozoic	Permian	Guadalupian Series	Artesia Group	Tansill Formation; Capitan Limestone	***	Part of the Capitan Reef aquifer	Part of the Capitan Reef aquifer
Paleozoic	Permian	Guadalupian Series	Artesia Group	Yates Formation; Capitan Limestone	***	Part of the Capitan Reef aquifer	Part of the Capitan Reef aquifer
Paleozoic	Permian	Guadalupian Series	Artesia Group	Seven Rivers Formation; Capitan Limestone	***	Part of the Capitan Reef aquifer	Part of the Capitan Reef aquifer
Paleozoic	Permian	Guadalupian Series	Artesia Group	Queen Formation	SCU[5]	Goat Seep Limestone[6]	*
Paleozoic	Permian	Guadalupian Series	Artesia Group	Grayburg Formation	Artesian aquifer of the Roswell Basin aquifer system[7]	Goat Seep Limestone[6]; Limestone, sandstone, and shale aquifer	*
Paleozoic	Permian	Guadalupian Series		San Andres Limestone	Artesian aquifer of the Roswell Basin aquifer system[7]	Limestone, sandstone, and shale aquifer	*
Paleozoic	Permian	Leonardian Series		San Andres Limestone	LCU[8]	Limestone, sandstone, and shale aquifer	*

[1]The geospatial extent of Jurassic-age rocks in the study area was insufficient to justify inclusion in depictions of the geology and hydrogeology.
[2]As agreed upon by the authors.
[3]As defined by Murray (1961).
[4]Because of the regional nature of this study, the authors mapped the Rustler Formation as undivided throughout its extent.
[5]Semiconfining unit.
[6]Goat Seep Limestone part of the Capitan Reef aquifer was not included in the geologic map of the study area.
[7]Roswell Basin shallow alluvial aquifer not depicted.
[8]Lower confining unit.
*Not applicable—no surficial expression in the State in question within the study area.
**Not known to yield water in wells in the study area.
***Yields small amounts of water for local use.

Figure 3. Geologic extents of the uppermost (top) geologic units of interest (and their hydrogeologic-unit equivalents) in the Pecos River Basin, New Mexico and Texas.—Continued

Era	Period[1]	Series or group	Stratigraphic unit: Upper part of the Pecos River Basin in New Mexico (modified from Matherne and Stewart, 2012)	Stratigraphic unit: Roswell Basin–northwest shelf and Rio Hondo Basin (modified from Kelley, 1971; Harris, 1987; Land, 2003; Stafford, 2013)	Stratigraphic unit: Delaware Basin (modified from Harris, 1987; Powers and Holt, 1999; Land, 2003; Standen and others, 2009; Stafford, 2013)
Cenozoic	Quaternary and Early Tertiary	Holocene to Pleistocene	Alluvium	Pecos Valley alluvium	Pecos Valley alluvium
Cenozoic	Quaternary and Early Tertiary	Holocene to Pleistocene	Alluvium	Gatuna Formation	Gatuna Formation
Cenozoic	Tertiary	Late Pleistocene to Oligocene	Hiatus or interruption in the continuity of the rock record	Ogallala Formation	Ogallala Formation
Cenozoic	Tertiary	Late Pleistocene to Oligocene	Hiatus or interruption in the continuity of the rock record	Sierra Blanca Volcanics	Sierra Blanca Volcanics
Mesozoic	Cretaceous	Gulfian Series: Terlingua Group	Hiatus or interruption in the continuity of the rock record	Mesaverde Formation	Hiatus or interruption in the continuity of the rock record
Mesozoic	Cretaceous	Comanchean Series[3]: Washita Group	Hiatus or interruption in the continuity of the rock record	Mesaverde Formation	Hiatus or interruption in the continuity of the rock record
Mesozoic	Cretaceous	Comanchean Series[3]: Fredericksburg Group	Hiatus or interruption in the continuity of the rock record	Mancos Shale	Hiatus or interruption in the continuity of the rock record
Mesozoic	Cretaceous	Comanchean Series[3]: Trinity Group	Hiatus or interruption in the continuity of the rock record	Mancos Shale; Dakota Sandstone	Hiatus or interruption in the continuity of the rock record
Mesozoic	Triassic	Dockum Group	Upper: Chinle Formation	Upper: Cooper Canyon Formation[4]	Upper: Cooper Canyon Formation[4]
Mesozoic	Triassic	Dockum Group	Upper: Chinle Formation	Upper: Trujillo Formation	Upper: Trujillo Formation
Mesozoic	Triassic	Dockum Group	Lower: Santa Rosa Sandstone	Lower: Tecovas Formation	Lower: Tecovas Formation
Mesozoic	Triassic	Dockum Group	Lower: Santa Rosa Sandstone	Lower: Santa Rosa Sandstone	Lower: Santa Rosa Sandstone
Paleozoic	Permian	Ochoan Series	Hiatus or interruption in the continuity of the rock record	Dewey Lake Redbeds	Dewey Lake Redbeds
Paleozoic	Permian	Ochoan Series	Hiatus or interruption in the continuity of the rock record	Rustler Formation: Forty-niner Member	Rustler Formation: Forty-niner Member
Paleozoic	Permian	Ochoan Series	Hiatus or interruption in the continuity of the rock record	Rustler Formation: Magenta Dolomite Member	Rustler Formation: Magenta Dolomite Member
Paleozoic	Permian	Ochoan Series	Hiatus or interruption in the continuity of the rock record	Rustler Formation: Tamarisk Member	Rustler Formation: Tamarisk Member
Paleozoic	Permian	Ochoan Series	Hiatus or interruption in the continuity of the rock record	Rustler Formation: Culebra Dolomite Member	Rustler Formation: Culebra Dolomite Member
Paleozoic	Permian	Ochoan Series	Hiatus or interruption in the continuity of the rock record	Rustler Formation: Los Medaños member[6]	Rustler Formation: Los Medaños member[6]
Paleozoic	Permian	Ochoan Series	Hiatus or interruption in the continuity of the rock record	Salado Formation	Salado Formation
Paleozoic	Permian	Ochoan Series	Hiatus or interruption in the continuity of the rock record	Castile Formation	Castile Formation
Paleozoic	Permian	Guadalupian Series: Artesia Group	Artesia Group: Tansill Formation	Artesia Group: Tansill Formation; Capitan Limestone	Capitan Limestone; Delaware Mountain Group: Bell Canyon Formation
Paleozoic	Permian	Guadalupian Series: Artesia Group	Artesia Group: Yates Formation	Artesia Group: Yates Formation; Capitan Limestone	Capitan Limestone; Delaware Mountain Group: Bell Canyon Formation
Paleozoic	Permian	Guadalupian Series: Artesia Group	Artesia Group: Seven Rivers Formation	Artesia Group: Seven Rivers Formation; Capitan Limestone	Capitan Limestone; Delaware Mountain Group: Bell Canyon Formation
Paleozoic	Permian	Guadalupian Series: Artesia Group	Artesia Group: Queen Formation	Artesia Group: Queen Formation; Goat Seep Limestone	Goat Seep Limestone; Delaware Mountain Group: Cherry Canyon Formation
Paleozoic	Permian	Guadalupian Series: Artesia Group	Artesia Group: Grayburg Formation	Artesia Group: Grayburg Formation; Goat Seep Limestone	Goat Seep Limestone; Delaware Mountain Group: Cherry Canyon Formation
Paleozoic	Permian	Guadalupian Series	San Andres Limestone	San Andres Limestone	Delaware Mountain Group: Brushy Canyon Formation
Paleozoic	Permian	Guadalupian Series	Glorieta Sandstone	San Andres Limestone	Cutoff Formation
Paleozoic	Permian	Leonardian Series	Yeso Formation	Yeso Formation / Upper Victorio Peak Limestone	Bone Spring Limestone

[1]The geospatial extent of Jurassic-age rocks in the study area was insufficient to justify inclusion in depictions of the geology and hydrogeology.
[2]As agreed upon by the authors.
[3]As defined by Murray (1961).
[4]Although referred to as "Cooper Member" in the National Geologic Map Database (U.S. Geological Survey, 2017a), since about 1994, this unit has been referred to as the "Cooper Canyon Formation" in New Mexico Bureau of Mines publications (Lehman, 1994).
[5]Because of the regional nature of this study, the authors mapped the Rustler Formation as undivided throughout its extent.
[6]Although referred to as "Virginia Draw Member" in the National Geologic Map Database (U.S. Geological Survey, 2017a), since about 1993 this unit has been referred to as the "Los Medaños member" in the journal of New Mexico Geology (Powers and Holt, 1999).

Figure 4. Hydrostratigraphic section in the Pecos River Basin study area, New Mexico and Texas (modified from Kelley, 1971; Rees and Buckner, 1980; Harris, 1987; Small and Ozuna, 1993; Powers and Holt, 1999; Land, 2003; Standen and others, 2009; Ewing and others, 2012; Matherne and Stewart, 2012; Pearson and others, 2012; Stafford, 2013).

Stratigraphic unit					Mapped geologic unit[2]			General lithology
Red Bluff Reservoir–upper part of the Pecos River Basin in Texas (modified from Standen and others, 2009; Ewing and others, 2012)		Lower part of the Pecos River Basin in Texas (modified from Rees and Buckner, 1980; Small and Ozuna, 1993; Pearson and others, 2012)						
Pecos Valley alluvium and dissolution trough fill		Hiatus or interruption in the continuity of the rock record			Pecos Valley alluvium			Alluvial/eolian deposits sand/silt/gravel/clay/caliche
Hiatus or interruption in the continuity of the rock record		Hiatus or interruption in the continuity of the rock record			Ogallala Formation			Sand/clay/gravel
Hiatus or interruption in the continuity of the rock record		Boquillas Formation			Cretaceous undivided			Marl/limestone
		Buda Limestone						
		Georgetown Formation						Limestone/clay/sand/shale
		Edwards Limestone						
		Trinity Sand	Maxon Sand					
			Glen Rose Formation					
			“Basal” sand (informal)					
Upper	Cooper Canyon Formation[4]	Upper	Cooper Canyon Formation[4]		Upper part of the Dockum Group			Siltstone/mudstone/sandstone/ conglomerate/shale
	Trujillo Formation		Trujillo Formation					
Lower	Tecovas Formation	Lower	Tecovas Formation		Lower part of the Dockum Group			Mudstone/sandstone/conglomerate
	Santa Rosa Sandstone		Santa Rosa Sandstone					
Dewey Lake Redbeds		Dewey Lake Redbeds			Dewey Lake Redbeds			Shale/sand/sandstone/conglomerate
Rustler Formation	Forty-niner Member	Rustler Formation	Forty-niner Member		Rustler Formation[5]			Shale/silt/sandstone/dolomite/ halite/gypsum/anhydrite
	Magenta Dolomite Member		Magenta Dolomite Member					
	Tamarisk Member		Tamarisk Member					
	Culebra Dolomite Member		Culebra Dolomite Member					
	Lower gypsum and mud (informal)		Los Medaños member[6]					
	Siltstone (informal)							
Salado Formation		Salado Formation			Salado Formation			Halite/anhydrite/clay with beds of postash salts
Castile Formation		Castile Formation			Castile Formation			Anhydrite/calcite-banded anhydrite/halite minor amounts of limestone/sandstone
Delaware Mountain Group	Bell Canyon Formation	Artesia Group	Tansill Formation	Capitan Limestone	Tansill Formation	Capitan Limestone	Limestone/dolomite	Dolomite/anhydrite/siltsone/clay/gypsum
			Yates Formation		Yates Formation			Sandstone/dolomite/limestone/siltstone
			Seven Rivers Formation		Seven Rivers Formation			Anhydrite/dolomite/gypsum/silt/clay
	Cherry Canyon Formation		Queen Formation		Queen Formation			Sandstone/dolomite/anhydrite
			Grayburg Formation		Grayburg Formation			Dolomite/sandstone/anhydrite
	Brushy Canyon Formation	San Andres Limestone			San Andres Limestone			Limestone/dolomite/gypsum/anhydrite
Bone Spring Limestone								

Figure 4. Hydrostratigraphic section in the Pecos River Basin study area, New Mexico and Texas (modified from Kelley, 1971; Rees and Buckner, 1980; Harris, 1987; Small and Ozuna, 1993; Powers and Holt, 1999; Land, 2003; Standen and others, 2009; Ewing and others, 2012; Matherne and Stewart, 2012; Pearson and others, 2012; Stafford, 2013).—Continued

The geologic and hydrogeologic setting contributed to the development of the aquifers in the study area. The States of New Mexico and Texas use different approaches to define the boundaries of their aquifers and in some cases use different names for aquifers that formed during the same geologic time period. It is important to describe these differences so that the following discussion about the aquifers will be better understood. In New Mexico, aquifers are defined as groundwater basins, aquifers, or both (Land, 2016b). There are 39 declared groundwater basins defined in New Mexico, and each basin contains a source of groundwater that the State of New Mexico has jurisdiction over regulation of use (New Mexico Interstate Stream Commission and New Mexico Office of the State Engineer, 2018). Additionally, statewide there are nine defined major and minor aquifers in New Mexico, some of which may be included in one of the groundwater basins (New Mexico Interstate Stream Commission and New Mexico Office of the State Engineer, 2002). In Texas there are 22 defined major and minor aquifers (George and others, 2011; Texas Water Development Board, 2019a). For this report, the downdip limits of most of the aquifers in Texas are defined by a dissolved-solids concentration of 3,000 mg/L (Ashworth and Flores, 1991). The discussion that follows regarding the aquifers in the study area refers to the parts of the aquifers that are generally used for public supply, irrigation, livestock, and some industrial purposes. The main aquifers in the study area in New Mexico are the Pecos River Basin alluvial aquifer; High Plains aquifer; sandstone and shale aquifer; limestone, sandstone, and shale aquifers; Capitan Reef aquifer; and Roswell Basin Artesian aquifer (which along with the Pecos River Basin alluvial aquifer are called the Roswell Basin aquifer system). The main aquifers in the study area in Texas are the Pecos Valley aquifer, Edwards-Trinity aquifer system, Dockum aquifer, Rustler aquifer, and Capitan Reef aquifer. Although these are the aquifers mapped in each State they may or may not be at or near the surface, which means that they may not be shown on figure 3, which depicts the geologic units that are at or near the surface geospatially. Understanding the geology and hydrogeology of the basin is helpful for understanding the potential sources of salinity to the Pecos River. Overviews of the aquifers and aquifer systems that correspond to the geologic units in the study area are provided. Many of the geologic units and their hydrogeologic-unit equivalents extend regionally beyond their mapped boundaries within the study area (figs. 3 and 4).

Pecos Valley Aquifer

The Pecos Valley aquifer is composed of Pecos Valley alluvium and covers all or parts of Andrews, Crane, Ector, Loving, Pecos, Reeves, Upton, Ward, and Winkler Counties in Texas and parts of Eddy and Lea Counties in New Mexico (fig. 3). The Pecos Valley aquifer is a major aquifer in Texas, primarily used for irrigation. Several cities use the Pecos Valley aquifer for public supply in Texas, with the cities of Midland, Odessa, and Monahans being the largest users (Jones, 2004; Texas Water Development Board, 2019a). The quality of the water in the Pecos Valley aquifer varies from fresh (dissolved-solids concentrations less than 1,000 mg/L) to very saline (dissolved-solids concentrations greater than 10,000 mg/L) (Winslow and Kister, 1956; Meyer and others, 2012).

In New Mexico, the Pecos Valley aquifer is called the Pecos River Basin alluvial aquifer and is used for domestic purposes, livestock, and some irrigation (New Mexico Interstate Stream Commission and New Mexico Office of the State Engineer, 2016). The towns of Loving and Otis, N. Mex., use the aquifer for public supply (Hendrickson and Jones, 1952; Barroll and others, 2004).

High Plains Aquifer

The High Plains aquifer crops out in the northeastern and east-central parts of the study area and is a major aquifer in Texas; where it is present, it is used as the primary water source for irrigation and public supply (George and others, 2011). The High Plains aquifer is commonly referred to as the “Ogallala aquifer” where it is found in Texas. Although the High Plains aquifer occurs in the study area in parts of Chaves, Curry, De Baca, Eddy, Guadalupe, Lea, Quay, and Roosevelt Counties in New Mexico and very small parts of Andrews, Ector, and Winkler Counties in Texas, the Pecos River does not intersect the High Plains aquifer (fig. 3), and the aquifer does not contribute to the salinity of the Pecos River. In western Texas, the water quality of the High Plains aquifer is slightly saline to moderately saline with dissolved-solids concentrations between 1,000 and 10,000 mg/L (Winslow and Kister, 1956; Hopkins, 1993).

Edwards-Trinity Aquifer System

The Edwards-Trinity aquifer system is a major aquifer in the southern part of the study area in Texas; it is commonly referred to in much of the literature as the “Edwards-Trinity (Plateau) aquifer” (Ryder, 1996). Water from the Edwards-Trinity aquifer system is used primarily for irrigation, public supply, and livestock (Ashworth, 1990; George and others, 2011). Water quality ranges from freshwater (dissolved-solids concentration is less than 1,000 mg/L) to slightly saline (dissolved-solids concentration of 1,000–3,000 mg/L) (Winslow and Kister, 1956; George and others, 2011). Areas in which the groundwater contains dissolved-solids concentrations greater than 5,000 mg/L occur in extreme western Ward County and the central part of Reeves County, south and west of Pecos, Tex. (Ashworth, 1990). In parts of the Edwards-Trinity aquifer system that have not been developed for irrigation such as in Terrell and southern Pecos Counties, the recharge and discharge have remained almost in equilibrium, and the aquifer contributes flow to the Rio Grande and the Pecos River through seeps and springs (Rees and Buckner, 1980).

Dockum Aquifer

The Dockum aquifer is a minor aquifer used primarily for irrigation in Texas; it underlies the Pecos Valley alluvium in Crane, Ector, Loving, Pecos, Reeves, Ward, and Winkler Counties and the Edwards-Trinity aquifer system in Crockett, Reagan, and Upton Counties. The aquifer is used for irrigation, livestock, and some industrial purposes. The cities of Pecos and Kermit, Tex., use the Dockum aquifer for public supply. The quality of water in the Dockum aquifer is generally slightly saline to moderately saline, with dissolved-solids concentrations averaging about 5,000 mg/L (Bradley and Kalaswad, 2003).

Although the Dockum Group units are water bearing in New Mexico and used locally for livestock, the term "Dockum aquifer" is not used (Wilson, 2013; New Mexico Interstate Stream Commission and New Mexico Office of the State Engineer, 2016). The water-bearing units of the Dockum Group (Chinle Formation and Santa Rosa Sandstone) are called the sandstone and shale aquifer (Matherne and Stewart, 2012; New Mexico Interstate Stream Commission and New Mexico Office of the State Engineer, 2016).

Rustler Aquifer

The Rustler aquifer is a minor aquifer in New Mexico and Texas. In Texas, the Rustler aquifer is used primarily for irrigation in Pecos and Reeves Counties and for livestock in Culberson, Loving, Pecos, and Ward Counties. The water quality of the Rustler aquifer where used for municipal, irrigation, livestock, and some industrial purposes is generally slightly saline to moderately saline with dissolved-solids concentrations averaging about 2,800 mg/L (Brown, 1998). Although the Rustler Formation is water bearing in New Mexico and used locally as a water source, the term "Rustler aquifer" is not used (New Mexico Interstate Stream Commission and New Mexico Office of the State Engineer, 2016). In New Mexico the water-bearing units of the Rustler Formation are called the limestone, sandstone, and shale aquifers and along with the sandstone and shale aquifers, and the Pecos River Basin alluvial aquifer, are the main sources of water east of the Pecos River in Eddy and Lea Counties (New Mexico Interstate Stream Commission and New Mexico Office of the State Engineer, 2016).

Capitan Reef Aquifer

The Capitan Reef aquifer is a minor aquifer in New Mexico and Texas. In Texas, the aquifer is commonly referred to as the "Capitan Reef Complex aquifer," whereas in New Mexico the aquifer is commonly referred to as the "Capitan Reef Limestone aquifer" or the "Capitan aquifer" (Richey and others, 1984; Uliana, 2001). In this report the name "Capitan Reef aquifer" is used. The water quality of the Capitan Reef aquifer is poor and over much of its extent is considered very saline or brine (Uliana, 2001; Land, 2016b).

In New Mexico, the Capitan Reef aquifer is considered fresh near its recharge area in the Guadalupe Mountains west of the Pecos River in Eddy County (Barroll and others, 2004) and is used for irrigation and public supply. Carlsbad, N. Mex., obtains most of its water supply from the Capitan Reef aquifer (Hood and Kister, 1962; Barroll and others, 2004; Land, 2016b). The aquifer is also used in New Mexico as a source of water for enhanced oil recovery and potash mining (Richey and others, 1984; Land, 2016b). The Capitan Reef aquifer discharges to the Pecos River from springs in Carlsbad (Land, 2016b).

In Texas, the Capitan Reef aquifer is used primarily for irrigation in Culberson, Hudspeth, and Pecos Counties (Richey and others, 1984). The quality of water in the Capitan Reef aquifer is moderately saline with an average dissolved-solids concentration greater than 3,000 mg/L; the aquifer contains predominately sodium-chloride-sulfate type water (Uliana, 2001).

Roswell Basin Aquifer System

The Roswell Basin aquifer system is a major aquifer in New Mexico; it is commonly referred to simply as the "Roswell Artesian Basin" by the State agencies in New Mexico (Fielder and Nye, 1933; Land and Newton, 2007). Water withdrawn from the Roswell Basin aquifer system is used primarily for irrigation; it is also used for public supply and for commercial and industrial applications (Robson and Banta, 1995). It extends from north of Roswell south to Brantley Lake in New Mexico. The Roswell Basin aquifer system is composed of a shallow alluvial aquifer and an underlying artesian carbonate aquifer (hereinafter referred to as the "artesian aquifer"). The shallow alluvial aquifer is composed of Quaternary gravel, sand, silt, and clay. The water quality of the shallow alluvial aquifer is variable, with dissolved-solids concentrations ranging from about 500 to 5,000 mg/L (Robson and Banta, 1995). The Queen Formation and the upper part of the Grayburg Formation act as semiconfining units to the underlying artesian aquifer. The artesian aquifer is composed of the lower part of the Grayburg Formation and the middle to upper part of the San Andres Limestone. The water quality of the artesian aquifer is variable. In the western part of the artesian aquifer, dissolved-solids concentrations range from about 700 to 2,600 mg/L (Robson and Banta, 1995), whereas dissolved-solids concentrations in the northwestern part of the artesian aquifer range from 7,000 to 12,000 mg/L (Robson and Banta, 1995).

Recharge to the artesian aquifer is from precipitation and from upward movement of water from the underlying Yeso Formation. Water in the artesian aquifer moves vertically through the semiconfining units to the shallow aquifer and then to the Pecos River (Daniel B. Stephens and Associates, 1995a). There are also numerous sinkhole lakes and springs that discharge from the artesian aquifer, and the salinity in some of these lakes and springs can be very high. Land and Newton (2007) reported that chloride concentrations measured in sinkhole lakes and springs at Bitter Lake National Wildlife Refuge (BLNWR) range from approximately 1,100 to 3,500 ppm (mg/L), whereas chloride concentrations measured in a spring issuing in Lea Lake were 2,950 ppm (mg/L). Land (2003) reported a chloride concentration of 15,600 ppm (mg/L) and a dissolved-solids concentration of 38,200 ppm (mg/L) for a sample of water collected from a sinkhole lake at Bottomless Lakes State Park. There is a freshwater-saltwater interface in the artesian aquifer near Roswell that moves westward during irrigation season when groundwater withdrawals are higher, and precipitation is typically lower, and moves eastward following irrigation season when groundwater withdrawals are lower, and precipitation is typically higher (Hood and Kister, 1962; Land and Newton, 2007). Russell (1989) stated that the San Andres Limestone is more saline north and east of Roswell and that overpumping of the artesian aquifer causes salt encroachment.

Methods

Two strategies were used to compile data in support of this assessment. First, existing geologic and hydrogeologic data, including historical water-quality data, were obtained from local, State, and Federal agencies. These data were obtained digitally from the source agencies or gathered from published reports. The compiled data were reviewed for possible data gaps. Second, to help fill in these data gaps, streamflow and water-quality data were collected by the USGS in February 2015.

Geologic and Hydrogeologic Data Compilation

To aid in the understanding of how the underlying geology may contribute to the salinity of the Pecos River in the study area, the horizontal extent of and depth to the base of the geologic and hydrogeologic units that underlie the study area were mapped for the Quaternary-aged through the Permian-aged units. Data pertaining to geologic and hydrogeologic processes were compiled from various previous studies, including Page and Adams (1940), Mear and Yarbrough (1961), Welder (1983), and the Texas Water Development Board (TWDB) Brackish Resource Aquifer Characterization System (BRACS) database (Texas Water Development Board, 2016a). BRACS was designed to map and characterize brackish aquifers of Texas in greater detail than previous studies (Texas Water Development Board, 2016a). Because a BRACS study was completed in 2012 within the basin on the Pecos Valley aquifer (Meyer and others, 2012), a large amount of published structural data was available from the BRACS database for shallow geologic units near the Pecos Valley aquifer.

Structural interpretations from previous studies done by local, State, and Federal agencies were compiled and supplemented with additional data, such as geophysical logs. Data from borehole geophysical logs such as natural gamma, formation electrical resistivity, and caliper logs are commonly used to characterize and identify geologic units (Keys, 1997), and natural gamma, electric, and electromagnetic (EM) induction logs collectively can be useful in identifying lithologies and contact depths of the strata penetrated in the borehole. Geophysical log data exist for numerous sites in the study area from previous scientific investigations or petroleum explorations. Geophysical logs and associated well data were compiled from the New Mexico Energy, Minerals and Natural Resources Department, the Railroad Commission of Texas, TWDB, University of Texas University Lands, and the USGS GeoLog Locator (Houston and others, 2019; U.S. Geological Survey, 2019). Each geophysical log was evaluated to determine if the log penetrated the desired geologic units and provided useful data for determining the tops and bases of the geologic and hydrogeologic units or identifying other structural features. The best quality geophysical logs used to determine the tops and bases of geologic and hydrogeologic units were natural gamma, electric, and EM induction logs.

Natural Gamma Logs

Natural gamma logs provide a record of gamma radiation detected at depth in a borehole. Fine-grained sediments that contain abundant clay tend to be more radioactive than quartz-grained sandstones or carbonates (Keys, 1997). Natural gamma logs were the most useful of all of the geophysical log types, in part because of their versatility; they can be used in wells cased in either polyvinyl chloride (PVC) or steel and filled with either fluid or air. Natural gamma logs existed for many wells in the study area and typically provided a good indication of the tops and bases of geologic and hydrogeologic units.

Electric Logs

Electric logs use a series of electrodes mounted on the downhole probe and a surface electrode in the ground to measure potential (or voltage) that varies with the electrical properties of fluids and rock materials. Electric logs require an uncased, fluid-filled hole to allow the current to flow into the formation. The following types of data are provided by electric logs: normal resistivity, lateral resistivity, spontaneous potential, and single-point resistance (Keys, 1997).

Normal resistivity logs are useful for determining and correlating various lithologies but may be affected by the resistivity of the fluids in the borehole and formation (Keys, 1997). The lateral resistivity log increases the resolution and decreases the effects of adjacent beds in comparison with the normal resistivity logs (Keys, 1990). Spontaneous potential (SP) is one of the oldest logging techniques and uses a simple method of measuring the potentials produced by various salinity conditions (Keys, 1990). SP is a function of the chemistry of fluids in the borehole and adjacent rocks, the temperature, and the clay present; SP is not related directly to porosity and permeability (Keys, 1997). The single-point resistance log uses the same circuitry as SP and shows the resistance measured between the electrode in the well and an electrode at the land surface (Keys, 1990).

Electromagnetic Induction Logs

EM induction probes measure conductivity in air- or water-filled holes and perform well in open holes or PVC-cased holes. The measurement of conductivity commonly is reciprocated to provide a measurement of resistivity, and logs of both resistivity and conductivity are presented (Keys, 1997). Conductivity is affected by the salinity of borehole and formation fluids and the lithology. Generally, pure carbonates, sands, and gravels have lower conductivity (thus higher resistivity) than do clays or shales (Keys, 1997).

Hydrogeologic-Unit Mapping Methods

Stratigraphic picks (tops and bases of hydrogeologic units) were identified from the geophysical logs. The stratigraphic picks were then used to determine the horizontal extent of the hydrogeologic units and their vertical relation to overlying and underlying units. The following hydrogeologic units were mapped in the study area (fig. 3): Pecos Valley alluvium (Pecos River Basin alluvial aquifer, Pecos Valley aquifer); Ogallala Formation (High Plains aquifer); Cretaceous undivided (Edwards-Trinity aquifer system); upper and lower parts of the Dockum Group (sandstone and shale aquifer, Dockum aquifer); Dewey Lake Redbeds; Rustler Formation (limestone, sandstone, and shale aquifers, Rustler aquifer); Salado Formation; Castile Formation; Capitan Limestone; Tansill, Yates, Seven Rivers, Queen, and Grayburg Formations; and San Andres Limestone. The lower part of the Grayburg Formation and the upper to middle part of the San Andres Limestone form the artesian aquifer of the Roswell Basin. The Capitan Reef aquifer includes the Capitan Limestone. Geologic framework data were used to evaluate the structural features such as extent, bed orientation, unit thickness, outcrop and subcrop locations, and fault zones.

Geologic and lithologic descriptions, identified from compiled data, were used to improve the understanding of the lithologic and geophysical properties of each hydrostratigraphic unit. Specifically, geologic descriptions and typical geophysical log responses were evaluated from Herald (1957) and Meyer and others (2012). Well reports and geophysical logs were evaluated to identify data that could be used to develop hydrogeologic contacts (tops and bases) of pertinent units. Where possible, published reports or hardcopy data were digitized and combined with existing digital data and are available in Houston and others (2019). Geophysical logs with applicable method (natural gamma, electric, and EM) and spatial data (which provided needed information for vertical or horizontal data gaps) were interpreted to identify the vertical extents (tops and bases) of each geologic unit penetrated by the well. Interpretations of geophysical data were combined with the reported data and are available in Houston and others (2019). Although geophysical logs are typically reliable sources of subsurface information, many of the logs for the study area were found to contain incorrect or missing information such as incorrect or indiscernible location information, missing or incorrect header information, unknown well-completion dates, insufficient calibration data, or reported borehole environments that were unsuitable for geophysical logging. Geophysical logs with unreliable, incorrect, or missing information were not used in this analysis.

Interpretations of the depths below land surface of the tops and bases of geologic units (geologic unit contacts) were converted to elevations relative to NAVD 88 by subtracting the depths from the elevations reported by the Advanced Spaceborne Thermal Emission and Reflection Radiometer version 2 (ASTERv2) digital elevation model (National Aeronautics and Space Administration, 2015). All hydrogeologic-unit contact grids were created by using Oasis montaj (Geosoft, 2015) to develop grids based on kriging, which is a geostatistical method that determines the most probable value at each grid node based on a statistical analysis of the entire dataset. This kriging method was chosen in part because of its utility for assessing clustered data. Variance maps automatically developed during the kriging process were used to evaluate the uncertainty in hydrogeologic-unit surface grids. Generally, as the distance between data points becomes greater, correlation between points lessens, and uncertainty in areas between points increases (Isaaks and Srivastava, 1989).

Preliminary hydrogeologic-unit surface grids for contacts (tops and bases) were periodically created during the interpretation process to help evaluate structural features, extents, and data coverage. Hydrogeologic-unit surface grids were interactively compared to interpreted contact elevations to evaluate outliers, grid accuracy, and clustered data. All outliers were evaluated through a correlation process to determine data-point uncertainty. The correlation process involved the comparison of the stratigraphic picks at a given site to the stratigraphic picks made at nearby sites to determine if it correlated with the nearby well picks. Throughout the process, all geologic contacts (tops and bases) were reviewed and revised as needed to provide a better representation of the stratigraphic unit.

Historical Water-Quality Data Compilation and Review

Methods of water-quality data review and analyses included gathering, compiling, and evaluating water-chemistry data and performing quality-assurance checks on the compiled data. The following discussion describes the data sources, data compilation, and comparison methods used to process, evaluate, and interpret water-quality data compiled for this study.

Data Sources

Water-quality data were downloaded, where available, from existing database resources hosted by various State and Federal agencies. Data were downloaded from the USGS National Water Information System (NWIS) (U.S. Geological Survey, 2017b), the U.S. Environmental Protection Agency Modernized Storage and Retrieval Repository (STORET) (U.S. Environmental Protection Agency, 2017), and the TWDB Groundwater Database (Texas Water Development Board, 2015a). Data were also obtained in digital format from the Texas Commission on Environmental Quality (TCEQ) (Cathy Anderson, TCEQ, written commun., 2015). Digital data were obtained from the New Mexico Environment Department (NMED) for their 2013 sampling event on the lower Pecos River (Gary Schiffmiller, NMED, written commun., 2015) and for their 2007 statewide lake survey (Kristopher Barrios, NMED, written commun., 2017). Monitoring data from the Seven Rivers Inc. well augmentation well field were obtained digitally from the New Mexico Interstate Stream Commission (NMISC) (Greg Lewis, NMISC, written commun., 2015). Stable hydrogen and oxygen isotope data collected by the USGS for the National Stream Quality Accounting Network (NASQAN) program were obtained digitally and included in the compilation (Coplen and Kendall, 2000). Stable-isotope, major-ion, and a small amount of hydrocarbon data collected by the Bureau of Land Management (BLM) were obtained digitally and included in the compilation (David Herrell, written commun., 2015). Stable-isotope data collected by the New Mexico Bureau of Geology and Mineral Resources were extracted from a digital copy of the report by Land and Huff (2010) and converted to a digital format. Data collected by Texas A&M AgriLife Extension in March, May, and July 2005 were extracted from Yuan and Miyamoto (2008) and converted to a digital format. Data collected by Texas Parks and Wildlife in October 1987 were extracted from Linam and Kleinsasser (1996) and converted to a digital format. Digital data were also obtained from the NMED Ground Water Quality Bureau for monitoring wells in the Nash Draw (Larry Shore and Melissa Mascarenas, written commun., 2016); however, the data were not compiled in time for this study. The Pecos Valley Artesian Conservancy District collects water-quality data in selected wells; however, these data were not included in this compilation. The resulting compilation of water-chemistry data and supporting documentation are available in Houston and others (2019).

Data Compilation and Comparison

The compiled water-quality data were evaluated for consistency between the disparate input data sources. Preprocessing steps for the dataset included site location adjustments, aquifer determination for groundwater wells and springs, and the aggregation of water-quality results. To maintain vertical consistency among all the sites, the elevations of each location were obtained from the ASTERv2 digital elevation model (National Aeronautics and Space Administration, 2015). There were 17 unique codes for site types (such as spring or groundwater well) among the different agencies. This number of site-type codes was reduced to six as defined by the USGS NWIS database (U.S. Geological Survey, 2017b).

The water-quality sampling results were aggregated so that similar constituents could be analyzed together when different collection and analytical methods were used (Bauch and others, 2014). Conversions were used, when needed, to match the units of the aggregated constituents. There were 12 unique codes for sample medium among the different agencies, some of which were grouped to reduce this number to 8 USGS sample mediums (air, bottom material, suspended sediment, solids, groundwater, leachate, surface water, and wastewater) as defined by the USGS NWIS database (U.S. Geological Survey, 2017b).

Data Quality Assurance

The water-quality sampling results were reviewed for quality control and quality assurance. This was done by verifying that the data met specific criteria. The types of quality-assurance assessments that were done on the water-quality data included computation of major-ion balances, identification of replicate results, comparison of filtered and unfiltered water-sample results, and a statistical analysis to remove outliers.

Major-ion balance errors were computed for the water-chemistry sampling results. If the percent difference between the anion and cation charge balances for a sample exceeded 10 percent, then the analytical data obtained from the sample were not used for water-quality analyses (Bauch and others, 2014). Major-ion balances were assessed by using the following equation:

$$Major\text{-}ion\ balance = (\Sigma cations - \Sigma anions) \times 100\ / (\Sigma cations + \Sigma anions) \qquad (1)$$

where

$\Sigma cations$ is the sum of the concentrations of dissolved cations, in milliequivalents per liter; and

$\Sigma anions$ is the sum of the concentrations of dissolved anion, in milliequivalents per liter.

For the identification of replicate results, similar sample results associated with the same sampling site and sample collection time, but provided by different reporting agencies, were assumed to correspond to an individual sample, and only one sample entry was retained for the final dataset used for water-quality analyses. The sample with the most constituents reported was retained, and if the number of constituents reported was identical, the reporting agency was used as the criterion for which sample to retain based on the following order: Federal, State, and local.

When the analytical results of a given constituent were reported for both filtered and unfiltered water samples, the relative percent difference between the filtered and unfiltered results was determined. If the difference between the filtered and unfiltered results exceeded 10 percent, then neither the filtered nor unfiltered results for that constituent were used for water-quality analyses (Bauch and others, 2014). The relative percent difference was computed as follows:

$$RPD = |C_1 - C_2| / ((C_1 + C_2) / 2) \times 100 \qquad (2)$$

where

- RPD is the relative percent difference;
- C_1 is the sample concentration of the filtered sample; and
- C_2 is the sample concentration of the unfiltered sample.

Statistical analyses including computation of averages, standard deviations (Helsel and Hirsch, 2002), and modified z-test statistics (Iglewicz and Hoaglin, 1993) were performed on the remaining sample results to identify outliers within each constituent. Because of the potential for high variability in major-ion and trace element concentrations, the log-normal of the sampling result was used for all statistical analyses for these constituents. Censored data, or data with “less than” or “greater than” qualifiers, were incorporated into the statistical analyses based on specific criteria (Helsel and Hirsch, 2002). The term “censored data” in this study refers to a concentration measured by the laboratory that is less than a minimum detection level either for the method used to quantify detection of a constituent or for the equipment used to quantify detection of a constituent and is referred to as a “nondetected value” (Bauch and others, 2014). Estimates were made for nondetected values representing censored data by using either the Kaplan-Meier or the adjusted maximum likelihood estimates (Helsel, 2005). The Kaplan-Meier estimate was used if less than 50 percent of the data were censored (Bauch and others, 2014). If 50–80 percent of the data were censored, the adjusted maximum likelihood estimate was used for the censored data (Bauch and others, 2014). If more than 80 percent of the data were censored, only the minimum and maximum statistics were used for analysis (Bauch and others, 2014). A modified z-test was performed for each constituent to remove the outliers, with each result having a z-score value (Iglewicz and Hoaglin, 1993). If the z-score value was greater than 3.5, the result was considered an outlier and was flagged as a questionable result (Iglewicz and Hoaglin, 1993; Houston and others, 2019).

Streamflow Measurement Methods

Synoptic streamflow measurements were made by using standard USGS wading methods at 29 sites in February 2015. Stream width was measured by using a tagline, and depth was measured by using a wading rod while the water velocity was measured with either a hand-held pygmy Price current meter or a hand-held acoustic Doppler current velocimeter (U.S. Geological Survey, 2004) (hereinafter referred to as a “FlowTracker”) attached to the wading rod. The midsection method of computing streamflow was used (Rantz and others, 1982). Check measurements were made at 28 of the 29 sites to ensure that streamflow measurements were within 5 percent of each other.

Water-Quality Sampling Methods

Water-quality samples were collected in February 2015 from 26 sites in the basin (figs. 5–9, table 1). A total of 24 of the 26 sites were surface-water sampling sites. There were 20 surface-water sampling sites on the Pecos River. Four of the remaining sites consisted of (1) a surface-water sampling site at the BLNWR, where a sample was collected of inflow to the Pecos River near the BLNWR south weir inflow; (2) a surface-water sampling site on the Rio Hondo spring channel near Roswell (a short [about 1.5 miles long] restored channel of the Rio Hondo at the BLNWR) (U.S. Fish and Wildlife Service, 2019); (3) a surface-water sampling site at the Lea Lake outflow at Bottomless Lakes State Park; and (4) a surface-water sampling site on Salt Creek near Orla, Tex. The final two sites were artesian wells completed in the San Andres Limestone, near Imperial, Tex.; water-quality samples were collected from each of these artesian wells in February 2015 (fig. 5, table 1).

Water-quality sample collection and processing followed standard USGS methods documented in the “National Field Manual for the Collection of Water-Quality Data” (U.S. Geological Survey, variously dated). Surface-water samples were collected either by using an equal-width increment method or by using a composite multiple grab sample composed of a minimum of three grab samples collected at different locations across the channel when the measured velocity was less than 1.5 feet per second. Samples were collected by using a 1-liter Teflon bottle and composited in a Teflon churn for processing. Grab samples were collected from the two artesian wells. One of the two artesian wells (USGS site number 311323102435200) (table 1) was inaccessible by field vehicle; therefore, the field team kayaked through a shallow lake formed by the artesian well to the wellhead for sampling. The sampling point was 2 inches below the surface of the water in the wellhead region. Equipment was cleaned prior to sampling according to established USGS protocols (Wilde, 2004). All samples were processed onsite and preserved with acid when appropriate, packed in coolers on ice if required, and shipped overnight to one of three USGS laboratories, depending on the constituents that were analyzed.

Figure 5. Selected water-quality sampling sites in the Pecos River Basin study area in New Mexico and Texas, including sites sampled by the U.S. Geological Survey in February 2015.

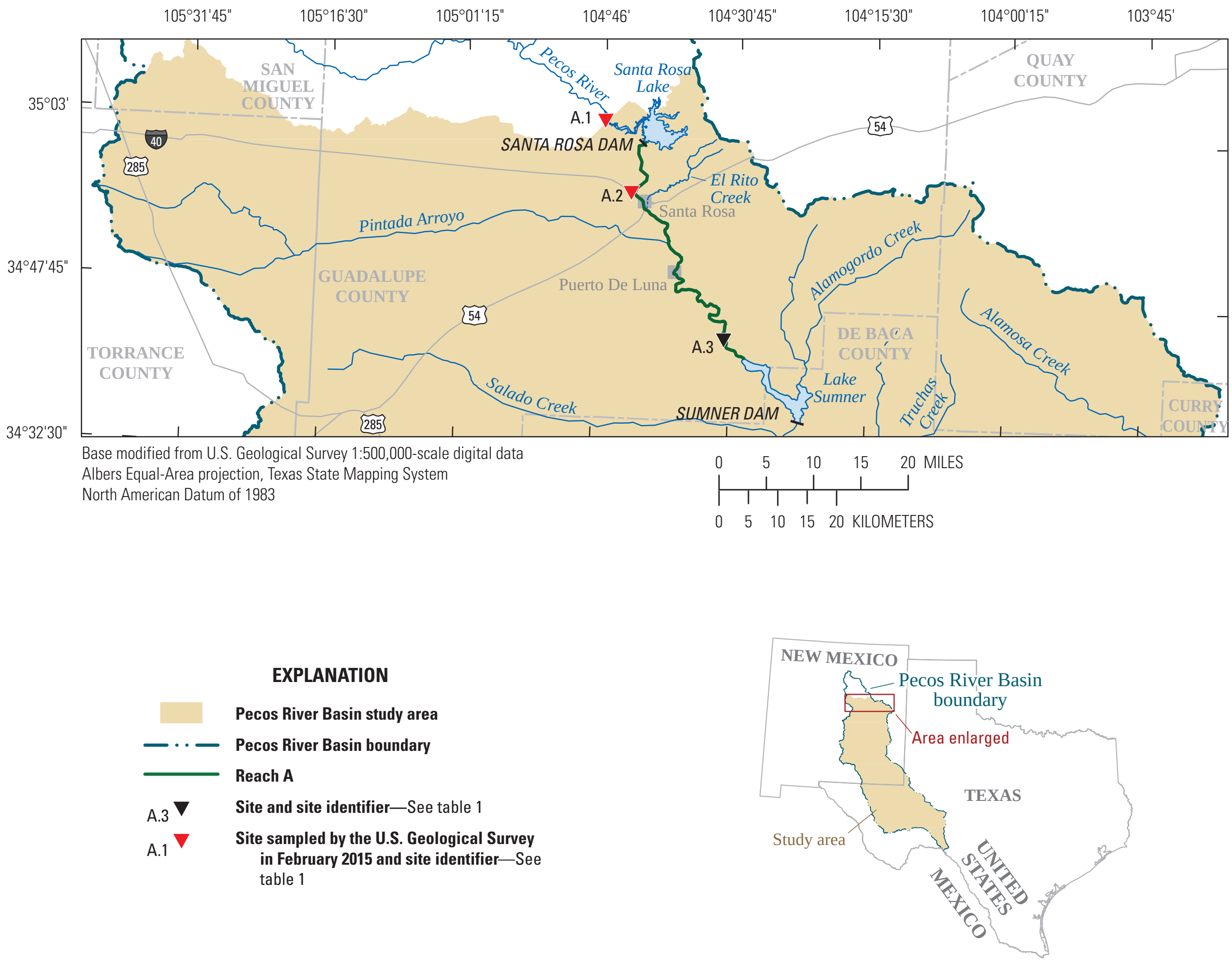

Figure 6. Locations of streamflow measurement sites and tributary inflow in reach A, Santa Rosa Lake to Lake Sumner, along the Pecos River in New Mexico.

Water-Quality Analysis Methods

The USGS National Water Quality Laboratory in Lakewood, Colorado, analyzed the samples collected in February 2015 for dissolved solids, major ions (calcium, magnesium, potassium, sodium, bromide, chloride, fluoride, silica, and sulfate), nutrients (ammonia, nitrite, nitrite plus nitrate, total nitrogen, orthophosphate, and phosphorus), and trace elements (boron, iron, manganese, and strontium). The USGS Reston Stable Isotope Laboratory in Reston, Virginia, analyzed samples for oxygen-18 (^{18}O) to oxygen-16 (^{16}O) and deuterium (^{2}H) to protium (^{1}H) isotopic ratios. The USGS National Research Program Metal and Metalloid Isotope Laboratory in Menlo Park, California, analyzed samples for strontium-87 (^{87}Sr) to strontium-86 (^{86}Sr) isotopic ratios.

Dissolved solids were determined by residue on evaporation at 180 degrees Celsius (°C) (Fishman and Friedman, 1989). Major-anion concentrations were measured by using ion-exchange chromatography, and major-cation concentrations were measured by using inductively coupled plasma-atomic emissions spectrometry, as described by Fishman (1993). Nutrient concentrations were measured by using methods described by Fishman (1993) and by Patton and Kryskalla (2003). Trace element concentrations were measured by using collision-reaction cell inductively coupled plasma-mass spectrometry (Fishman and Friedman, 1989; Fishman, 1993; Struzeski and others, 1996; Garbarino and others, 2006) or inductively coupled plasma-mass spectrometry (Faires, 1993; Garbarino, 1999). The ^{18}O, ^{16}O, ^{2}H, and ^{1}H isotope compositions were measured by using techniques described in Révész and Coplen (2008a, b). ^{87}Sr and ^{86}Sr isotope compositions were measured by thermal-ionization mass spectrometry following procedures described by Bullen and others (1996).

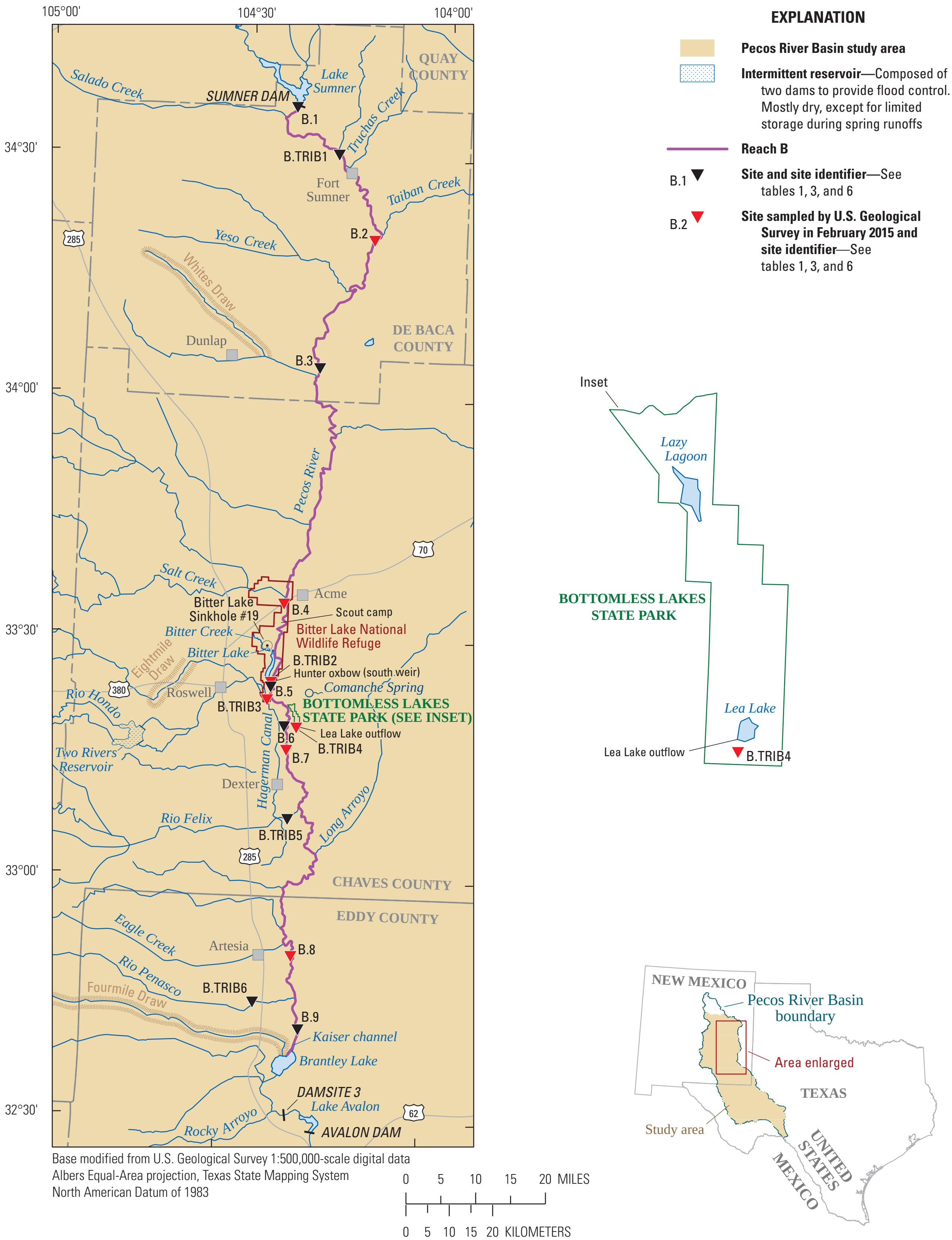

Figure 7. Locations of streamflow measurement sites and tributary inflow in reach B, Lake Sumner to Brantley Lake, along the Pecos River in New Mexico.

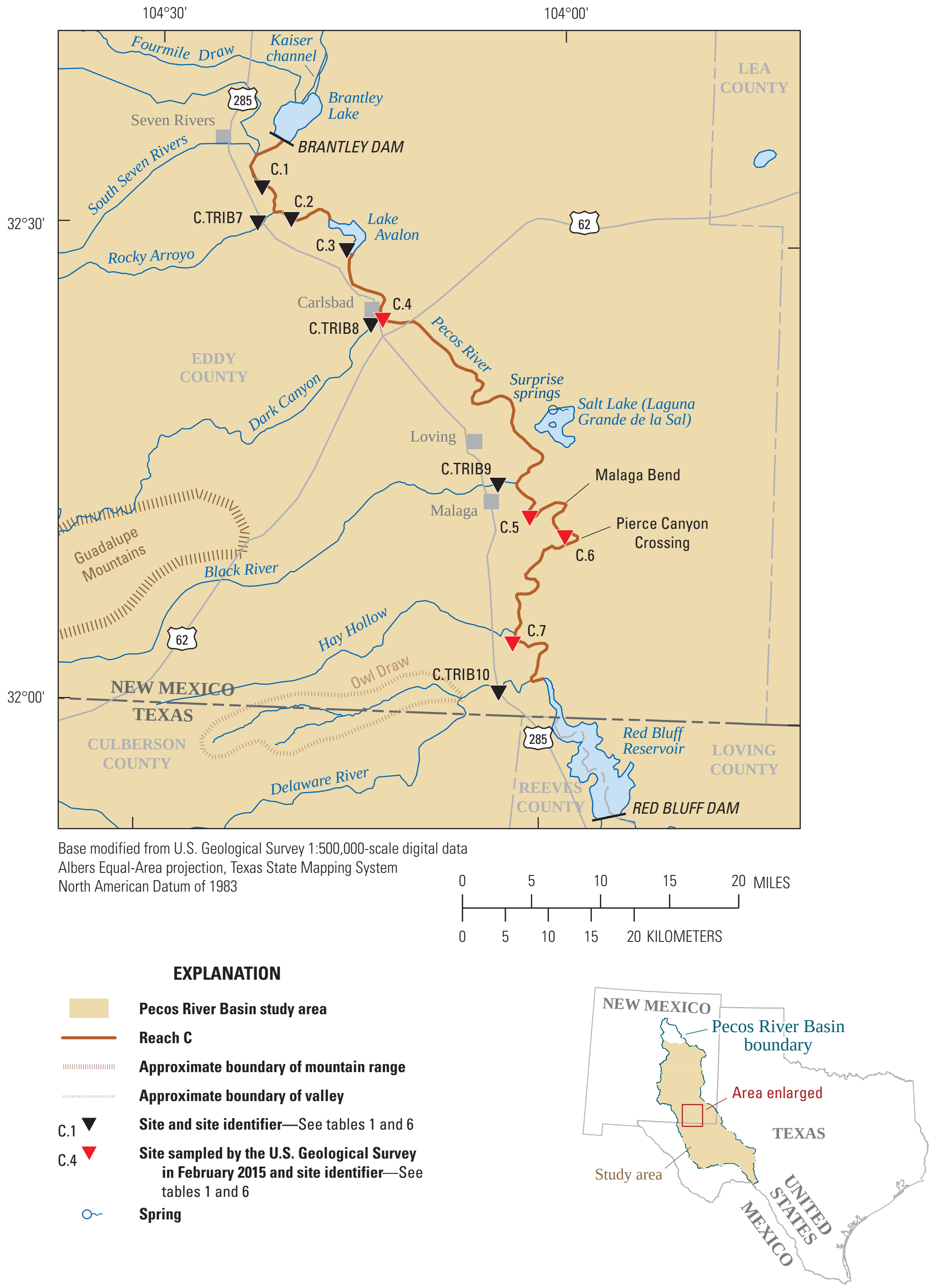

Figure 8. Locations of streamflow measurement sites and tributary inflow in reach C, Brantley Lake to Red Bluff Reservoir, along the Pecos River in New Mexico.

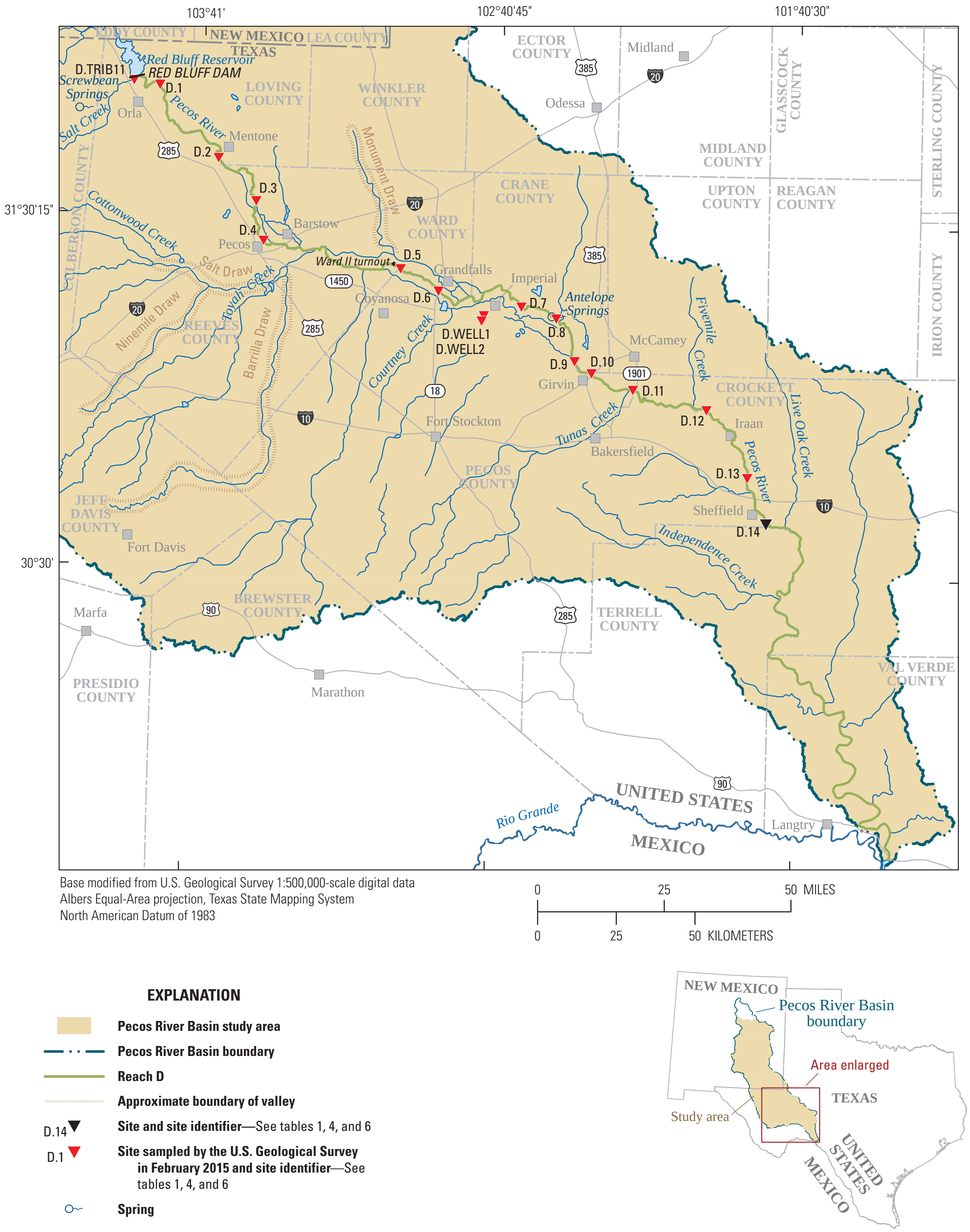

Figure 9. Locations of streamflow measurement sites and tributary inflow in reach D, Red Bluff Reservoir to the confluence of the Pecos River and the Rio Grande in Texas.

Table 1. Selected water-quality sites in the Pecos River Basin, New Mexico and Texas.

[NAD 83, North American Datum of 1983; TRIB, tributary; BLM, Bureau of Land Management; HIST, historical; MRK, Farm to Market 1053. Sites shown in red font were sampled by the U.S. Geological Survey in February 2015; sites shown in black font are historical]

Site identifier (figs. 6, 7, 8, 9)	Station number	Station name	Latitude in decimal degrees (NAD 83)	Longitude in decimal degrees (NAD 83)	Sample date
A.1	08382650	Pecos River above Santa Rosa Lake, N. Mex.	35.05944	104.76111	2/22/2015
A.2	345701104422710	Pecos River above Santa Rosa, N. Mex.	34.95028	104.7075	2/22/2015
A.3	08383500	Pecos River near Puerta De Luna, N. Mex.	34.73004	104.52468	12/13/2010
B.2	08385522	Pecos River below Taiban Creek near Fort Sumner, N. Mex.	34.33227	104.18116	2/25/2015
B.4	08386000	Pecos River near Acme, N. Mex.	33.5714	104.372	2/23/2015
B.TRIB2	332430104235610	Bitter Lake National Wildlife Refuge south weir inflow, N. Mex.	33.40833	104.39889	2/23/2015
B.TRIB3	332218104242310	Rio Hondo Spring Channel near Roswell, N. Mex.	33.37174	104.40647	2/23/2015
B.TRIB4	331856104195310	Lea Lake outflow, N. Mex.	33.31556	104.33139	2/24/2015
B.7	08394033	Pecos River south boundary (BLM wetlands) near Dexter, N. Mex.	33.26833	104.35442	2/24/2015
B.8	08396500	Pecos River near Artesia, N. Mex.	32.84091	104.32387	2/24/2015
C.HIST1	PRIS 01	Pecos River upstream of Tansill Dam, N. Mex.	32.42488	104.22144	6/11/2014
C.HIST2	PRIS 02	Pecos River downstream of lower Tansill Dam, N. Mex.	32.41137	104.22128	6/11/2014
C.4	08405200	Pecos River below Dark Canyon at Carlsbad, N. Mex.	32.41025	104.21621	2/24/2015
C.HIST3	PRIS 05	Pecos River site east of County Road 170 and Juan Pablo Road, N. Mex.	32.36143	104.12026	6/11/2014
C.HIST4	60PecosR067.0	Pecos River below Harroun (Ten-Mile) Dam, N. Mex.	32.31269	104.0599	2/19/2013
C.HIST5	PRIS 07	Pecos River upstream of Black River, N. Mex.	32.2476	104.04437	6/11/2014
C.HIST6	PRIS 08	Pecos River downstream of Black River	32.23469	104.04668	6/11/2014
C.5	08406500	Pecos River near Malaga, N. Mex.	32.20748	104.02367	2/26/2015
C.HIST7	PRIS 10	Pecos River at Dog Town Road, N. Mex.	32.21877	104.00236	6/11/2014
C.HIST8	PRIS 09	Pecos River at Malaga Bend downstream of Dog Town Road, N. Mex.	32.21979	103.99038	6/11/2014
C.HIST9	PRIS 12	Pecos River at east extent of Malaga Bend, N. Mex.	32.21464	103.98255	6/11/2014
C.HIST10	PRIS 11	Pecos River at Malaga Bend upstream of Pierce Canyon Crossing, N. Mex.	32.21137	103.98775	6/11/2014
C.HIST11	PRIS 13	Pecos River upstream of Pierce Canyon Crossing, N. Mex.	32.20007	103.99991	6/11/2014
C.6	08407000	Pecos River at Pierce Canyon Crossing, N. Mex.	32.18879	103.9789	2/25/2015
C.HIST12	PRIS 14	Pecos River downstream from Pierce Canyon, N. Mex.	32.16272	104.01528	6/11/2014
C.HIST13	PRIS 15	Pecos River upstream of Red Bluff Draw, N. Mex.	32.09133	104.03728	6/11/2014
C.7	08407500	Pecos River at Red Bluff, N. Mex.	32.07516	104.03955	2/25/2015
C.HIST14	PRIS 16	Pecos River upstream of Delaware River, N. Mex.	32.04738	104.01539	6/11/2014
C.HIST15	PRIS 17	Pecos River downstream of Delaware River, N. Mex.	32.03724	104.00339	6/11/2014
D.TRIB11	315300103550900	Salt Creek at Red Bluff Lake Road near Orla, Tex.	31.88322	103.91908	2/25/2015
D.1	08412500	Pecos River near Orla, Tex.	31.87261	103.83168	2/25/2015
D.3	313256103294600	Pecos River at Barstow Dam near Barstow, Tex.	31.54793	103.49602	2/26/2015
D.5	08437710	Pecos River at Ranch Road 1776 near Grandfalls, Tex.	31.36672	103.00558	2/24/2015
D.6	311820102523900	Pecos River at Highway 18 near Grandfalls, Tex.	31.3054	102.87721	2/24/2015
D.WELL1	311418102432601	Artesian well MRK east near Imperial, Tex.	31.23833	102.72389	2/25/2015
D.WELL2	311323102435200	Artesian well southeast of Farm to Market 1053 near Imperial, Tex.	31.22308	102.731	2/25/2015

Table 1. Selected water-quality sites in the Pecos River Basin, New Mexico and Texas.—Continued

[NAD 83, North American Datum of 1983; TRIB, tributary; BLM, Bureau of Land Management; HIST, historical; MRK, Farm to Market 1053. Sites shown in red font were sampled by the U.S. Geological Survey in February 2015; sites shown in black font are historical]

Site identifier (figs. 6, 7, 8, 9)	Station number	Station name	Latitude in decimal degrees (NAD 83)	Longitude in decimal degrees (NAD 83)	Sample date
D.7	311557102355600	Pecos River at Old Crane Road near Imperial, Tex.	31.26619	102.59945	2/25/2015
D.8	311402102285400	Pecos River at Horsehead Road near Imperial, Tex.	31.23387	102.4817	2/24/2015
D.10	08446550	Pecos River near Girvin, Tex. (flood gage)	31.11268	102.41775	2/24/2015
D.11	310204102131500	Pecos River at Ranch Road 1901 near McCamey, Tex.	31.03418	102.22077	2/23/2015
D.12	305849101582900	Pecos River at State Highway 349 near Iraan, Tex.	30.98035	101.97471	2/22/2015
D.13	304718101500600	Pecos River at Crockett County Road 306 near Iraan, Tex.	30.78853	101.83483	2/23/2015
D.14	08447000	Pecos River near Sheffield, Tex.	30.65947	101.77028	7/23/2013
D.HIST16	13248	Pecos River upstream of Independence Creek, Tex.	30.44589	101.72073	5/15/2014
D.HIST17	14163	Pecos River downstream of Independence Creek, Tex.	30.44139	101.72	5/15/2014

Quality Assurance and Control of Water-Quality Data

Quality-control data were collected to assess the precision and accuracy of sample-collection procedures and laboratory analyses during the water-quality synoptic sampling in February 2015 (table 1). Quality-control samples consisted of two field-blank samples (one in New Mexico and one in Texas) and two sequential-replicate samples (one in New Mexico and one in Texas) collected by the field teams.

Field-blank samples were collected and processed at a sampling site prior to collection of environmental samples to measure the amount of potential contamination that might be introduced by sample collection equipment, sample collection methods, and sample processing procedures used during the collection of environmental samples. The concentration of each constituent measured in the field-blank sample collected by the New Mexico field team was less than its laboratory reporting level. Concentrations of calcium, magnesium, sodium, potassium, chloride, sulfate, manganese, and strontium were slightly greater than their laboratory reporting levels in the field-blank sample collected by the Texas field team. The detected concentrations in the field-blank sample collected in Texas were negligible compared to concentrations in the environmental samples, indicating that the sample collection equipment, sample collection methods, and sample processing procedures did not introduce appreciable contamination.

Sequential-replicate samples are collected to assess variability introduced by sample collection, processing, and analysis. Sequential-replicate samples should be collected close in time to the environmental sample to minimize changes in concentrations related to hydrologic differences. Relative percent differences for constituents measured in the New Mexico replicate sample pairs were within 5 percent except for sodium and iron; sodium and iron concentrations were within 6 percent. Concentration differences for the Texas replicate samples exceeded a relative percent difference of 5 percent for several constituents, including carbonate, ammonia, calcium, magnesium, sodium, potassium, fluoride, silica, boron, manganese, strontium, and bromide. Most of the relative percent differences in these concentrations were between 10 and 20 percent and are likely a result of different hydrologic conditions when each replicate sample was collected or a result of variations in sample collection associated with different field teams. Each sample of the Texas replicate pair was collected by a separate field team, which caused a delay between the collections of the two samples, and therefore each likely was collected during slightly different hydrologic conditions.

Data Release

Data collected and compiled for the study and supporting documentation are available in a companion data release (Houston and others, 2019). The data release contains water-chemistry results from the USGS sampling in February 2015, the compiled historical water-chemistry data, salinity input locations, and other salinity-related data. The data release also includes depth to the base of 16 mapped geologic units with some or all of their geospatial extents contained within the basin, including the San Andres Limestone; the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations; the Capitan Limestone; the Castile, Salado, and Rustler Formations; the Dewey Lake Redbeds; the Dockum Group (divided into the upper and lower parts of the Dockum Group in this report); the Cretaceous undivided; the Ogallala Formation; and the Pecos Valley alluvium.

Pecos River Basin Salinity Assessment

The elevated salinity of the Pecos River has been the subject of numerous studies. A detailed literature review was done to summarize published information regarding the sources of salinity in the Pecos River and the processes that contribute to elevated salinity.

One of the questions considered was whether the saline water entering the Pecos River is entering the river primarily in New Mexico or whether some of the saline water is entering the river in Texas. The answer to this question has implications on the design of future projects tasked with intercepting saline water (or the minerals that contribute to saline water) before they reach the Pecos River. As part of the literature review, the USGS documented scientific recommendations made by researchers who had previously worked in the basin (app. 1).

Previous Salinity Studies by Reach

To aid in the discussion of the various geographic features, an alphanumeric naming convention was created for the four main reaches of the Pecos River in the study area (reaches A through D) and for sites within each reach (fig. 5). Each of the four main reaches also includes subreaches. The Pecos River from Santa Rosa Lake to Lake Sumner was named reach A (fig. 6). The Pecos River from Lake Sumner to Brantley Lake was named reach B (fig. 7). The Pecos River from Brantley Lake to Red Bluff Reservoir was named reach C (fig. 8). The Pecos River from Red Bluff Reservoir to the confluence of the Pecos River and the Rio Grande was named reach D (fig. 9). Previously identified sources of salinity in each subreach are described in a downstream order.

At the regional scale, Miyamoto and others (2006) and Gregory and others (2014) stated that there are four reaches of the Pecos River responsible for most of the salt load in the river. Salt load is a measure of the movement of the salts in a water body at a specific time (the concentration of the constituent multiplied by the rate of the flow of the water). Three of the four reaches they identified as responsible for most of the salt load are in New Mexico: Santa Rosa Lake to Puerto de Luna (a subreach within reach A), Acme to Artesia (a subreach within reach B), and Malaga to Pierce Canyon Crossing (a subreach within reach C). Miyamoto and others (2006) stated that in 2005 these three reaches contributed 89 percent of the salt load to the Pecos River upstream from Red Bluff Reservoir. The fourth reach is in Texas, from Coyanosa to Girvin (a subreach within reach D) (Gregory and others, 2014).

Santa Rosa Lake to Puerto de Luna—Subreach in Reach A

According to the literature, the first appreciable increase in salinity in the Pecos River occurs in the reach of the Pecos River from Santa Rosa Lake to Puerto de Luna (figs. 1 and 6) (Miyamoto and others, 2006; Yuan and others, 2007). Calcium and sulfate ions are the primary ions contributing to the salinity of the Pecos River (Miyamoto and others, 2006). The NMED reported that specific conductance increases by an order of magnitude from approximately 250 microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25 °C) downstream from Tecolote Creek (and upstream from Santa Rosa Lake) to greater than 2,500 μS/cm at 25 °C downstream from El Rito Creek (New Mexico Environment Department, 2004). The NMED further stated that there is an increase in streamflow between Santa Rosa Lake and Puerto de Luna attributable to sinkhole springs that discharge at a rate of approximately 6.68 cubic feet per second (ft^3/s) (more than 4 million gallons of water per day) to Blue Hole, a water body formed by the springs (New Mexico Environment Department, 2004). The water from Blue Hole discharges to El Rito Creek (Joseph, 2001; New Mexico Environment Department, 2004, 2007, 2013). Two historical instantaneous flow measurements were made by the USGS at Blue Hole sinkhole springs and compiled for this study, one in 1939 of 672 gallons per minute (1.5 ft^3/s) and one in 1952 of 3,000 gallons per minute (6.68 ft^3/s) (U.S. Geological Survey, 2017b). In addition to Blue Hole, there are many other sinkhole lakes and springs that issue from the San Andres Limestone and eventually discharge to the Pecos River (Dinwiddie and Clebsch, 1973; Land, 2009) in the Santa Rosa Lake to Puerto de Luna subreach. The NMED stated that when there are no releases from the dam at Santa Rosa Lake the average streamflow in Pecos River near Santa Rosa is 73 ft^3/s (New Mexico Environment Department, 2004).

Acme to Artesia—Subreach in Reach B

Reimus and others (2012) surveyed salinity inputs into the Pecos River between Acme and Artesia (fig. 7). Specifically, their study focused on a 31-mile subreach from the northern boundary of the BLNWR to Dexter, N. Mex. The BLNWR is approximately 10 miles northeast of Roswell. Reimus and others (2012) concluded that all saline inputs to the Pecos River between Lake Sumner and Brantley Lake originate in this 31-mile subreach from one or more of the following sources: spring inflow and underflow from the BLNWR, inflows at the south end of the BLNWR (near hunter oxbow at the south weir), inflow from the Rio Hondo, and outflows from Lea Lake at Bottomless Lakes State Park. Reimus and others (2012) concluded that approximately 40 percent of the dissolved-solids concentrations and 75–80 percent of the sodium chloride concentrations that reach Brantley Lake originate in this 31-mile reach. They further stated that the saline water from these sources originates from the Roswell artesian aquifer. Reimus and others (2012) stated that there is a chloride anomaly east of Roswell that was caused by large withdrawals historically from the Roswell artesian aquifer, which brought water that was relatively more saline into the aquifer from deeper geologic units or from east of the Pecos River.

From 2010 to 2012 Reimus and others (2012) collected continuous specific-conductance data within the identified 31-mile subreach of the Pecos River. Reimus and others (2012) reported that the specific conductance increases in the Pecos River and in tributaries to the Pecos River as these streams flow from west to east. They also reported increases in specific conductance in the Pecos River from the north boundary of the BLNWR to a scout camp site within the refuge on the west bank of the Pecos River (fig. 7). They noted that there were no tributary streams with flow during their survey period between the upstream and downstream ends of the 31-mile reach they studied and concluded that the increases in specific conductance were inflows of saline spring flows or saline groundwater contributing to streamflow. The surveys by Reimus and others (2012) also indicated that the specific conductance in the Pecos River increases downstream to the point where hunter oxbow empties into the Pecos River; the natural drainage from the BLNWR is through hunter oxbow. Downstream from where hunter oxbow empties into the Pecos River, specific conductance remained constant except near the confluence of the Pecos River with the Rio Hondo, where increases in specific conductance were observed (Reimus and others, 2012).

The NMED sampled Bitter Lake and a sinkhole they referred to as “Bitter Lake sinkhole no. 19” in June 2007 at BLNWR as part of a statewide lake survey (New Mexico Environment Department, 2007). The conductivity for the sample from Bitter Lake was 32,900 µS/cm at 23.67 °C, and conductivity for the sample from Bitter Lake sinkhole no. 19 was 34,710 µS/cm at 26.7 °C. Conductivity values were converted to specific conductance in µS/cm at 25 °C by using the following equation:

$$SC = C / 1 + r\ (T - 25) \tag{3}$$

where

- SC is the specific conductance of the sample, in microsiemens per centimeter at 25 °C;
- C is the conductivity of the sample, in microsiemens;
- r is a temperature correction coefficient of 0.02; and
- T is the temperature of the sample, in degrees Celsius.

By converting the conductivity values, a specific-conductance value of 33,799 µS/cm at 25 °C was indicated for the sample from Bitter Lake, and a specific-conductance value of 33,569 µS/cm at 25 °C was indicated for the sample from Bitter Lake sinkhole no. 19.

Miyamoto and others (2007) also studied the salinity inputs to the Pecos River between Acme and Artesia, focusing on the sinkhole lakes at Bottomless Lakes State Park. Miyamoto and others (2007) stated that there are dozens of sinkhole lakes, many filled with saline artesian water along a fault zone, and that saline water from these sinkhole lakes flows into wetlands and then to the Pecos River. According to Miyamoto and others (2007), salinity in these sinkhole lakes ranges from 15,000 to 35,000 mg/L, adding approximately 261,000 tons of salt to the Pecos River annually. Stafford and others (2009) stated that the source of the saline water to these lakes is from upward movement of water from the San Andres Limestone through fractures in the overlying Seven Rivers Formation and that some of these lakes overflow into adjacent wetlands and then drain to the Pecos River. Land (2016a) stated that, because of the decline in hydraulic head in the underlying artesian aquifer, the water levels in these sinkhole lakes have dropped and that only Lea Lake continues to provide water to the wetlands that subsequently drain to the Pecos River.

Smith (2012) stated that the salinity affecting the Pecos River in Chaves and De Baca Counties, N. Mex., and part of Eddy County, N. Mex., originates from an area east of the Pecos River; Smith (2012) further stated that, in addition to Lea Lake, east of the Pecos River there are two saline springs, Comanche Spring and the spring in Eightmile Draw, that are discharging groundwater to the Pecos River. Smith (2012) noted that a specific-conductance value of 8,200 micromhos per centimeter (µmho/cm; equivalent to µS/cm at 25 °C) was measured in a sample collected at Comanche Spring in December 1978 by Geohydrology Associates, Inc., for the BLM. A specific-conductance value of 4,440 µmho/cm was also measured in a sample collected from Comanche Spring in 2007 (Smith, 2012). There were two other specific-conductance values reported in the USGS NWIS database for this site: 4,160 µS/cm at 25 °C in July 1952 and 5,200 µS/cm at 25 °C in June 1971 (U.S. Geological Survey, 2017b). Smith (2012) reported that the spring in Eightmile Draw discharges saline groundwater to the Pecos River; however, no water-chemistry data were provided to substantiate this statement. Additionally, Smith (2012) stated that there are two diabase dikes, Railroad Mountain and El Camino Del Diablo, trending east and west for 30 and 25 miles, respectively, which may be routing flow from an underlying brine aquifer towards Lea Lake, Comanche Spring, and the spring in Eightmile Draw.

Malaga to Pierce Canyon Crossing—Subreach in Reach C

The subreach from Malaga to Pierce Canyon Crossing within reach C (fig. 8) has been extensively studied as a known source of salinity to the basin. Miyamoto and others (2006, 2008) and Gregory and others (2013) stated that the largest source of saline water discharging into the Pecos River in this subreach comes from a brine aquifer near Malaga Bend (fig. 8). Havens and Wilkins (1980) concluded that the saline water is likely originating from the contact of the Rustler and Salado Formations, where the water was measured moving upward through the rocks before discharging to the Pecos River at a rate of approximately 0.5 ft^3/s. The discharge of saline water to the Pecos River in the Malaga Bend region was documented as early as the 1940s (Richey and others, 1984). Miyamoto and others (2006) estimated that the discharge of saline water in the Malaga Bend region produces a salt load greater than

172,000 tons of salt per year (approximately 472 tons per day). Theis and Sayre (1942) estimated that a load of as much as 342 tons per day of sodium chloride was added to the Pecos River in the Malaga Bend region. Because Miyamoto and others (2006) estimated a salt load which is much higher compared to the load estimated by Theis and Sayre (1942), the load estimated by Miyamoto and others (2006) likely refers to the total load of all dissolved solids.

The Malaga Bend Experimental Salinity Alleviation Project was authorized by Congress in 1958 (Gregory and others, 2013). Studies began in 1963 to investigate if the salinity of the Pecos River could be reduced by pumping saline groundwater near Malaga Bend (Cox and Havens, 1965). It was determined that pumping saline groundwater from a brine aquifer near Malaga Bend at a rate greater than 0.5 ft^3/s would lower the potentiometric head in the aquifer and could reduce the discharge of saline groundwater to the river by about 70 percent (Havens and Wilkins, 1980). The USGS and the Pecos River Commission monitored the effects of pumping groundwater near Malaga Bend on the salinity of the Pecos River until 1976, when the project was discontinued because it was discovered that the pumped saline groundwater was leaking into the river from the surface depression where it was stored (Thompson, 2008). In the 1970s, saline groundwater was also pumped from Malaga Bend and transported by pipeline to Culberson County, Tex., for use in enhanced oil recovery; however, in 1977 pumping discontinued because of problems with the pump and casing (Clark, 1987). From 1992 through 2005, several private companies proposed to harvest the salt, but harvesting the salt during this period did not prove viable for a variety of reasons including leakage problems and environmental concerns (Bureau of Reclamation, 1993; Bureau of Reclamation, written commun., 1992). In 2010, Southwest Salt Company, LLC (hereinafter “Southwest Salt”), took over the project, drilled a new well, and constructed new evaporation ponds to harvest the salt. As of 2018, four evaporation ponds were in use at the Southwest Salt plant, and the operation was pumping about 200 acre-feet per year (0.3 ft^3/s) of saline groundwater (Suzy Valentine, TCEQ, written commun., 2018). The plant has the potential to produce and market 90,000 tons of salt per year (approximately 247 tons per day) and is permitted to pump as much as 400 gallons per minute of groundwater (645 acre-feet per year, or 0.9 ft^3/s; Gregory and others, 2013), which is also the maximum allowed per the Pecos River masters manual (Suzy Valentine, TCEQ, written commun., 2018). The Pecos River Commission, the NMED, and the TCEQ monitor the reduction in salt load in the Pecos River downstream from Malaga Bend. According to measurements made for Southwest Salt from 2010 to 2013, before the pumping of saline groundwater at the Southwest Salt plant began, the salinity of groundwater at Malaga Bend was greater than 6,700 mg/L; since 2013 the salinity has been averaging about 4,500 mg/L (Suzy Valentine, TCEQ, written commun., 2018). There has also been a decrease of about 28 percent in the average daily salt load downstream from Malaga Bend compared to the salt load upstream from Malaga Bend since pumping at the salt plant began (Suzy Valentine, TCEQ, written commun., 2018). The “brine aquifer” near Malaga Bend as discussed in the literature extends approximately 4 miles west-southwest of Malaga, extends approximately 30 miles east-northeast to U.S. Highway 62, and covers approximately 200 square miles. The approximate location has been delineated from figure 14 in Mercer (1983) and can be obtained digitally in the data release (Houston and others, 2019).

Miyamoto and others (2007) reported that the Delaware River contributes 25 percent of the flow into Red Bluff Reservoir. Although streamflow in the Delaware River has been measured continuously since 1937 at USGS streamflow-gaging station 08408500 Delaware River near Red Bluff, N. Mex., there is no regular monitoring of the salinity of the Delaware River. The NMED collected the most recent comprehensive water-quality sample from the Delaware River on September 25, 2013, and reported a dissolved-solids concentration of 2,950 mg/L (Gary Schiffmiller, NMED, written commun., 2015). The streamflow measurement at a nearby USGS streamflow-gaging station on the Delaware River for the same date and time was 8.5 ft^3/s, which corresponds to a dissolved-solids load of 67.6 tons per day (U.S. Geological Survey, 2017b). Streamflow at the nearby station in the Delaware River was measured approximately monthly from May 2006 to February 2011, and specific conductance was measured approximately monthly from November 2003 to February 2011 by the USGS. The USGS also collected water-quality samples at streamflow-gaging station 08407500 Pecos River at Red Bluff, N. Mex., approximately 4 miles upstream from the Delaware River confluence, on February 25, 2015. On that same day the USGS reported a dissolved-solids concentration of 6,300 mg/L and measured a streamflow of 71 ft^3/s, which correspond to a dissolved-solids load of 1,206 tons per day (U.S. Geological Survey, 2017b). On June 11, 2014, the BLM sampled a site on the Pecos River approximately 2 miles upstream from the confluence of the Delaware River and reported a dissolved-solids concentration of 5,790 mg/L (David Herrell, written commun., 2015). The BLM also sampled a site on the Pecos River about 1 mile downstream from the Delaware River confluence on the same day and reported a dissolved-solids concentration of 3,150 mg/L (David Herrell, written commun., 2015). No streamflow measurements were made by the BLM in association with the collection of these samples in 2014, so the dissolved-solids load cannot be computed. A saline spring that issues into Owl Draw approximately 12 miles upstream from the confluence of Owl Draw and the Delaware River was sampled by the USGS once in the early 1980s. On September 2, 1983, the USGS measured a dissolved-solids concentration of 3,420 mg/L in a sample collected from this spring and estimated the discharge as 1.5 gallons per minute (0.002 ft^3/s) (U.S. Geological Survey, 2017b). No other sampling results or streamflow measurements were found in the literature for this spring, and it is unknown if it is still flowing.

Red Bluff Reservoir to Confluence of Rio Grande and Pecos River—Reach D

Red Bluff Reservoir near the Texas-New Mexico border (fig. 9) was constructed in 1936 to provide irrigation water for seven irrigation districts in Texas (Dowell and Breeding, 1967). Evaporation losses of water and elevated salinity are concerns of Red Bluff Reservoir water managers, permitted irrigators, and farmers and ranchers downstream from the reservoir. Average dissolved-solids concentrations of 5,000 mg/L have been measured on the Pecos River upstream from the reservoir and the inflow of the Delaware River (Miyamoto and others, 2006). An improvement of the quality of water entering the reservoir from New Mexico would be beneficial to water managers, irrigators, and other users. Salinity of the water released from the reservoir averages 6,150 mg/L (Miyamoto and others, 2007).

Water loss occurs at Red Bluff Reservoir as a result of seepage into the underlying Rustler Formation (Ewing and others, 2012). Miyamoto and others (2007) concluded that half of the water that flowed into Red Bluff Reservoir during 1991–2001 was lost through evaporation or seepage; Miyamoto and others (2007) also stated that the increase in flow between Red Bluff Reservoir and Orla may be return flow from reservoir seepage. Miyamoto and others (2007) noted that there is not a streamflow-gaging station for monitoring discharge at the Red Bluff Reservoir outflow gate. Rather, streamflow is measured in the Pecos River 10.7 miles downstream from Red Bluff Reservoir at the streamflow-gaging station at Orla. Salt Creek, a perennial tributary, empties into the Pecos River upstream from this streamflow-gaging station.

Brune (1981) reported that there were two spring complexes (Red Bluff Springs and Allison Spring) that provide water (or at one time provided water) to Red Bluff Reservoir. Red Bluff Springs in Loving County, Tex., was considered moderately saline and likely issued from the Rustler Formation (fig. 1*B*). Brune (1981) reported that a chloride concentration of 2,200 mg/L was measured in a sample collected in May 1978 from Red Bluff Springs. It is unknown whether Red Bluff Springs still flows and, if so, how much salinity it contributes to Red Bluff Reservoir. Allison Spring is also in Loving County, Tex., near the Texas-New Mexico border, and was considered a freshwater spring (fig. 1*B*). Allison Spring was submerged when Red Bluff Reservoir filled for the first time in 1937 (Dowell and Breeding, 1967). No other information was found in the literature, and it is unknown if this spring is still flowing.

Belzer and Hart (2007) stated that Salt Creek (also known as Screwbean Creek), the only perennial tributary to the Pecos River upstream from Girvin, adds salt both to the Pecos River and to the groundwater near the Pecos River. Upper Rio Grande Basin and Bay Expert Science Team (BBEST) (2012) stated that the source of the salt in Salt Creek is Rustler Springs, whereas Brune (1981) stated that the source of the salt in Salt Creek is Screwbean Springs (fig. 1*B*). Brune (1981) also stated that Screwbean Springs issue from fractures or faults from the Rustler and Castile Formations. Brune (1981) compiled water-quality analyses done on various springs throughout Texas and reported that concentrations of sodium (88 mg/L), chloride (60 mg/L), sulfate (1,680 mg/L), and dissolved solids (2,460 mg/L) were measured in a sample collected from Rustler Springs in 1976. Brune (1981) also reported that a sodium concentration of 88 mg/L, a chloride concentration of 116 mg/L, a sulfate concentration of 1,914 mg/L, and a dissolved-solids concentration of 3,120 mg/L were measured in a sample collected from Screwbean Springs in 1904. No other information was found in the literature about Screwbean Springs.

Miyamoto and others (2006) stated that two creeks, Salt Draw and Toyah Creek, are potential sources of salinity upstream from the Coyanosa to Girvin subreach within reach D. Salt Draw and Toyah Creek enter the Pecos River as subsurface seepage between Pecos and Coyanosa.

Miyamoto and others (2006) stated that saline water intrusion into the Pecos River between Coyanosa and Girvin, a subreach in reach D, has a pronounced effect on salinity of the streamflow. The following publications from the literature discuss potential sources of the higher salt loads in this reach compared to upstream reaches of the Pecos River. Miyamoto and others (2006) stated that the source of salt in this subreach is saline groundwater. Upper Rio Grande BBEST (2012) stated that between a concrete dam that diverts the Pecos River into irrigation canals (called the Ward II turnout) and Girvin there are springs that contribute water to the Pecos River at a dissolved-solids concentration ranging from 12,000 to 15,000 mg/L. Upper Rio Grande BBEST (2012) also stated that this section of the Pecos River continuously has water, even during the most recent drought in 2011. According to Jensen and others (2006), water in the Pecos River between Grandfalls and Girvin increases in salinity by contacting natural salt deposits.

Hoff (2012) evaluated the chloride to bromide concentration ratio (Cl/Br ratio) in samples collected along the Pecos River between Pecos and Girvin by the TCEQ between 2008 and 2010. Hoff (2012) concluded that the greatest increase in the Cl/Br ratio was between Grandfalls and Imperial, contending that a deep groundwater source such as the Capitan Reef aquifer might be affecting the water quality in this subreach. The flow path of the deep groundwater from the Capitan Reef aquifer to the Pecos River may be a fault near the intersection of Highway 18 and Farm to Market Road 1450 that was identified by Armstrong and McMillion (1961).

Brune (1981) reported that several springs issue into the Pecos River in the Grandfalls to Girvin subreach including Antelope Springs, which is near Horsehead Crossing, a ford on the Pecos River near site D.8. Analyses of a sample collected by TWDB in May 1965 from the Pecos River near Horsehead Crossing indicated a sodium concentration of 5,070 mg/L, a chloride concentration of 8,290 mg/L, a sulfate concentration of 4,140 mg/L, and a dissolved-solids concentration of 19,200 mg/L. In July 2008, the TCEQ collected a sample from the Pecos River at TCEQ station 20399, which is near USGS station 311402102285400 Pecos River at Horsehead Road near Imperial, Tex. A chloride concentration of 3,400 mg/L was measured in this July 2008 TCEQ sample, along with a sulfate concentration of 2,480 mg/L and a dissolved-solids concentration of 9,550 mg/L (Houston and others, 2019). In a sample collected by the USGS in February 2015 at station 311402102285400, the sodium, chloride, and sulfate concentrations were 3,129 mg/L, 6,061 mg/L, and 3,017 mg/L, respectively; the dissolved-solids concentration was 16,323 mg/L in this sample (Houston and others, 2019).

According to Miyamoto and others (2006), the water quality of the Pecos River begins to improve south of Girvin as a result of fresher inflows from groundwater discharge and tributaries. However, water-quality data collected from the Pecos River by the USGS in February 2015 indicate that specific-conductance values remained high between USGS station 08446550 Pecos River near Girvin, Tex. (site D.9), and USGS station 304718101500600 Pecos River at Crockett County Road 306 near Iraan, Tex. (site D.13), with values reported at these stations of 24,051 and 21,407 μS/cm at 25 °C, respectively (Houston and others, 2019). Between February 1 and March 1, 2015, specific-conductance values ranging from approximately 17,000 to 18,500 μS/cm at 25 °C were measured at the nearest downstream site, USGS station 08447000 Pecos River near Sheffield, Tex. (site D.14, a real-time, continuous water-quality monitoring station) (table 1) (Houston and others, 2019).

Yuan and others (2007) examined the dissolved-solids concentrations at the Pecos River near Langtry, Tex., and found what the authors termed a “decadal variability in salinity similar to the Pacific Decadal Oscillation (PDO).” Yuan and others (2007) concluded that stream salinity is above average when the PDO is in its warm phase and below average when the PDO is in its cold phase. In other words, Yuan and others (2007) contended that long-term changes in salinity and streamflow in the Pecos River are climate related.

Other Sources of Salinity in the Pecos River Basin

In addition to the specific reaches discussed in the previous sections, there are other areas or processes that are potentially contributing to the salinity of water in the basin and (or) contributing to the poor quality of the water. The Nash Draw in New Mexico is a closed surface-water basin formed by dissolution of underlying evaporite units, particularly the Rustler and Salado Formations, and by erosion (Bachman, 1981; Lambert, 1983). The Nash Draw is approximately 5 miles east of Loving and approximately 17 miles east of Carlsbad (fig. 8) (Bachman, 1981). At its closest point, the Nash Draw is approximately 1 mile east of the Pecos River. The Nash Draw is considered an active karst system, and a brine aquifer referred to by Mercer (1983) underlies the Nash Draw, mirroring the surface expression of the Nash Draw (Powers and others, 2006; Goodbar and Goodbar, 2014; Houston and others, 2019). The Nash Draw contains several lakes or playas including Salt Lake (referred to locally as “Laguna Grande de la Sal”). The Nash Draw is the location of much of the potash mining in southeastern New Mexico (Mercer, 1983). Minerals rich in potassium such as sylvite (potassium chloride) and langbeinite (potassium magnesium sulfate) are the principal minerals mined; these minerals are mainly used to make fertilizer (Barker and Austin, 1993; Bureau of Land Management, 2016). The relation between the groundwater system in the Nash Draw and the Pecos River is not well understood, specifically the relation of the shallow karstic features and the underlying brine aquifer, which is discharging to the Pecos River (Powers and others, 2006; Goodbar and Goodbar, 2014). According to Geohydrology Associates, Inc. (1978), researchers trying to answer the question as to whether the groundwater from the potash mining area will reach the Pecos River were not in agreement. Investigators from Architecture, Engineering, Consulting, Operations, and Maintenance (AECOM; 2011) stated that the Nash Draw drains to Salt Lake and potentially to the Pecos River.

Irrigation return flows are one potential source of salinity to the basin. Hood and Kister (1962, p. 7) explained, “irrigation exposes large amounts of water to the atmosphere, and even though fresh water is applied, the return water from irrigated areas may be saline. In the river valleys where return flow from irrigation is used and reused several times, the water becomes more and more saline.” Causapé and others (2004, p. 212) further explained, “the return flows from arid and semiarid irrigated agriculture may increase salt and nitrate concentrations of the receiving water systems, limiting their agricultural, industrial, urban, and ecological uses.” LaFave (1987) suggested that the irrigation return flows become more saline through the process of evapotranspiration and the leaching of natural salts as the return flows percolate through the unsaturated zone before returning to the Pecos River. Evapotranspiration decreases the volume of water in a body of water, thereby concentrating the salts left behind, which in turn can contribute to the salinity of the Pecos River.

Part of the elevated salinity in the Pecos River in New Mexico, as well as in Texas, is a result of rock-water interactions between irrigation return flows and salt deposits in the Permian Basin (fig. 2); the irrigation return flows become enriched with dissolved salts before returning to the river or recharging groundwater that discharges to the river (Pillsbury, 1981; Hoagstrom, 2009). According to Reimus and others (2012), the Carlsbad Irrigation District needs to use more water for irrigation than it would otherwise because of the relatively high salinity levels of the Pecos River. According to Ashworth (1990), the quality of groundwater in Ward County, Tex., has deteriorated as a result of irrigation return flow. Ashworth (1990) reported that groundwater in Ward County contains between 7,000 and 10,000 mg/L of dissolved solids.

Oil and gas activities in Texas and New Mexico are another potential source of salinity to the basin. Currently (2019) the preferred method of disposal of oil field wastewater is injection into saltwater disposal wells. From the review of the literature, there are more than 1,000 saltwater disposal wells in the basin (State of New Mexico Oil Conservation Division, 2019; Railroad Commission of Texas, 2016). The spatial distribution of these wells has been compiled and is available in Houston and others (2019). In Texas, some of the saltwater disposal wells are completed in the San Andres Limestone and in overlying units of the Artesia Group particularly in Crane, Crockett, Pecos, and Upton Counties. There are many artesian wells that were also completed in the San Andres Limestone that continue to flow, raising concern that saltwater from disposal wells may migrate to the artesian wells (Rold, 1971; Richter and others, 1990). In the Yates and Toborg Oil Fields in northeastern Pecos County near Iraan there are approximately 30 active injection wells that have an injection zone from 327 to 510 ft below land surface (Railroad Commission of Texas, 2016). This represents a shallow range in depths for an injection zone; the injection zone could coincide with the freshwater interval at some wells.

Another possible source of salinity in the basin in Texas, and particularly in Pecos County, is wells that were drilled originally as oil-test wells but encountered water under pressure and then converted to a different use, primarily irrigation. Some of these artesian wells continue to discharge highly saline water (dissolved-solids concentrations greater than 91,000 mg/L), which may make its way into the Pecos River, either directly or during flood events. According to Armstrong and McMillion (1961) there were 27 artesian wells in northern Pecos County and 1 in Bakersfield, Tex. (fig. 9), completed in the San Andres Limestone, 1 artesian well completed in the Yates Formation, 11 artesian wells completed in the Rustler Formation, 1 artesian well completed in the Capitan Limestone, and 2 artesian wells completed in the Pecos Valley alluvium. Most of the wells completed in the San Andres Limestone are between 2,100 and 2,900 ft below land surface and were drilled between 1926 and 1957 (Armstrong and McMillion, 1961). According to an investigator from Trident Environmental, there are at least 40 artesian wells in the Pecos County area that were drilled in the San Andres Limestone that may be abandoned or improperly plugged (Gil Van Deventer, written commun., 2017).

The USGS sampled two of the artesian wells in the study area in February 2015. Although the wells are located approximately one-half mile from each other and completed at approximately the same depth in the San Andres Limestone, the water-chemistry results from the two wells were different. A chloride concentration of greater than 1,800 mg/L was measured in the sample collected from the first artesian well (USGS station 311418102432601), whereas a chloride concentration of greater than 50,000 mg/L was measured in the sample collected from the other artesian well (USGS station 311323102435200) (Houston and others, 2019). Likewise, a dissolved-solids concentration of more than 7,500 mg/L was measured in the sample collected from the first artesian well (USGS station 311418102432601), whereas a dissolved-solids concentration greater than 91,000 mg/L was measured in the sample collected from the second artesian well (USGS station 311323102435200) (Houston and others, 2019).

Mapped Geologic Units and Their Relation to Salinity of the Pecos River Basin

To better understand the relation between the geology and salinity issues of the study area, the USGS mapped the vertical and horizontal extents of geologic units in the study area from the Permian to the Quaternary Periods (figs. 3 and 4). Geologic units with some or all of their geospatial extents contained within the basin include the following: the San Andres Limestone; the Artesia Group, which includes the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations; the Capitan Limestone; the Castile, Salado, and Rustler Formations; the Dewey Lake Redbeds; the Dockum Group (divided into the upper and lower parts of the Dockum Group in this report); the Cretaceous undivided; the Ogallala Formation; and the Pecos Valley alluvium. Some of these formations contain hydrogeologic units that have rocks that dissolve and directly contribute saline water to the Pecos River, whereas the water in other hydrogeologic units has become more saline over time because of infiltrating irrigation return flows. Some hydrogeologic units are discharging water to the Pecos River, whereas others are being recharged by the (sometimes saline) Pecos River.

Across the study area, there are many local-scale extents of shallow alluvial deposits along tributaries and low-lying areas that were not mapped. Including the extents of shallow alluvial deposits, given the large size of the study area, was beyond the scope of this report. The structure surfaces with the spatial extent and depth below land surface are available in Houston and others (2019). A discussion of the lithology of the geologic units in the study area and how they may contribute to salinity of the Pecos River follows.

San Andres Limestone

The San Andres Limestone is the geologic unit with the largest mapped spatial extent in the basin; it is the uppermost mapped unit for nearly 200 miles (north to south) of the western basin (fig. 3). The Guadalupian Series San Andres Limestone was deposited during the middle Permian Period and is the oldest formation that is included in this assessment. The San Andres Limestone is an oil reservoir and an aquifer, containing fresh and saline water and oil at different depths (Armstrong and McMillion, 1961; Summers, 1972; Land, 2003; Stafford and others, 2008a). The San Andres Limestone is composed of dolomite and limestone in Texas and of limestone and dolomitic limestone in New Mexico. North of Roswell and west of the Pecos River, the

San Andres Limestone contains beds of gypsum and anhydrite (Armstrong and McMillion, 1961; Hood and Kister, 1962; Elliott and Warren, 1989). Mourant and Shomaker (1970) stated that east of the Pecos River in De Baca County the San Andres Formation contains beds of salt but that west of the Pecos River there is little to no salt. In New Mexico, the San Andres Limestone is the primary water-bearing unit in the carbonate aquifer that is part of the Roswell Basin aquifer system (Land and Newton, 2007). Armstrong and McMillion (1961) reported that the concentration of dissolved solids in wells sampled in the San Andres Limestone in Texas exceeded 5,000 ppm (mg/L) with high sulfate concentrations. Despite the high dissolved-solids concentrations, the San Andres Limestone was used locally as an aquifer in Pecos County (Armstrong and McMillion, 1961).

Artesia Group

The Artesia Group is part of the Guadalupian Series, and the rocks composing this group were deposited during the Permian Period (Tait and others, 1962). The rocks that compose the Artesia Group are discussed from oldest to youngest.

Grayburg Formation

The basal unit of the Artesia Group, the middle Permian-age Grayburg Formation, covers the majority of the eastern and southern subsurface of the basin, underlying many of the tributaries to the Pecos River including Salt Creek, Bitter Creek, and the Rio Hondo in New Mexico but does not directly underlie the Pecos River (figs. 3–5). The Grayburg Formation is composed of dolomite, sandstone, and anhydrite (Tait and others, 1962). Because the Grayburg Formation is typically separated from the Pecos River by multiple formations across the study area, it likely has minimal interaction with the river but may allow vertical movement of groundwater between adjacent formations.

Queen Formation

The middle Permian-age Queen Formation includes most of the eastern and southern parts of the basin; the uppermost mapped extent of it coincides with less than 1 river mile of the Pecos River in New Mexico (fig. 3). Near Roswell, the Pecos River flows along the border where the Seven Rivers and Queen Formations are near surface, and these formations may interact with the Pecos River in this location. The Queen Formation is composed of sandstone, dolomite, and anhydrite (Tait and others, 1962).

Seven Rivers Formation

The middle Permian-age Seven Rivers Formation is present in the subsurface in most of the eastern and southern part of the basin and is the uppermost mapped unit for nearly 110 river miles of the Pecos River in New Mexico (fig. 3). From near Dunlap, N. Mex., to Artesia the western extent of the near-surface Seven Rivers Formation is near or upgradient from the Pecos River and may interact with surface water in this location. The Seven Rivers Formation is composed of dolomite, anhydrite, gypsum, silt, and clay (Cox, 1967). Stafford and Nance (2009, p. 1) explained, “proximal to the current location of the Pecos River, hypogenic dissolution in interbedded carbonate/evaporite facies of the Seven Rivers Formation has produced three-dimensional network caves and vertical collapse structures, which allow vertical movement of groundwater to adjacent formations.” According to Stafford and others (2008b), natural artesian discharge from the Roswell Basin aquifer system still occurs along the west side of the Pecos River east of Roswell. They further stated that the discharge is preferentially moving through solution-enhanced fractures in the Seven Rivers Formation.

Yates Formation

The middle Permian-age Yates Formation is present in the subsurface throughout most of the eastern and southern parts of the basin and is the uppermost mapped unit for nearly 20 river miles of the Pecos River in New Mexico (fig. 3). From about 15 miles north of Roswell to near the town of Seven Rivers, the western extent of the Yates Formation is generally coincident with the Pecos River; where coincident, the Yates Formation may affect the salinity of the Pecos River through rock-water interactions. The Yates Formation is composed of sandstone, dolomite, anhydrite, and siltstone (Tait and others, 1962). Bjorklund and Motts (1959) stated that north of Carlsbad the evaporite facies of the Yates Formation is present in the subsurface evidenced by sinkholes and collapse structures. The evaporite facies of the Yates Formation also underlies the alluvium from Rocky Arroyo downstream to damsite 3 (Bjorklund and Motts, 1959).

Tansill Formation

The middle Permian-age Tansill Formation is the uppermost mapped unit from about 20 miles downstream from Fort Sumner to about 10 miles upstream from Carlsbad, a distance of more than 50 river miles of the Pecos River (fig. 3). The Tansill Formation may interact with the Pecos River in the areas where it is near surface and parallel to the river. At depth, the spatial extent of the Tansill Formation includes a large part of the study area as it extends southeast from where it crops out to cover most of the lower part of the basin (Houston and others, 2019). The Tansill Formation consists of dolomite, anhydrite, siltstone, clay, and gypsum (Cox, 1967). Cox (1967) explained that the Tansill Formation contains interconnected solution openings in the dolomite units from Lake Avalon to Carlsbad Springs (fig. 1*A*) and that water moves through these solution channels and may discharge at Carlsbad Springs. Water from Lake Avalon leaks into the Tansill Formation (Bjorklund and Motts, 1959; Cox, 1967).

Capitan Limestone

Located in the west-central and southern parts of the basin, the mapped extent of the middle Permian-age Capitan Limestone does not directly underlie the Pecos River (fig. 3). The Capitan Limestone crops out in a horseshoe-shaped unit that rims the Delaware Basin, which is referred to as the “Capitan Reef” (fig. 2). The Capitan Limestone and the underlying Goat Seep Limestone are the units that make up the Capitan Reef aquifer and consist of shelf-margin reef facies composed of dolomite and limestone from the Guadalupian Series (fig. 4) (Uliana, 2001; Clark and others, 2014). The back-reef part of the Capitan Limestone facies transitions to the Artesia Group units of the Seven Rivers, Yates, and Tansill Formations. The back-reef units of the Artesia Group extend to the northwest shelf in New Mexico (Richey and others, 1984; Standen and others, 2009).

Ochoan Series

The Ochoan Series was deposited in the later part of the Permian Period. From oldest to youngest, the following formations compose the Ochoan Series in the study area.

Castile Formation

The late Permian-age Castile Formation is found in the west-central part of the basin and is the uppermost mapped unit for nearly 7 river miles of the Pecos River upstream from Carlsbad (fig. 3). The Castile Formation is composed of anhydrite, calcite-banded anhydrite, halite, and minor amounts of limestone and sandstone (Mercer, 1983). The Castile Formation outcrops in Culberson County, Tex., and Eddy County, N. Mex. (Kirkland and Evans, 1980). Where the Castile Formation outcrops there are numerous sinkholes and caves as a result of upward migration of water from the Bell Canyon Formation and overland flow and runoff during monsoon season (fig. 4) (Stafford, 2013).

Salado Formation

The late Permian-age Salado Formation is found in the central part of the basin and is the uppermost mapped unit for more than 11 river miles of the Pecos River upstream from Carlsbad (fig. 3). The Salado Formation differs from the underlying Castile Formation in that it is composed mostly of halite and a lesser amount of anhydrite and clay; it contains potash minerals such as sylvite and orange polyhalite as opposed to the calcite of the Castile Formation (Garza and Wesselman, 1959). The Salado Formation or the contact between the Salado and Rustler Formations are described by Miyamoto and others (2006) as the source of the saline discharge into the Pecos River at Malaga Bend (fig. 1). Additionally, a sink, near Wink, in Winkler County, Tex., is thought to have formed because of the dissolution of halite in the Salado Formation and subsequent collapse of the overlying units (Johnson, 1989). Whereas the dissolution of the halite in the Salado Formation is a natural process, the presence of an active oil field near the sink is thought to have hastened the collapse (Johnson, 1989; Warren, 2005).

The Salado Formation is important geologically throughout the study area for its mining and nuclear development applications. The Salado Formation is regionally important economically because it contains the “McNutt potash zone” in eastern Eddy and western Lea Counties, which is mined for potash minerals (Mercer, 1983). The Waste Isolation Pilot Plant (WIPP) nuclear waste storage facility, which is east of Carlsbad, N. Mex., and east of the Pecos River, was constructed in the basal salt unit of the Salado Formation (U.S. Department of Energy, 2012). The Project Gnome underground nuclear test site is near the WIPP nuclear waste storage facility; a nuclear device was detonated at this site, also in the basal salt unit of the Salado Formation, in December 1961 (Gard, 1968).

According to Blackwell (1974), in northeastern Pecos County, southeast of Iraan in the Yates and Toborg Oil Fields, faulting or fractures in the Salado Formation below the Pecos River may provide a geologic connection between the underlying geologic units in the Yates and Toborg Oil Fields and the Pecos River. Stafford and others (2009) stated that these fields developed because of karstic processes or hypogenic karst, whereby solution channels and caves were formed in the subsurface because of groundwater moving upward and dissolving the overlying rocks.

Rustler Formation

Located in the central to southern part of the basin, the Rustler Formation is the uppermost mapped unit for more than 40 river miles of the Pecos River between Carlsbad and Malaga (fig. 3). The Rustler Formation consists of late Permian-age sediments deposited unconformably on the Salado Formation (Mercer, 1983). Meyer and others (2012) stated that the Rustler Formation is composed of shale, silt, sandstone, dolomite, and evaporites (halite, gypsum, and anhydrite). The Rustler Formation is commonly divided into five members: a basal unit that has not been officially named but has been referred to in several reports as “the Los Medaños member” (Lorenz, 2006; Powers and others, 2006; AECOM, 2011; Intera Incorporated, 2016) followed in ascending order by the Culebra Dolomite, Tamarisk, Magenta Dolomite, and Forty-niner Members (fig. 4). AECOM (2011, p. 3-4–3-5) stated, “the brine aquifer that discharges to the Pecos River at Malaga Bend is contained within the Los Medaños member of the Rustler Formation and was formed by the dissolution of the underlying Salado Formation.” The brine aquifer contains average dissolved solids of 300,000 mg/L. AECOM (2011) also stated that dissolution of the Tamarisk Member of the Rustler Formation has resulted in the collapse of the Culebra Dolomite and potentially the Magenta Dolomite near Salt Lake; this dissolution and collapse of the members of the Rustler Formation may provide the source of saline water to Salt Lake and to a spring complex referred to locally as “surprise springs” (fig. 8).

Dewey Lake Redbeds

The mapped extent of the late Permian-age Dewey Lake Redbeds is in the central part of the basin (fig. 3). The Dewey Lake Redbeds are composed of siltstone, sandstone, and shale and underlie nearly 9 river miles of the Pecos River including Red Bluff Reservoir (figs. 3 and 4) (Bjorklund and Motts, 1959; AECOM, 2011). The Dewey Lake Redbeds lie conformably on the Rustler Formation (Bachman, 1984) and are not considered an aquifer in the study area (Meyer and others, 2012).

Dockum Group

The Triassic-age rocks of the Dockum Group overlie the Permian-age rocks of the Ochoan Series (fig. 4). The Dockum Group is composed of shale, sand, sandstone, and conglomerate (Bradley and Kalaswad, 2003). In the north-central part of the study area, the mapped extent of the Dockum Group is the uppermost mapped unit for nearly 215 river miles of the Pecos River from Santa Rosa Lake to approximately 20 miles downstream from Fort Sumner, N. Mex (fig. 3). For this study, the Dockum Group has been divided into the lower part of the Dockum Group (referred to hereinafter as the “lower Dockum”) and the upper part of the Dockum Group (hereinafter referred to as the “upper Dockum”). In New Mexico the lower Dockum consists of the Santa Rosa Sandstone, and the upper Dockum consists of the Chinle Formation (Matherne and Stewart, 2012). In Texas the lower Dockum consists of the Santa Rosa Sandstone and the Tecovas Formation (Ewing and others, 2008), and the upper Dockum consists of the Trujillo Formation and the Cooper Member, which is often referred to in the literature as the “Cooper Canyon Formation” (U.S. Geological Survey, 2017a).

Cretaceous Undivided

In the southern part of the study area, the Cretaceous-age rocks that unconformably overlie the Dockum Group were mapped together as one geologic unit for this assessment and are referred to herein as the “Cretaceous undivided.” The Cretaceous undivided is the uppermost mapped unit for nearly 185 river miles of the Pecos River from Girvin, Tex., to the confluence of the Pecos River and the Rio Grande (fig. 3) and includes the Trinity, Fredericksburg, Washita, and Terlingua Groups (fig. 4). The Cretaceous undivided consists of marl, limestone, clay, sand, and shale deposited in marine environments (Rees and Buckner, 1980; Barker and Ardis, 1992, 1996; Meyer and others, 2012).

The Cretaceous undivided is an important source of groundwater in the study area, and rock-water interactions contribute to the relatively high concentrations of dissolved solids (greater than 3,000 mg/L) documented in the groundwater in parts of Culberson and Reeves Counties, Tex. (Rees and Buckner, 1980). In the parts of Culberson and Reeves Counties where relatively saline groundwater is found, the uppermost geologic units are the Castile, Salado, and Rustler Formations (fig. 3). As rainfall infiltrates these formations and provides recharge to the water-bearing units of the Cretaceous undivided (Edwards-Trinity aquifer system), rock-water interactions in the evaporite units of the Castile, Salado, and Rustler Formations occur, increasing the dissolved-solids concentrations in parts of Culberson and Reeves Counties (Rees and Buckner, 1980; Ashworth, 1990). Because groundwater from Culberson and Reeves Counties flows towards the Pecos River (Bumgarner and others, 2012), areas of relatively saline groundwater in these two counties likely contribute to the salinity of the Pecos River.

Ogallala Formation

Late Miocene- to Pliocene-age rocks that include the Ogallala Formation overlie the Cretaceous-age units in the study area. The Ogallala Formation is composed mainly of sand and gravel near the base and sand and clay in the upper part, with pebble- to boulder-size gravel lenses common along the basal surface (Seni, 1980; Gustavson, 1996; Texas Water Development Board, 2015b) (fig. 4). The Ogallala Formation, although in the study area, does not underlie the Pecos River and therefore does not contribute salinity to the Pecos River.

Pecos Valley Alluvium

For nearly 240 river miles of the Pecos River, the Pecos Valley alluvium is the uppermost mapped unit. The Pecos Valley alluvium is composed of sand, silt, clay, gravel, and caliche (Jones, 2004; Mace and others, 2004; Meyer and others, 2012) (fig. 4). The Pecos River is a natural discharge point for the aquifer contained within the Pecos Valley alluvium (White, 1971; Jones, 2004). Natural sources of salinity to the Pecos Valley alluvium originate from interaquifer flow from underlying Permian units and from salts in the soils near the Pecos River (Ashworth, 1990; Jones, 2001). Richey and others (1984) stated that the Rustler Formation (Rustler aquifer) is likely recharging the Pecos Valley alluvium in northern Reeves County in an area where the Dewey Lake Redbeds are absent. Anthropogenic sources of salinity to the Pecos Valley alluvium include the following: saltwater disposal from oil and gas fields, oil field spills, irrigation return flow, and the upwelling of relatively higher saline water from deeper formations induced by the pumping of wells (Ashworth, 1990; Meyer and others, 2012). Elevated sulfate levels in the Pecos Valley alluvium in Reeves County are attributed to flow from the underlying Rustler Formation (Ashworth, 1990; Texas Water Development Board, 2015b). In some parts of Reeves, Pecos, and Ward Counties in Texas, water-level declines have resulted in the Pecos River losing water to the Pecos Valley alluvium (Jones, 2004).

Streamflow Gains and Losses

Streamflow measurements were made by the USGS in February 2015 at sites in four reaches in the basin (table 2). The naming convention for the reaches of the Pecos River described in the “Pecos River Basin Salinity Assessment” section of this report was also used for the streamflow measurement sites and is repeated here for the convenience of the reader: the Pecos River from Santa Rosa Lake to Lake Sumner is reach A, the Pecos River from Lake Sumner to Brantley Lake is reach B, the Pecos River from Brantley Lake to Red Bluff Reservoir is reach C, and the Pecos River from Red Bluff Reservoir to the confluence of the Pecos River and the Rio Grande is reach D. Streamflow gains or losses were computed only in reach B (fig. 7, table 3) and the part of reach D from Orla to Sheffield (fig. 9, table 4) because they are the two primary reaches of interest for their potential sources of salinity to the Pecos River.

Reach B and the part of reach D from Orla to Sheffield were segmented into discrete subreaches to compute streamflow gains and losses. The streamflow gain or loss (tables 3 and 4) was estimated by measuring the difference in streamflow between the upstream and the downstream sites used to define each reach or subreach (figs. 6–9; tables 3 and 4). Streamflow gains and losses can be attributed to groundwater discharge to streams and groundwater recharge from streams, respectively (Winter and others, 1998). The following discussion on the computation of streamflow gains and losses is modified from Braun and Grzyb (2015, p. 18–21).

The difference between inflows and outflows, referred to as the streamflow gain or loss, *G*, is computed as

$$G = Q_D - Q_U - I + D - R - S + E \qquad (4)$$

where

- Q_D is the measured streamflow at the downstream boundary of the reach, in cubic feet per second;
- Q_U is the measured streamflow at the upstream boundary of the reach, in cubic feet per second;
- I is the measured streamflow of tributaries emptying to the Pecos River in the reach, in cubic feet per second;
- D is the measured streamflow of diversions from the reach, in cubic feet per second;
- R is the measured streamflow of return flows to the reach, in cubic feet per second;
- S is the measured discharge from inflows from springs or seeps, in cubic feet per second; and
- E is estimated evaporation losses, in cubic feet per second.

A positive value for *G* indicates a gaining stream reach, whereas a negative value for *G* indicates a losing stream reach. Streamflow measurements were made in February 2015 prior to any reservoir releases; therefore, no diversions (*D*) or return flows (*R*) were taking place in these two reaches during the time of the measurements. Spring and (or) seep contributions to streamflow were not observed in either reach and, as a result, were not included as a separate source in the flux computations. However, any springs or seeps that issue into the Pecos River would be included in the computation of the gain or loss (*G*) for the reach in question. Streamflow measurements were made at selected tributaries (*I*) emptying to the Pecos River and subtracted from estimated streamflow gain or loss within a subreach. The following equation was used to compute the estimated amount of streamflow lost to evaporation (*E*) in each reach:

$$E_{reach} = Lf\,(W \times L) \times E_{lake} \qquad (5)$$

where

- E_{reach} is the evaporation within each stream reach, in cubic feet per second;
- Lf is a dimensionless daylight factor (varies by day and location);
- W is the average of the stream widths measured at the upstream and downstream boundaries of the reach, in feet;
- L is reach length, in feet; and
- E_{lake} is estimated lake evaporation, in cubic feet per second.

The lake evaporation (E_{lake}) within each of the reaches was computed by using mean lake evaporation data from several quadrangles (numbers 304, 404, and 504 for reach B and 604, 605, and 706 for reach D) provided by the Texas Water Development Board (2016b). The lake evaporation was applied to each subreach to compute an estimated evaporation loss for the subreach in cubic feet per second. Evaporative losses were assumed to occur only during the daylight hours, so the lake evaporation value applied to each subreach was multiplied by a daylight factor (ratio of 24 hours to the hours of daylight) as described in Ockerman (2002, p. 7). Data used in the computation of evaporative loss estimates are available in Houston and others (2019).

Table 2. U.S. Geological Survey streamflow-gaging stations and other streamflow measuring sites in the Pecos River Basin, New Mexico and Texas, February 2015.

[USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; ft^3/s, cubic foot per second; m, measured; i, instantaneous streamflow value obtained from the USGS National Water Information System (U.S. Geological Survey, 2017b); rm, obtained from a routine measurement made by either the New Mexico or Texas Water Science Center, value obtained from the USGS National Water Information System (U.S. Geological Survey, 2017b); TRIB, tributary; BLM, Bureau of Land Management]

Site identifier (figs. 6, 7, 8, 9)	Stream reach (figs. 6, 7, 8, 9)	USGS station number	USGS station name	Latitude in decimal degrees (NAD 83)	Longitude in decimal degrees (NAD 83)	Date of measurement	Streamflow (ft^3/s)	Streamflow measured or obtained from a rating	Streamflow measurement error rating
A.1	A	08382650	Pecos River above Santa Rosa Lake, N. Mex.	35.05944	104.76111	2/22/2015	1.7	m	Poor
A.2	A	345701104422710	Pecos River above Santa Rosa, N. Mex.	34.95028	104.70750	2/22/2015	3.0	m	Good
A.3	A	08383500	Pecos River near Puerto De Luna, N. Mex.	34.73008	104.52491	2/22/2015	76.0	i	Fair
B.1	B	08384500	Pecos River below Sumner Dam, N. Mex.	34.60406	104.38792	2/25/2015	23.0	i	Fair
B.TRIB1	B	08385000	Fort Sumner Main Canal near Fort Sumner, N. Mex.	34.50828	104.27836	2/25/2015	0.0	i	Fair
B.2	B	08385522	Pecos River below Taiban Creek near Fort Sumner, N. Mex.	34.33222	104.18111	2/25/2015	34.7	m	Good
B.3	B	08385630	Pecos River near Dunlap, N. Mex.	34.06333	104.30667	2/25/2015	41.6	m	Good
B.4	B	08386000	Pecos River near Acme, N. Mex.	33.57186	104.37360	2/23/2015	29.2	m	Poor
B.TRIB2	B	332430104235610	Bitter Lake National Wildlife Refuge south weir inflow, N. Mex.	33.40833	104.39889	2/23/2015	6.8	m	Poor
B.5	B	332350104235410	Pecos River at Highway 380, N. Mex.	33.39865	104.39865	2/23/2015	43.2	m	Good
B.TRIB3	B	332218104242310	Rio Hondo Spring Channel near Roswell, N. Mex.	33.37174	104.40647	2/23/2015	3.4	m	Good
B.6	B	08394024	Pecos River north boundary (BLM wetlands) near Dexter, N. Mex.	33.31725	104.36167	2/24/2015	61.1	m	Good
B.TRIB4	B	331856104195310	Lea Lake outflow, N. Mex.	33.31556	104.33139	2/24/2015	7.7	m	Fair
B.7	B	08394033	Pecos River south boundary (BLM wetlands) near Dexter, N. Mex.	33.26833	104.35442	2/24/2015	66.3	m	Fair
B.TRIB5	B	08394500	Rio Felix at Old Hwy Bridge near Hagerman, N. Mex.	33.12511	104.34496	2/24/2015	0.0	i	Unspecified
B.8	B	08396500	Pecos River near Artesia, N. Mex.	32.84086	104.32383	2/24/2015	73.0	m	Fair
B.TRIB6	B	08398500	Rio Peñasco at Dayton, N. Mex.	32.74345	104.41413	2/26/2015	0.0	i	Fair
B.9	B	08399500	Pecos River (Kaiser Channel) near Lakewood, N. Mex.	32.68938	104.29922	2/26/2015	80.9	i	Fair
C.1	C	08401500	Pecos River below Brantley Dam near Carlsbad, N. Mex.	32.54319	104.37110	2/26/2015	25.1	rm	Fair
C.TRIB7	C	08401900	Rocky Arroyo at Highway Bridge near Carlsbad, N. Mex.	32.50608	104.37499	2/24/2015	0.0	rm	Unspecified
C.2	C	08402000	Pecos River at damsite 3 near Carlsbad, N. Mex.	32.51123	104.33329	2/27/2015	24.4	rm	Fair
C.3	C	08404000	Pecos River below Avalon Dam, N. Mex.	32.48086	104.26298	2/25/2015	0.0	rm	Excellent

Table 2. U.S. Geological Survey streamflow-gaging stations and other streamflow measuring sites in the Pecos River Basin, New Mexico and Texas, February 2015.—Continued

[USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; ft^3/s, cubic foot per second; m, measured; i, instantaneous streamflow value obtained from the USGS National Water Information System (U.S. Geological Survey, 2017b); rm, obtained from a routine measurement made by either the New Mexico or Texas Water Science Center, value obtained from the USGS National Water Information System (U.S. Geological Survey, 2017b); TRIB, tributary; BLM, Bureau of Land Management]

Site identifier (figs. 6, 7, 8, 9)	Stream reach (figs. 6, 7, 8, 9)	USGS station number	USGS station name	Latitude in decimal degrees (NAD 83)	Longitude in decimal degrees (NAD 83)	Date of measurement	Streamflow (ft^3/s)	Streamflow measured or obtained from a rating	Streamflow measurement error rating
C.TRIB8	C	08405150	Dark Canyon at Carlsbad, N. Mex.	32.40333	104.22944	2/27/2015	0.0	rm	Excellent
C.4	C	08405200	Pecos River below Dark Canyon at Carlsbad, N. Mex.	32.40928	104.21497	2/24/2015	29.4	m	Fair
C.TRIB9	C	08406000	Black River at Malaga, N. Mex.	32.24087	104.06469	2/26/2015	18.2	m	Good
C.5	C	08406500	Pecos River near Malaga, N. Mex.	32.20754	104.02388	2/26/2015	70.2	m	Fair
C.6	C	08407000	Pecos River at Pierce Canyon Crossing, N. Mex.	32.18853	103.97939	2/25/2015	64.8	m	Poor
C.7	C	08407500	Pecos River at Red Bluff, N. Mex.	32.07519	104.03944	2/25/2015	71.3	m	Poor
C.TRIB10	C	08408500	Delaware River near Red Bluff, N. Mex.	32.02314	104.05446	2/26/2015	5.9	rm	Fair
D.TRIB11	D	315300103550900	Salt Creek at Red Bluff Lake Road near Orla, Tex.	31.88322	103.91908	2/25/2015	2.3	m	Fair
D.1	D	08412500	Pecos River near Orla, Tex.	31.87263	103.83158	2/25/2015	7.7	m	Good
D.2	D	08414000	Pecos River near Mentone, Tex.	31.66874	103.62657	2/26/2015	9.7	m	Fair
D.3	D	313256103294600	Pecos River at Barstow Dam near Barstow, Tex.	31.54878	103.49603	2/26/2015	13.0	m	Good
D.4	D	08420500	Pecos River at Pecos, Tex.	31.43652	103.46740	2/25/2015	12.5	rm	Fair
D.5	D	08437710	Pecos River at Farm to Market 1776 near Grandfalls, Tex.	31.36681	103.00599	2/24/2015	22.2	m	Good
D.6	D	311820102523900	Pecos River at Highway 18 near Grandfalls, Tex.	31.30553	102.87747	2/24/2015	24.1	m	Good
D.7	D	311557102355600	Pecos River at Old Crane Road near Imperial, Tex.	31.26581	102.59900	2/25/2015	26.9	m	Good
D.8	D	311402102285400	Pecos River at Horsehead Road near Imperial, Tex.	31.23389	102.48169	2/24/2015	29.5	m	Good
D.9	D	08446500	Pecos River near Girvin, Tex.	31.11320	102.41764	2/24/2015	35.0	i	Fair
D.10	D	08446550	Pecos River near Girvin, Tex. (flood gage)	31.07937	102.36035	2/24/2015	31.4	m	Good
D.11	D	310204102131500	Pecos River at Ranch Road 1901 near McCamey, Tex.	31.03447	102.22097	2/23/2015	36.7	m	Good
D.12	D	305849101582900	Pecos River at State Highway 349 near Iraan, Tex.	30.98033	101.97461	2/22/2015	48.4	m	Good
D.13	D	304718101500600	Pecos River at Crockett County Road 306 near Iraan, Tex.	30.78843	101.83502	2/23/2015	38.6	m	Fair
D.14	D	08447000	Pecos River near Sheffield, Tex.	30.65961	101.77012	2/23/2015	50.0	i	Fair

Table 3. Summary of streamflow measurement results, measurement error ratings, and potential measurement errors for subreaches on the Pecos River between Lake Sumner and Brantley Lake, New Mexico, February 2015.

[USGS, U.S. Geological Survey; ft^3/s, cubic foot per second; BLM, Bureau of Land Management; positive value indicates gain or inflow entering the subreach; negative value indicates loss or outflow leaving the subreach. Green font indicates a verifiable streamflow gain that was larger than the measurement uncertainty associated with the streamflow measurements made in this subreach, and red font indicates a verifiable streamflow loss that was larger than the measurement uncertainty associated with the streamflow measurements made in this subreach]

Upstream site identifier	Downstream site identifier	Subreach from upstream site identifier to downstream site identifier (fig. 7)	Subreach length (river miles)	USGS station name of upstream streamflow measurement site (table 2, fig. 7)	USGS station name of downstream streamflow measurement site (table 2, fig. 7)	Upstream streamflow measurement site: Streamflow (ft^3/s)	Upstream streamflow measurement site: Date of measurement	Upstream streamflow measurement site: Streamflow measurement error rating	Upstream streamflow measurement site: Potential error associated with streamflow measurement (ft^3/s)
B.1	B.2	B.1–B.2	34.3	Pecos River below Sumner Dam, N. Mex.	Pecos River below Taiban Creek near Fort Sumner, N. Mex.	23.0	2/25/2015	Fair	0.08
B.2	B.3	B.2–B.3	29.7	Pecos River below Taiban Creek near Fort Sumner, N. Mex.	Pecos River near Dunlap, N. Mex.	34.7	2/25/2015	Good	0.05
B.3	B.4	B.3–B.4	50.9	Pecos River near Dunlap, N. Mex.	Pecos River near Acme, N. Mex.	41.6	2/25/2015	Good	0.05
B.4	B.5	B.4–B.5	16.8	Pecos River near Acme, N. Mex.	Pecos River at Highway 380, N. Mex.	29.2	2/23/2015	Poor	0.10
B.5	B.6	B.5–B.6	9.6	Pecos River at Highway 380, N. Mex.	Pecos River north boundary (BLM wetlands) near Dexter, N. Mex.	43.2	2/25/2015	Good	0.05
B.6	B.7	B.6–B.7	4.8	Pecos River north boundary (BLM wetlands) near Dexter, N. Mex.	Pecos River south boundary (BLM wetlands) near Dexter, N. Mex.	61.1	2/24/2015	Good	0.05
B.7	B.8	B.7–B.8	55.7	Pecos River south boundary (BLM wetlands) near Dexter, N. Mex.	Pecos River near Artesia, N. Mex.	66.3	2/24/2015	Fair	0.08
B.8	B.9	B.8–B.9	12.7	Pecos River near Artesia, N. Mex.	Pecos River (Kaiser Channel) near Lakewood, N. Mex.	73.0	2/24/2015	Fair	0.08

Table 3. Summary of streamflow measurement results, measurement error ratings, and potential measurement errors for subreaches on the Pecos River between Lake Sumner and Brantley Lake, New Mexico, February 2015.—Continued

[USGS, U.S. Geological Survey; ft^3/s, cubic foot per second; BLM, Bureau of Land Management; positive value indicates gain or inflow entering the subreach; negative value indicates loss or outflow leaving the subreach. **Green** font indicates a verifiable streamflow gain that was larger than the measurement uncertainty associated with the streamflow measurements made in this subreach, and **red** font indicates a verifiable streamflow loss that was larger than the measurement uncertainty associated with the streamflow measurements made in this subreach]

Upstream site identifier	Downstream site identifier	Subreach from upstream site identifier to downstream site identifier (fig. 7)	Subreach length (river miles)	Downstream streamflow measurement site				Difference in measured streamflow in subreach from upstream to downstream site (ft^3/s)	Estimated evaporation loss within subreach	Tributary inflow from streams within reach (ft^3/s)	Estimated streamflow gain or loss within subreach (ft^3/s)	Sum of potential error associated with streamflow measurements at the sites defining upstream and downstream extent of the subreach (ft^3/s)
				Streamflow (ft^3/s)	Date of measurement	Streamflow measurement error rating	Potential error associated with streamflow measurement (ft^3/s)					
B.1	B.2	B.1–B.2	34.3	34.7	2/25/2015	Good	0.05	11.7	0.8	0.0	**12.50**	2.53
B.2	B.3	B.2–B.3	29.7	41.6	2/25/2015	Good	0.05	6.9	1.3	2.0	**6.24**	2.71
B.3	B.4	B.3–B.4	50.9	29.2	2/23/2015	Poor	0.10	−12.4	2.0	0.0	**−10.43**	3.58
B.4	B.5	B.4–B.5	16.8	43.2	2/25/2015	Good	0.05	14.0	0.5	6.81	**7.75**	3.63
B.5	B.6	B.5–B.6	9.6	61.1	2/24/2015	Good	0.05	17.9	0.4	3.44	**14.87**	3.74
B.6	B.7	B.6–B.7	4.8	66.3	2/24/2015	Fair	0.08	5.1	0.2	0.0	5.39	6.12
B.7	B.8	B.7–B.8	55.7	73.0	2/24/2015	Fair	0.08	6.7	3.0	0.0	**9.71**	7.89
B.8	B.9	B.8–B.9	12.7	80.9	2/26/2015	Fair	0.08	7.9	0.5	0.0	8.37	8.72

Table 4. Summary of streamflow measurement results, measurement error ratings, and potential measurement errors for subreaches on the Pecos River between Orla and Sheffield, Texas, February 2015.

[USGS, U.S. Geological Survey; ft^3/s, cubic foot per second; positive value indicates gain or inflow entering the subreach; negative value indicates loss or outflow leaving the subreach. Green font indicates a verifiable streamflow gain that was larger than the measurement uncertainty associated with the streamflow measurements made in this subreach, and red font indicates a verifiable streamflow loss that was larger than the measurement uncertainty associated with the streamflow measurements made in this subreach]

Upstream site identifier	Down-stream site identifier	Subreach from upstream site identifier to downstream site identifier (fig. 9)	Subeach length (river miles)	USGS station name of upstream streamflow measurement site (table 2, fig. 9)	USGS station name of downstream streamflow measurement site (table 2, fig. 9)	Upstream streamflow measurement site			
						Streamflow (ft^3/s)	Date of measure-ment	Stream-flow measure-ment error rating	Potential error associated with streamflow measurement (ft^3/s)
D.1	D.2	D.1–D.2	31.9	Pecos River near Orla, Tex.	Pecos River near Mentone, Tex.	7.7	2/25/2015	Good	0.05
D.2	D.3	D.2–D.3	27.0	Pecos River near Mentone, Tex.	Pecos River at Barstow Dam near Barstow, Tex.	9.7	2/26/2015	Fair	0.08
D.3	D.4	D.3–D.4	13.0	Pecos River at Barstow Dam near Barstow, Tex.	Pecos River at Pecos, Tex.	13.0	2/26/2015	Good	0.05
D.4	D.5	D.4–D.5	48.3	Pecos River at Pecos, Tex.	Pecos River at Farm to Market 1776 near Grandfalls, Tex.	12.5	2/25/2015	Fair	0.08
D.5	D.6	D.5–D.6	14.5	Pecos River at Farm to Market 1776 near Grandfalls, Tex.	Pecos River at Highway 18 near Grandfalls, Tex.	22.2	2/24/2015	Good	0.05
D.6	D.7	D.6–D.7	34.7	Pecos River at Highway 18 near Grandfalls, Tex.	Pecos River at Old Crane Road near Imperial, Tex.	24.1	2/24/2015	Good	0.05
D.7	D.8	D.7–D.8	15.8	Pecos River at Old Crane Road near Imperial, Tex.	Pecos River at Horsehead Road near Imperial, Tex.	28.9	2/25/2015	Good	0.05
D.8	D.9	D.8–D.9	18.1	Pecos River at Horsehead Road near Imperial, Tex.	Pecos River near Girvin, Tex.	29.5	2/24/2015	Good	0.05
D.9	D.10	D.9–D.10	8.0	Pecos River near Girvin, Tex.	Pecos River near Girvin, Tex. (flood gage)	35.0	2/24/2015	Fair	0.08
D.10	D.11	D.10–D.11	14.8	Pecos River near Girvin, Tex. (flood gage)	Pecos River at Ranch Road 1901 near McCamey, Tex.	31.4	2/24/2015	Good	0.05
D.11	D.12	D.11–D.12	26.8	Pecos River at Ranch Road 1901 near McCamey, Tex.	Pecos River at State Highway 349 near Iraan, Tex.	36.7	2/23/2015	Good	0.05
D.12	D.13	D.12–D.13	23.1	Pecos River at State Highway 349 near Iraan, Tex.	Pecos River at Crockett County Road 306 near Iraan, Tex.	48.4	2/22/2015	Good	0.05
D.13	D.14	D.13–D.14	13.5	Pecos River at Crockett County Road 306 near Iraan, Tex.	Pecos River near Sheffield, Tex.	38.6	2/23/2015	Fair	0.08

Table 4. Summary of streamflow measurement results, measurement error ratings, and potential measurement errors for subreaches on the Pecos River between Orla and Sheffield, Texas, February 2015.—Continued

[USGS, U.S. Geological Survey; ft^3/s, cubic foot per second; positive value indicates gain or inflow entering the subreach; negative value indicates loss or outflow leaving the subreach. Green font indicates a verifiable streamflow gain that was larger than the measurement uncertainty associated with the streamflow measurements made in this subreach, and red font indicates a verifiable streamflow loss that was larger than the measurement uncertainty associated with the streamflow measurements made in this subreach]

Upstream site identifier	Down-stream site identifier	Subreach from upstream site identifier to downstream site identifier (fig. 9)	Subeach length (river miles)	Downstream streamflow measurement site				Difference in measured streamflow in subreach from upstream to downstream site (ft^3/s)	Estimated evaporation loss within subreach	Tributary inflow from streams within reach (ft^3/s)	Estimated streamflow gain or loss within subreach (ft^3/s)	Sum of potential error associated with streamflow measurements at the sites defining upstream and downstream extent of the subreach (ft^3/s)
				Stream-flow (ft^3/s)	Date of measure-ment	Streamflow measure-ment error rating	Potential error associated with streamflow measurement (ft^3/s)					
D.1	D.2	D.1–D.2	31.9	9.7	2/26/2015	Fair	0.08	2.0	1.00	0.00	**2.98**	0.86
D.2	D.3	D.2–D.3	27.0	13.0	2/26/2015	Good	0.05	3.3	0.67	0.00	**3.99**	1.01
D.3	D.4	D.3–D.4	13.0	12.5	2/25/2015	Fair	0.08	−0.5	0.18	0.00	−0.35	1.19
D.4	D.5	D.4–D.5	48.3	22.2	2/24/2015	Good	0.05	9.7	0.68	0.00	**10.37**	1.49
D.5	D.6	D.5–D.6	14.5	24.1	2/24/2015	Good	0.05	1.9	0.30	0.00	**2.21**	1.64
D.6	D.7	D.6–D.7	34.7	26.9	2/25/2015	Good	0.05	2.8	0.86	0.00	**3.66**	1.88
D.7	D.8	D.7–D.8	15.8	29.5	2/24/2015	Good	0.05	2.6	0.36	0.00	**2.98**	2.06
D.8	D.9	D.8–D.9	18.1	35.0	2/24/2015	Fair	0.08	5.5	0.47	0.00	**5.95**	3.17
D.9	D.10	D.9–D.10	8.0	31.4	2/24/2015	Good	0.05	−3.6	0.25	0.00	**−3.37**	3.21
D.10	D.11	D.10–D.11	14.8	36.7	2/23/2015	Good	0.05	5.3	0.43	0.00	**5.76**	2.41
D.11	D.12	D.11–D.12	26.8	48.4	2/22/2015	Good	0.05	11.7	0.84	0.00	**12.49**	3.04
D.12	D.13	D.12–D.13	23.1	38.6	2/23/2015	Fair	0.08	−9.7	0.66	0.00	**−9.07**	3.92
D.13	D.14	D.13–D.14	13.5	50.0	2/23/2015	Fair	0.08	11.4	0.42	0.00	**11.79**	5.05

For this study, a subreach is classified as verifiably gaining or losing if the difference in streamflow between the upstream and downstream measurements exceeds the sum of the errors associated with the streamflow measurements at the upstream and downstream sites. Sauer and Meyer (1992, p. 2) described how a measurement rating ranging from excellent to poor is assigned to a streamflow measurement. The ratings are a measure of how close a streamflow measurement is to actual streamflow and are based on observations made by the hydrographer pertaining to the conditions in the stream at the time of measurement, including stream channel uniformity and velocity variability across the stream, and on streamflow statistics computed by using the FlowTracker software as part of a streamflow measurement (U.S. Geological Survey, 2004; SonTek, 2009). Excellent, good, and fair discharge ratings, which are generally assigned to each streamflow measurement, allow for the computation of potential errors that are 2, 5, and 8 percent of the measured streamflow, respectively. A streamflow measurement with a poor rating is assumed to have a potential error greater than 8 percent of the measured streamflow. In this study, a value of 10 percent was used for the computation of error for a streamflow measurement with a poor rating.

For reach B, nine streamflow measurements were made on the main stem of the Pecos River, and all measurements were rated as good or fair except at the Pecos River near Acme, N. Mex., which was rated as poor (fig. 7, table 3). Two additional streamflow measurements were made on tributaries to the Pecos River in reach B, one at the site on each tributary—the BLNWR south weir inflow, N. Mex., site (B.TRIB2), which was assigned a rating of poor, and the Rio Hondo spring channel near Roswell, N. Mex., site (B.TRIB3), which was assigned a rating of good. Yeso Creek, a perennial stream that flows into the subreach B.2–B.3, between the Pecos River below Taiban Creek near Fort Sumner, N. Mex., and the Pecos River near Dunlap, N. Mex., was not measured during this sampling event. A USGS hydrographer familiar with this subreach reported that the estimated base flow in Yeso Creek is approximately 2–4 ft^3/s (Tim Evans, written commun., 2017). A conservative estimate of 2 ft^3/s was used for the Yeso Creek inflow. According to the USGS hydrographer no other streams are perennial in subreach B.2–B.3.

Of the eight subreaches in reach B, seven could be classified as gaining subreaches and one classified as losing; however, only five of the seven gaining subreaches could be classified as verifiably gaining because the gain in streamflow in these five subreaches exceeded the associated errors computed for each of the subreaches (table 3). The reach with the largest verifiable gain (14.87 ft^3/s) was subreach B.5–B.6 between the Pecos River at Highway 380, N. Mex. (site B.5), to the Pecos River north boundary (BLM wetlands) near Dexter, N. Mex. (site B.6). The Rio Hondo spring channel near Roswell, N. Mex. (site B.TRIB3), flows into this subreach. Subreach B.3–B.4, between the Pecos River near Dunlap, N. Mex. (site B.3), and the Pecos River near Acme, N. Mex. (site B.4), was the only subreach with a verifiable loss; with a length of nearly 51 river miles, subreach B.3–B.4 is the second longest subreach, and the loss of 10.43 ft^3/s equates to a loss of 0.20 ft^3/s per mile.

For reach D, 12 streamflow measurements were made on the main stem of the Pecos River, and 2 instantaneous streamflow values were obtained from the USGS NWIS database (table 2) (U.S. Geological Survey, 2017b). All measurements were rated good or fair (table 4). Of the 13 subreaches in reach D, 10 were gaining, and 3 were losing; all 10 gaining reaches could be classified as verifiably gaining because the gain in streamflow exceeded the associated error computed for that subreach. Subreach D.11–D.12, between the Pecos River at Ranch Road 1901 near McCamey, Tex. (site D.11), and the Pecos River at State Highway 349 near Iraan, Tex. (site D.12) (fig. 9), was the subreach with the largest verifiable gain (12.49 ft^3/s) (table 4). The largest verifiable loss (9.07 ft^3/s) was measured in subreach D.12–D.13, between the Pecos River at State Highway 349 near Iraan, Tex. (site D.12), and the Pecos River at Crockett County Road 306 near Iraan, Tex. (site D.13) (fig. 9, table 4). The subreach length between sites D.12 and D.13 is approximately 23 river miles.

Historical gain-loss studies done on the Pecos River were evaluated to see if comparisons to the gain-loss measurements in 2015 could be made. The summarized data from the previous gain-loss (seepage) studies in New Mexico can be found in Daniel B. Stephens (1995b, app. J), and the compiled historical streamflow measurements from the previous gain-loss studies in Texas are available in Houston and others (2019).

Previous gain-loss studies done by the USGS in New Mexico include several studies completed within reach B in the Acme to the Kaiser Channel subreach (the subreach from site B.4 to site B.9 in this report) (fig. 7, tables 2 and 3). Crouch and Welder (1988, p. 17) explained, “the Kaiser Channel was dredged in the late 1940s and early 1950s along the eastern edge of the Pecos River flood plain primarily to reduce overbank flow, but the channel cannot contain streamflows [in the Pecos River] greater than about 1,500 ft^3/s.” The Acme to the Kaiser Channel subreach ends about 9 miles upstream from Brantley Lake. Several gain-loss studies were completed in New Mexico between 1955 and 1970 in reach B. Eighteen of these gain-loss studies were done in the Acme to Artesia subreach (site B.4 to site B.8) (fig. 7, tables 2 and 3) between January 1955 and February 1963, one study was done in the Artesia to the Kaiser Channel subreach (site B.8 to site B.9) in March 1960, two were done in the Acme to the Kaiser Channel subreach (site B.4 to site B.9) between February 1969 and January 1970, and four studies were done in what the authors referred to as the Acme to Lake McMillan subreach (Daniel B. Stephens and Associates, 1995b) (site B.4 to about 4 miles downstream from site B.9) between February 1964 and February 1968. Lake McMillan no longer exists; Brantley Lake is about 2 miles downstream from where Lake McMillan was impounded. When Brantley Dam was completed in 1991, McMillan Dam was breached, and Lake McMillan was drained. Daniel B. Stephens and Associates (1995b) summarized the results of the historical gain-loss studies in reach B and reported that in general the Acme to the Kaiser Channel subreach was gaining and that various subsections within this subreach were gaining and losing during different time periods. During the USGS February 2015 gain-loss measurements, all five subreaches between sites B.4 and B.9 were gaining, although only three of these subreaches were classified as verifiably gaining (table 3).

Previous gain-loss studies in Texas include one that was done in May 1918 from Angeles, Tex. (near the New Mexico State line) (figs. 1 and 5), to Girvin (Texas Board of Water Engineers, 1960). This 1918 gain-loss study was done prior to the construction of Red Bluff Reservoir, and the streamflow gain-loss measurements from 1918 are not comparable to the gain-loss measurements made in 2015 for this study. Four historical gain-loss studies were done in Texas by the USGS in the 1960s: three from Orla to Girvin in March 1964, May 1965, and April 1967 and one from Girvin to Comstock, Tex., in February 1968. The three gain-loss studies in the subreach from Orla to Girvin were done during irrigation season and do not represent base-flow conditions (Grozier and others, 1966, 1968). Additionally, during this period (1964–67) there was an abandoned oil well approximately 7 miles downstream from Toyah Creek, approximately 1,000 feet from the Pecos River, that discharged saline water to a draw and then to the Pecos River (Grozier and others, 1966), which contributed to the streamflow and salinity in the river. The fourth gain-loss study, from Girvin to Comstock, was done in February 1968 and represents base-flow conditions (Spiers and Hejl, 1970). There are four subreaches in this historical USGS study that parallel the subreaches in this study, including the historical subreach from site 1 to site 3, which parallel subreaches D.9–D.10 and D.10–D.11 in this study; the historical subreach from site 3 to site 6, which parallels subreach D.11–D.12 in this study; the historical subreach from site 6 to site 8, which parallels subreach D.12–D.13 in this study; and the historical subreach from site 8 to site 11, which parallels subreach D.13–D.14 in this study (fig. 9). For a direct comparison, data were combined in the D.9–D.10 and D.10–D.11 subreaches to create a D.9–D.11 subreach (site 1 to site 3), and in 2015 the D.9–D.11 subreach was classified as gaining (2.39 ft^3/s), although not a verifiably gaining subreach, whereas in 1968 D.9–D.11 (site 1 to site 3) was a losing subreach (Spiers and Hejl 1970). The subreach D.11–D.12 was the subreach with the largest verifiable gain in 2015 (12.49 ft^3/s), whereas in 1968 D.11–D.12 (site 3 to site 6) was a losing subreach (Spiers and Hejl 1970). The subreach D.12–D.13 was classified as a losing reach in 2015, whereas in 1968 D.12–D.13 (site 6 to site 8) was a gaining reach. The subreach D.13–D.14 (site 8 to site 11) was classified as a gaining reach in both studies. Although comparisons were made to four reaches from the 2015 gain-loss study by using the results of the 1968 gain-loss study, no information on computation method or errors in measurement was provided in the Spiers and Hejl (1968) report. The compiled historical discharge measurements from the previous gain-loss studies in Texas are available in Houston and others (2019).

Data Gaps

Spatial, temporal, and analytical data gaps were identified during the compilation and analysis of data from the study area. Spatial data gaps were identified where surface-water monitoring sites were not sufficient to characterize loads or where the distribution of monitoring sites was insufficient to understand the water chemistry in a given area. Temporal data gaps were identified at locations where data were collected in the past but are not being collected currently (or vice versa). Analytical data gaps were identified where an analysis was incomplete (for example, not enough major ions to compute the major-ion balance), entire constituent groups were omitted (for example, major ions), or selected constituents were not sampled (for example, sodium).

Spatial data gaps were identified where the collection of additional surface-water-quality and groundwater-quality data is warranted in the study area. In New Mexico, the collection of additional surface-water-quality data would help fill data gaps in the subreaches of the Pecos River between Santa Rosa Lake and Santa Rosa, N. Mex., and in the subreaches of the Pecos River between Fort Sumner and Roswell, N. Mex., including the Rio Hondo. In Texas, the collection of additional surface-water-quality data would help fill data gaps in the subreaches of the Pecos River between Orla and Barstow and in the subreaches of the Pecos River between Sheffield and Independence Creek. Parts of the study area with few available groundwater-quality data are found in New Mexico and include the area between Santa Rosa Lake and Fort Sumner in the underlying geologic units of the Dockum Group, between Roswell and Artesia, in the underlying geologic units of the Artesia Group, and between Carlsbad and Malaga in the underlying geologic units of the Rustler Formation and Capitan Limestone near the Pecos River (figs. 3, 6–8).

The water-quality data include the analytical results of samples from 224 sites, collected by multiple agencies, along the main stem of the Pecos River. The period of record for these 224 sites is from July 1, 1900, to April 16, 2015. Of these 224 sites, only 143 were sampled more than once, and of those 143, only 60 have been sampled at least once since January 1, 2010. Furthermore, many of the USGS sites with historical records of long-term sample collection have different periods of record (table 5). The agencies that periodically collect water-quality data along the Pecos River usually do so to determine if water-quality standards within their State are being met and may not regularly analyze for salinity-related constituents.

The water-quality data assessment resulted in the flagging of samples and results after major-ion balance computations, mass balance comparisons, and a statistical analysis to exclude outliers. Of the total data compiled from

Table 5. U.S. Geological Survey streamflow-gaging stations where historical water-quality data were collected, Santa Rosa Lake, New Mexico, to Sheffield, Texas, 1959–2014.

[USGS, U.S. Geological Survey]

Site identifier (figs. 6, 7, 8, 9)	USGS station number	USGS station name	Date range of water-quality samples
A.1	08382650	Pecos River above Santa Rosa Lake, N. Mex.	1981–2010
A.3	08383500	Pecos River near Puerto de Luna, N. Mex.	1967–2011; 2014
B.2	08384500	Pecos River below Sumner Dam, N. Mex.	1959–66; 1979–86; 2003
B.4	08386000	Pecos River near Acme, N. Mex.	1959–98
B.8	08396500	Pecos River near Artesia, N. Mex.	1959–2011
C.4	08405200	Pecos River below Dark Canyon at Carlsbad, N. Mex.	1972; 1976; 1980–81; 1985; 1987–2003
C.5	08406500	Pecos River near Malaga, N. Mex.	1960–2003
C.6	08407000	Pecos River at Pierce Canyon Crossing, N. Mex.	1959–2003
C.7	08407500	Pecos River at Red Bluff, N. Mex.	1959–2003
D.1	08412500	Pecos River near Orla, Tex.	1969–2003
D.9	08446500	Pecos River near Girvin, Tex.	1960–64; 1967–82; 1987–93; 2005–12
D.14	08447000	Pecos River near Sheffield, Tex.	1968–77; 1986–93; 2012–14

approximately 50,000 water samples with approximately 500,000 analytical results, approximately 1 percent of the results were flagged as a questionable result in the dataset because of large relative percent differences (greater than 10 percent) in major-ion balance. Additionally, approximately 2 percent of the results had nutrient and trace element results that were flagged as a questionable result because of a large relative percent difference (greater than 10 percent) between filtered and unfiltered results for the same constituent in the same sample. After the modified z-test was performed on the remaining data, approximately 1 percent of the results for various sampled constituents were flagged as a questionable result after being identified as outliers.

Missing or incomplete information about how a sample was collected or how a sample was analyzed at the laboratory is another type of data gap. Because different agencies collect samples differently and different laboratories process samples differently, it is necessary to acquire and provide in the database as much information as possible about how a sample was collected or processed, especially when combining disparate water-chemistry data. Critical information includes whether a sample was filtered prior to analysis, the method of analysis, whether the result is for the total or dissolved phase, and the reporting limits established by each laboratory, such as the method detection levels and laboratory reporting levels for individual constituents.

Water-quality data gaps became more apparent during the process of analyzing the historical data. One problem when analyzing the historical data was that water chemistry in the Pecos River changes temporally. Therefore, relating changes found between the new and historical data collected along the main stem of the Pecos River can be a challenge because different samples can be associated with different hydrologic conditions, seasons, and land-use activities. Water-quality data collected on an ongoing basis for a least 5 years were only available from 12 sites on the Pecos River, and there is no period of sampling among all 12 sites that overlap (table 5). There is a relatively short period (1987–1993) when the period of sampling at 11 of the 12 sites overlaps (table 5). Because of the scarcity of water-quality data collected throughout the study area for a period of at least 5 years, it was difficult to make meaningful long-term water-quality comparisons throughout the basin. Historical isotopic data were lacking to compare to newly acquired isotopic data. Although the February 2015 USGS sampling was designed to help fill data gaps in areas along the Pecos River, data gaps remain. Additional isotopic data collected along the Pecos River and from groundwater wells, springs, and lake sites could verify results of existing samples, help fill in data gaps where no isotopic data exist, and further define areas providing groundwater inflow to the Pecos River.

Although there is a considerable amount of water-quality data for this study, not all of the constituents that were measured are relevant to salinity, and the constituents varied considerably between different sampling efforts. The lack of consistent sampling of the same constituents at the same sites along the main stem of the Pecos River precludes the possibility of assessing spatial or temporal changes in water quality that could help in understanding the progression of the salinity from upstream to downstream in the basin.

Water-Quality Results

Water-quality results for the surface-water samples collected by the USGS in February 2015 for 20 locations along the main stem of the Pecos River upstream from Santa Rosa Lake to downstream from Iraan were analyzed to assess differences in major-ion concentrations from site to site (fig. 5). Analyses of the major-ion concentrations were used as a mechanism to identify changes in sources of dissolved constituents and possible inputs to the Pecos River that may be adding to the salinity of the river. The concentrations of selected cations and anions in the historical and recently collected (February 2015) samples from the Pecos River are depicted in downstream order (fig. 10). Percent differences of major-ion concentrations between the sites sampled by the USGS in February 2015 also are depicted in downstream order (fig. 11). Percent differences were computed by comparing concentrations measured for a site to those measured for the next downstream site. Dissolved-solids concentrations (fig. 12) and instantaneous dissolved-solids loads (fig. 13) for the samples collected by the USGS in February 2015 are also shown in downstream order. Isotopic ratios for deuterium (δD) and oxygen ($\delta^{18}O$) (figs. 14 and 15) and ^{86}Sr isotopes (fig. 16) of the samples collected by the USGS in February 2015 are included in the discussion of water quality to help determine inputs of water to the Pecos River from other areas such as surface-water tributaries or groundwater inflow. Because surface-water quality can vary between seasons and years, as well as during different hydrologic conditions, it is difficult to make comparisons among historical water-quality samples, particularly if sites along the Pecos River have not been sampled consistently over time. Some additional data were included in the analysis of major ions, and these data were integrated with the February 2015 data and arranged in downstream order (table 6) to provide a more complete understanding of the entire basin. All water-quality data used in these comparisons were checked to ensure that the data quality was comparable with the quality of the data obtained from USGS water-quality samples, including an evaluation of major-ion balance, a comparison of total versus filtered sample values, and scrutiny of extreme concentration values. Only samples with complete analyses for the major ions discussed in this report (calcium, magnesium, sodium, bicarbonate, chloride, and sulfate) were included in the comparisons. Additional historical data included in the comparisons of water-quality results were collected in 2013 and 2014 except for one sample collected in 2010 (table 1).

Not many of the sites sampled by the USGS in February 2015 were sampled consistently in recent history (table 5). Of the 20 sites sampled on the main stem of the Pecos River in February 2015, only 8 of these sites were sampled periodically for the six major ions of interest during the 16 years prior to the February 2015 sampling (U.S. Geological Survey, 2017b; Houston and others, 2019). There are three additional locations on the Pecos River that were not among the 20 sites sampled by the USGS in February 2015 but were sampled more than once during January 2000–February 2015 (Houston and others, 2019). There are three locations not among the 20 sampled by the USGS in 2015 that have been sampled for major ions since January 2011 (U.S. Geological Survey, 2017b; Houston and others, 2019). Chloride and sulfate are the constituents most consistently analyzed for in samples collected from the study area, but at most sites the amount of data that were collected decreased after the mid-1990s (U.S. Geological Survey, 2017b; Houston and others, 2019). The lack of consistent sampling of major ions throughout the study area makes it difficult to evaluate changes in water quality over time (table 5). Sprague and others (2017) encountered similar issues when evaluating historical nutrient data from multiple sources for a trend analysis. Lack of documentation or incomplete documentation associated with the sampling added to the difficulties associated with combining scientific data (Sprague and others, 2017). Similarly, water-quality analysis on the Pecos River was difficult or impossible when including historical samples, so this report focuses on the water-quality results from the USGS sampling in February 2015 (table 6).

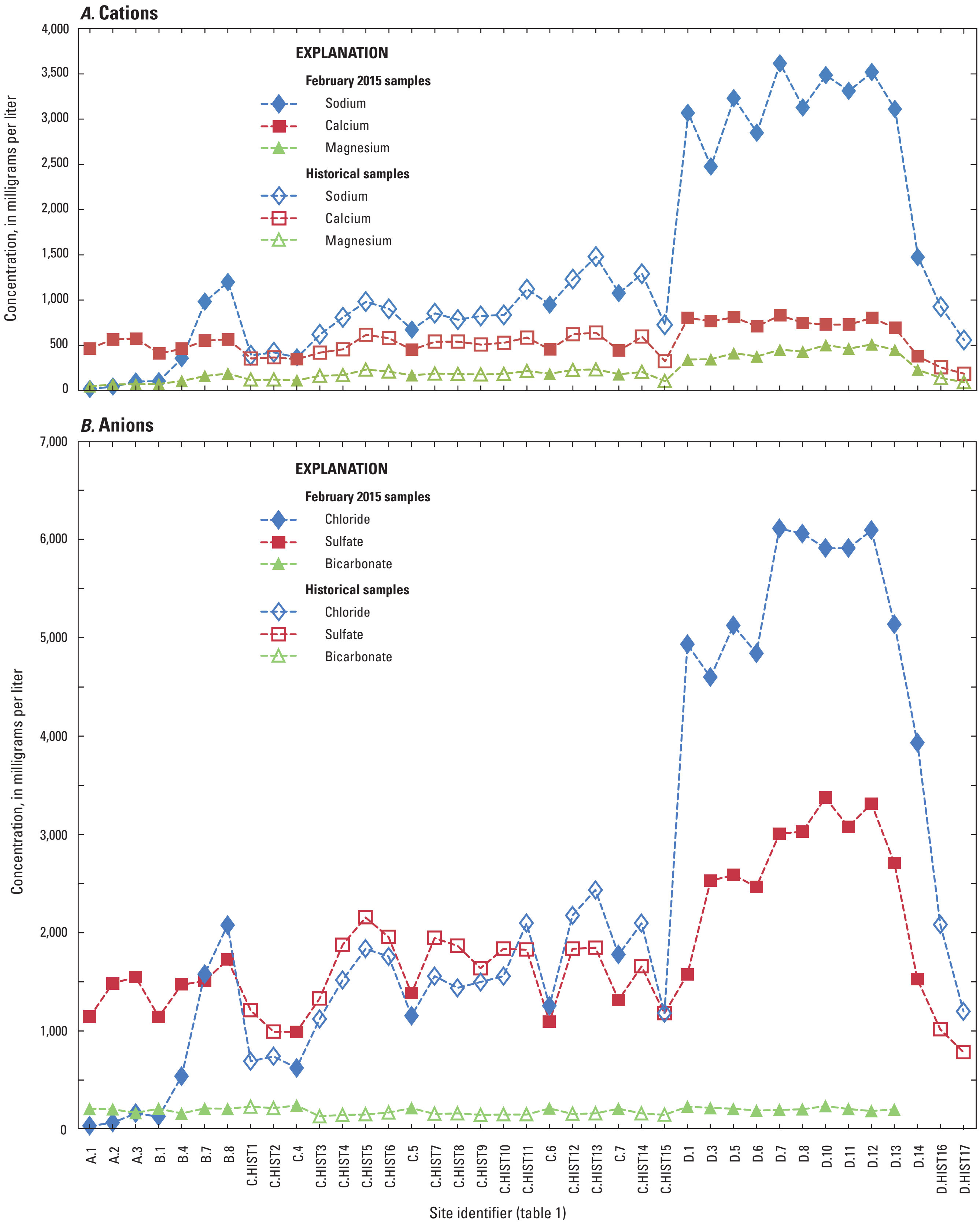

Figure 10. Selected *A*, cations and *B*, anions measured in samples collected from selected historical water-quality sites along the main stem of the Pecos River and water-quality sites sampled by the U.S. Geological Survey in February 2015 in New Mexico and Texas.

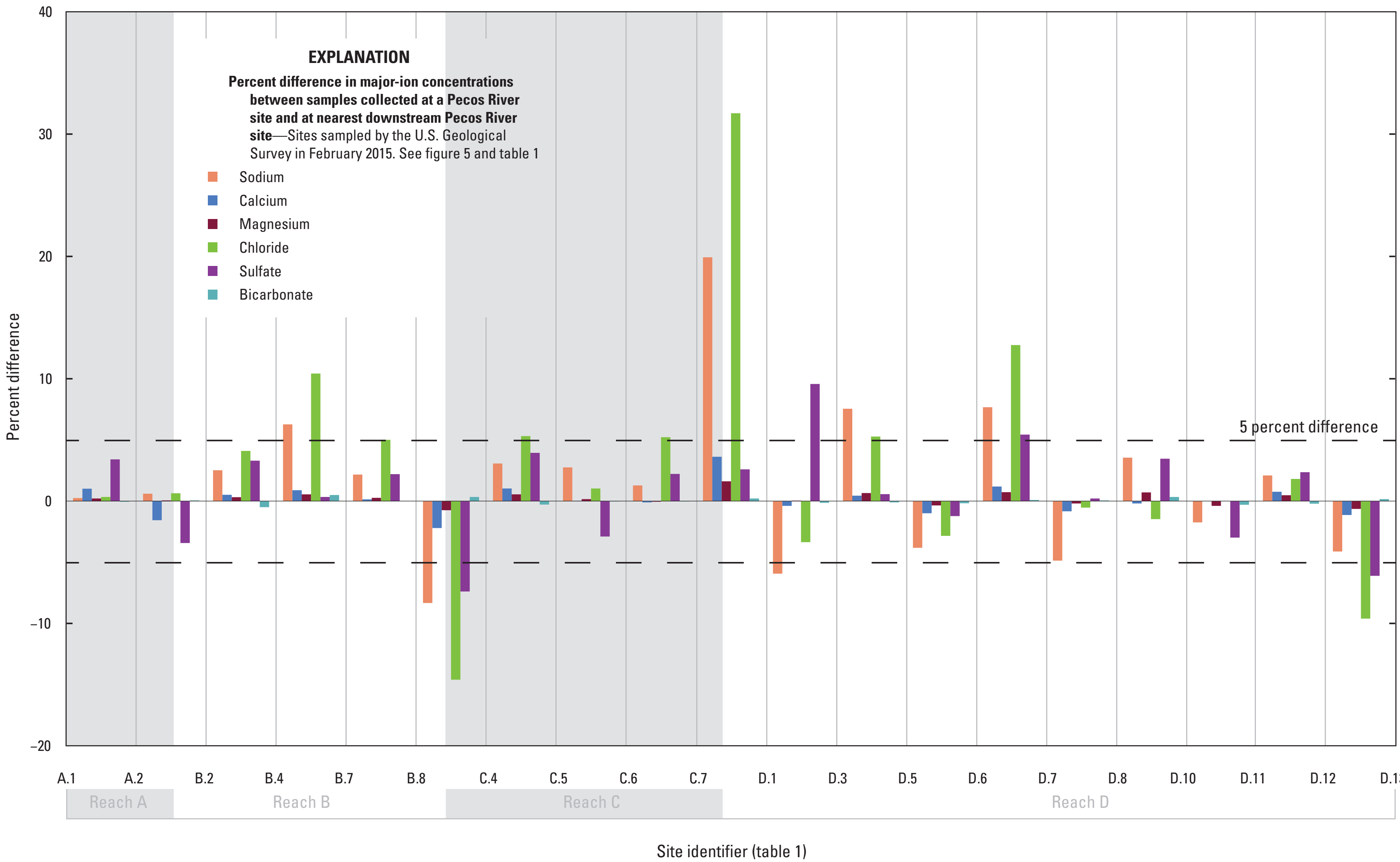

Figure 11. Percent differences in major-ion concentrations between water-quality sites sampled by the U.S. Geological Survey in February 2015 along the main stem of the Pecos River in New Mexico and Texas.

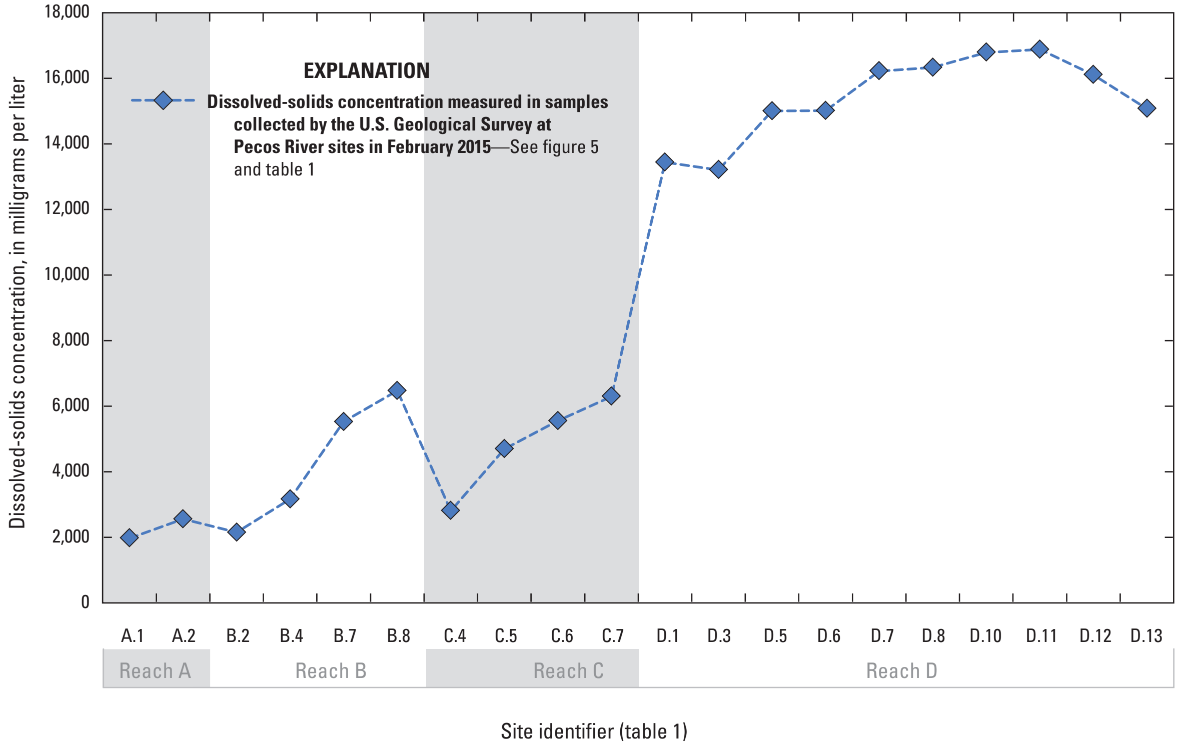

Figure 12. Dissolved-solids concentrations measured in samples collected by the U.S. Geological Survey in February 2015 from water-quality sites sampled along the main stem of the Pecos River in New Mexico and Texas.

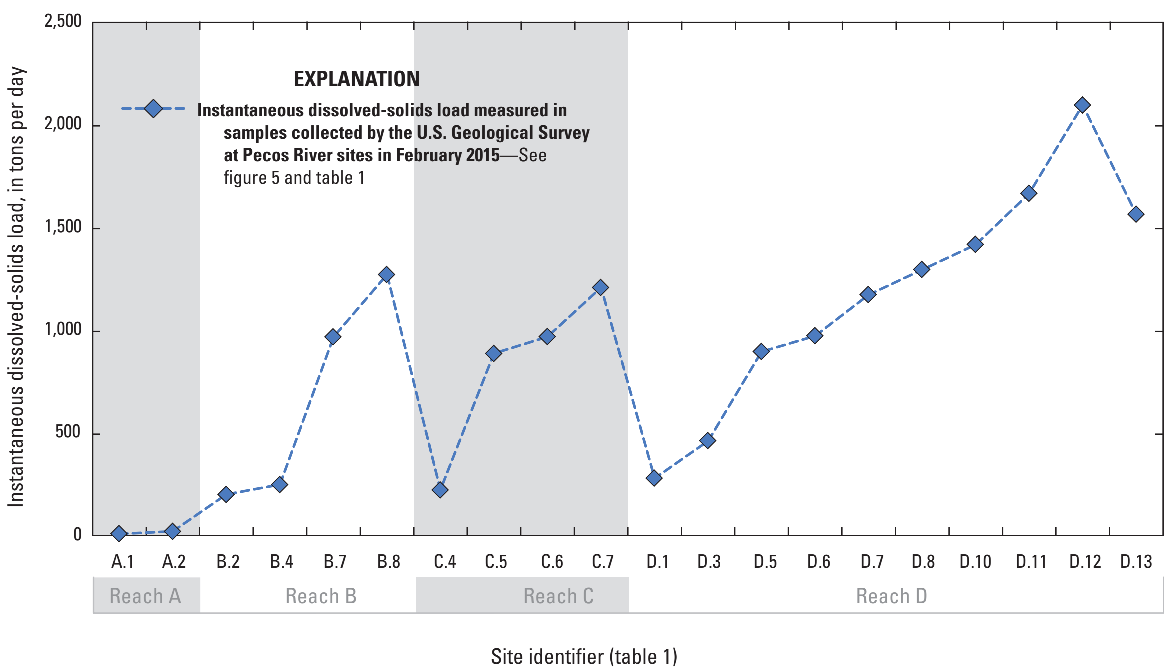

Figure 13. Instantaneous dissolved-solids loads measured in samples collected by the U.S. Geological Survey in February 2015 from water-quality sites sampled along the main stem of the Pecos River in New Mexico and Texas.

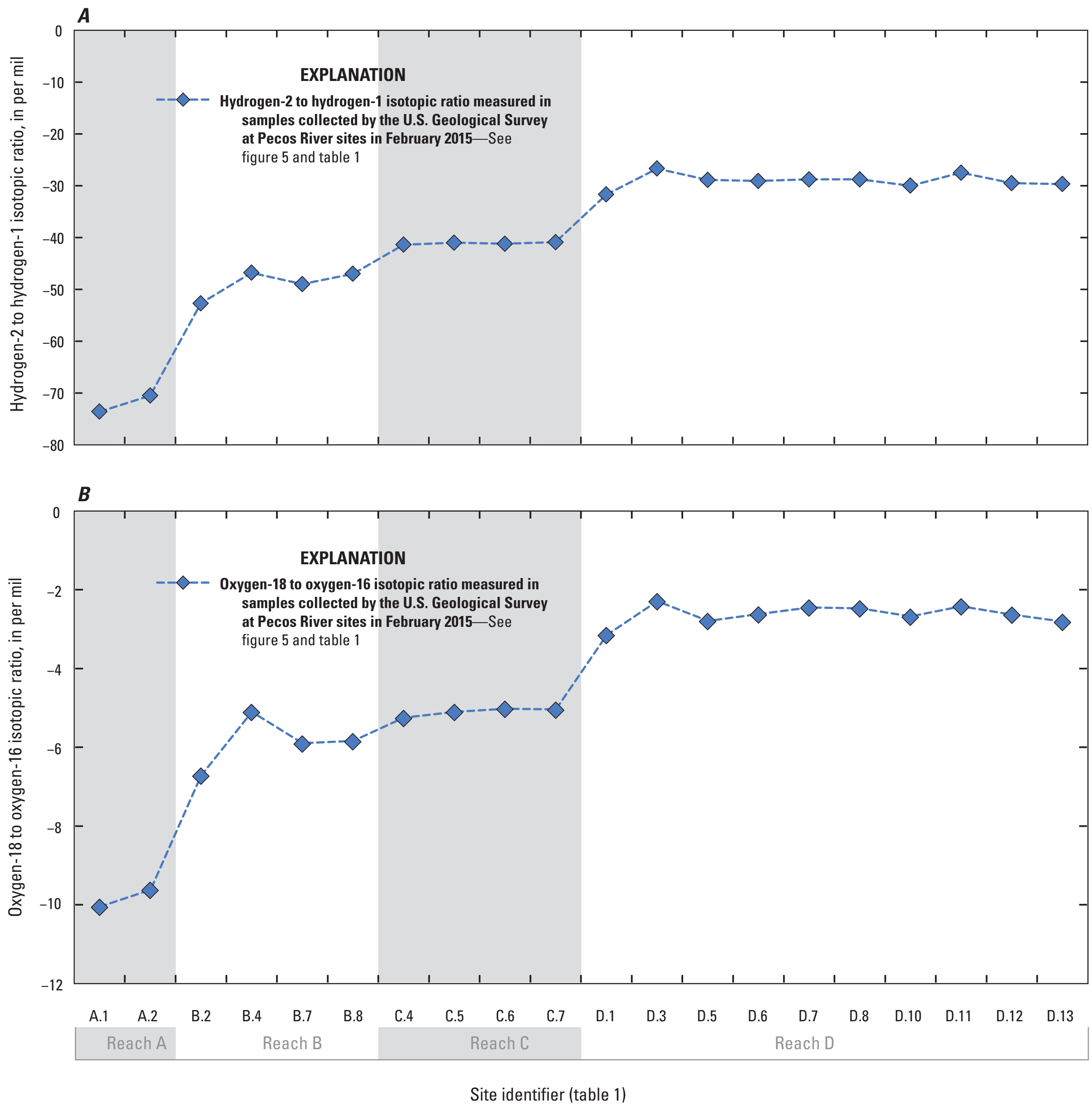

Figure 14. *A*, Hydrogen and *B*, oxygen isotopic ratios measured in water-quality samples collected along the main stem of the Pecos River in New Mexico and Texas by the U.S. Geological Survey in February 2015.

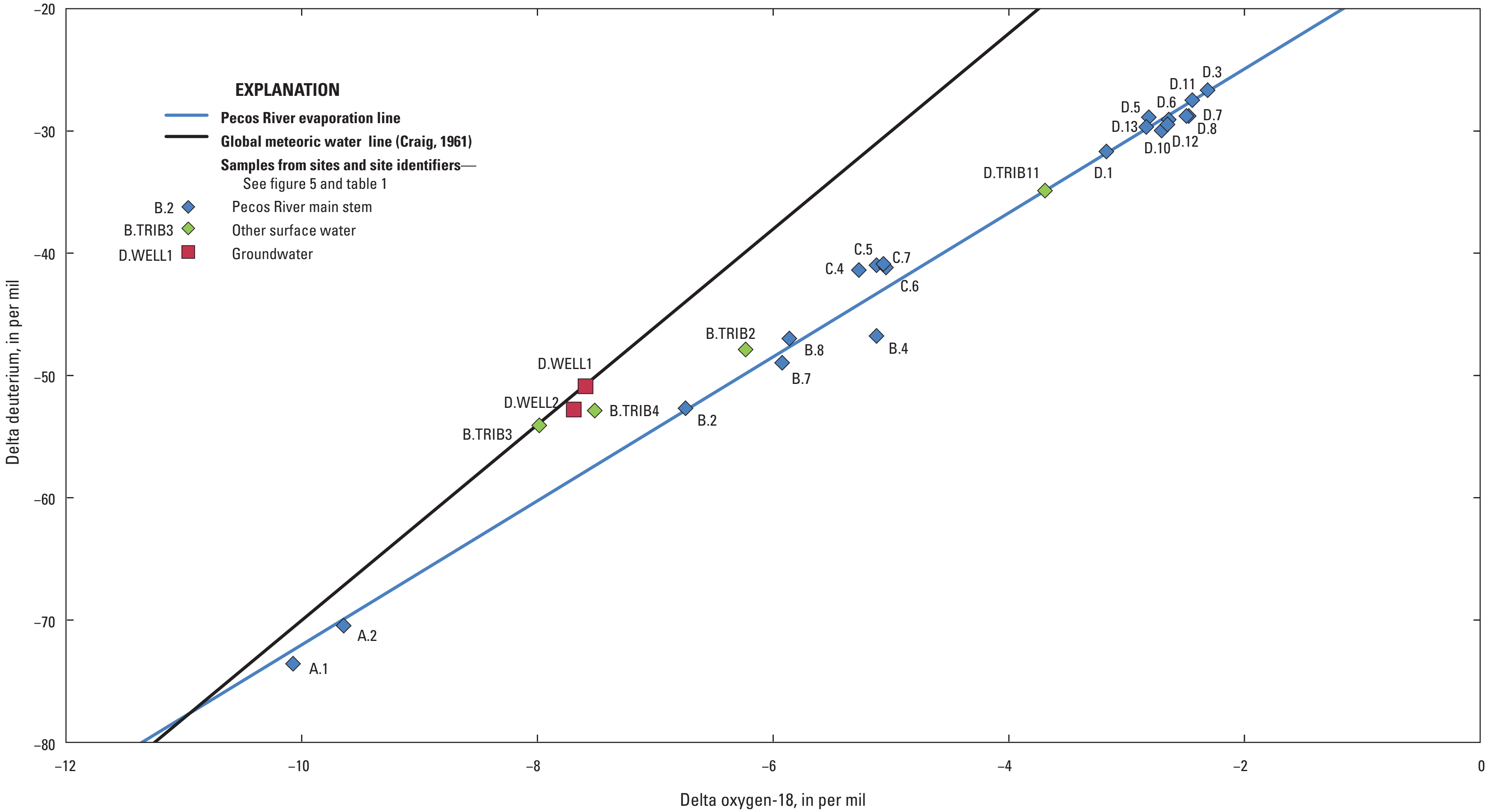

Figure 15. Deuterium versus oxygen-18 isotopic ratios measured in water-quality samples collected by the U.S. Geological Survey in February 2015 compared to the global meteoric water line at selected sampling sites in the Pecos River Basin in New Mexico and Texas.

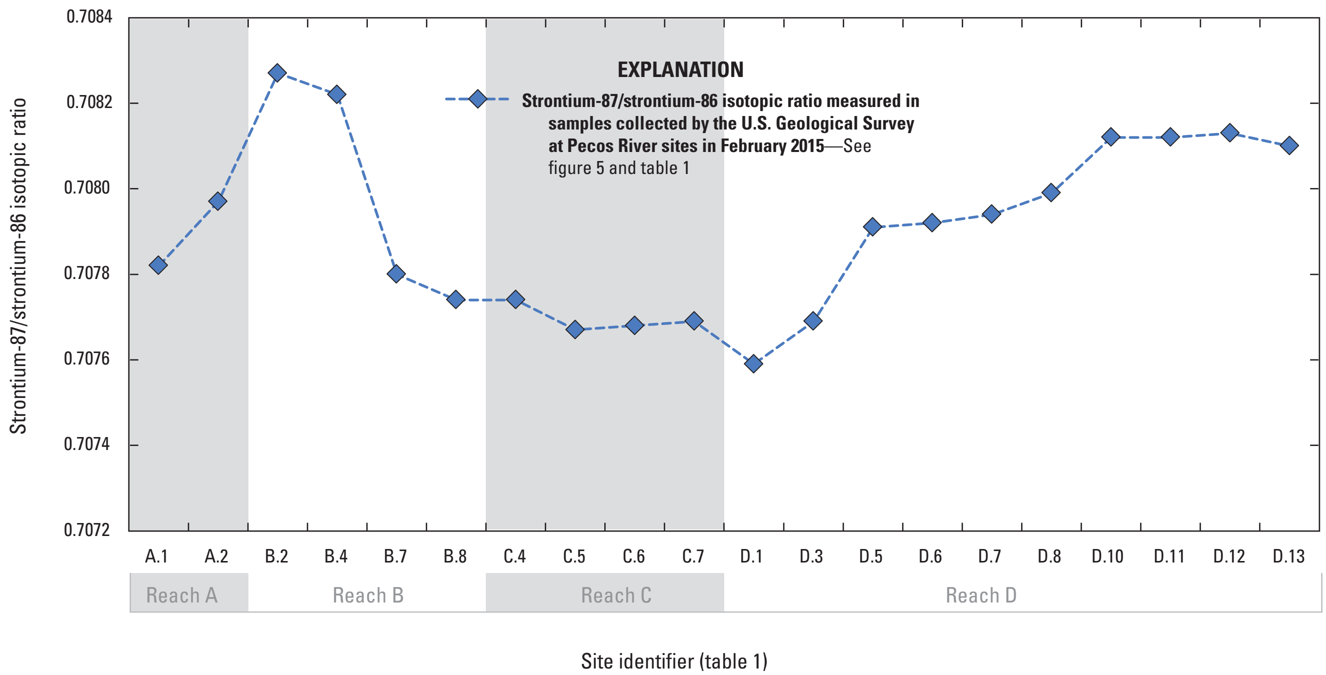

Figure 16. Strontium isotopic ratios measured in samples collected by the U.S. Geological Survey in February 2015 from water-quality sites sampled along the main stem of the Pecos River in New Mexico and Texas.

Major-Ion Concentrations

Major-ion concentrations for calcium, magnesium, sodium, bicarbonate, chloride, and sulfate were compared and evaluated from upstream to downstream for the 20 samples collected in February 2015 by the USGS and the samples collected historically by the USGS and other agencies from the main stem of the Pecos River (fig. 10). To evaluate changes in concentrations from upstream to downstream sites, all of the sites were identified by their downstream order on the Pecos River. The largest changes in concentrations among the six constituents were found for sodium, chloride, and sulfate. Percent differences in concentrations for sodium, chloride, and sulfate are greater than 5 percent between sites at several locations along the Pecos River (fig. 11). Changes in sodium concentrations are similar to the changes in chloride concentrations along the Pecos River, which is consistent with dissolution of sodium chloride contributing to salinity in the river.

Sodium (16.4 and 42.5 mg/L) and chloride (9 and 42 mg/L) concentrations are relatively low in the upper part of the basin near Santa Rosa Lake (sites A.1 and A.2, respectively) compared to the rest of the basin. However, calcium (464 and 566 mg/L) and sulfate (1,120 and 1,470 mg/L) concentrations near Santa Rosa Lake (sites A.1 and A.2, respectively) (table 6) are greater than sodium and chloride concentrations possibly because of dissolution of gypsum, which is prevalent in the upper part of the basin (Miyamoto and others, 2006).

The first noticeable increase in sodium and chloride concentrations occurs between Fort Sumner and Artesia (within reach B). Chloride concentrations increase from about 100 to slightly more than 2,000 mg/L, and sodium concentrations increase from about 100 to 1,200 mg/L (fig. 10, table 6). Several factors could be contributing to the higher salinity in this reach. Historical data indicate that the chloride concentration in groundwater near Roswell ranges from 500 to 4,000 mg/L (Houston and others, 2019). The chloride anomaly east of Roswell (Reimus and others, 2012) likely underlies all of the saline inputs from the Acme to Artesia reach except the Lea Lake outflow channel; these saline inputs include spring inflow and underflow from the BLNWR and inflow from the Rio Hondo (fig. 7). The inflow to the Pecos River on the BLNWR near the south weir (site B.TRIB2), the Rio Hondo spring channel near Roswell (site B.TRIB3), and the Lea Lake outflow channel (site B.TRIB4) were sampled by the USGS during February 2015. Sodium concentrations of 1,620 and 1,120 mg/L and chloride concentrations of 2,450 and 2,730 mg/L were measured in samples collected from site B.TRIB2 and site B.TRIB3, respectively. These concentrations indicate that the BLNWR south weir inflow and Rio Hondo inflow are likely sources contributing to the increasing saline concentrations in the Pecos River between Fort Sumner and Artesia. In addition, outflow from Lea Lake (site B.TRIB4) enters the Pecos River upstream from Dexter, and the sample from this location had sodium concentrations of 1,720 mg/L and chloride concentrations of 2,590 mg/L during the February 2015 water-quality sampling (Houston and others, 2019).

Table 6. Selected water-quality data including quality-control data from sites sampled by the U.S. Geological Survey in February 2015 in the Pecos River Basin, New Mexico and Texas.

[USGS, U.S. Geological Survey; deg C, degree Celsius; mg/L, milligram per liter; std, standard; µS/cm, microsiemens per centimeter; n/a, not collected; <, less than; BLM, Bureau of Land Management; TRIB, tributary; MRK, Farm to Market 1053; $CaCO_3$, calcium carbonate; SiO_2, silica; H, hydrogen; O, oxygen; Sr, strontium; per mil, a unit expressing the ratio of stable-isotope abundances of an element in a sample to those of a standard material. Sites at which quality-control data were collected are shown in blue font]

USGS station number	Site identifier (figs. 6, 7, 8, 9)	Sample date	USGS station name	Temperature, air (deg C)	Dissolved oxygen (mg/L)	pH (std units)	Specific conductance (µS/cm at 25 deg C)	Temperature, water (deg C)
08382650	A.1	2/22/2015	Pecos River above Santa Rosa Lake, N. Mex.	2.7	8.5	7.8	2,080	5.8
08382650	A.1	2/22/2015	Pecos River above Santa Rosa Lake, N. Mex. (replicate)	n/a	n/a	n/a	n/a	n/a
345701104422710	A.2	2/22/2015	Pecos River above Santa Rosa, N. Mex.	−4	10.2	7.7	2,490	6.5
345701104422710	A.2	2/22/2015	Field blank (N. Mex)	n/a	n/a	n/a	<5	n/a
08385522	B.2	2/25/2015	Pecos River below Taiban Creek near Fort Sumner, N. Mex.	16	10.9	8.1	2,440	5.7
08386000	B.4	2/23/2015	Pecos River near Acme, N. Mex.	0.5	11.6	8.1	3,950	3.6
08394033	B.7	2/24/2015	Pecos River south boundary (BLM wetlands) near Dexter, N. Mex.	7	11.2	8.1	7,830	3.5
08396500	B.8	2/24/2015	Pecos River near Artesia, N. Mex.	10.5	11.3	8.1	9,180	7.6
08405200	C.4	2/24/2015	Pecos River below Dark Canyon at Carlsbad, N. Mex.	5	10	8	3,820	9.9
08406500	C.5	2/26/2015	Pecos River near Malaga, N. Mex.	4	10.5	8.2	5,640	8.8
08407000	C.6	2/25/2015	Pecos River at Pierce Canyon Crossing, N. Mex.	17	11.6	8.3	7,330	8
08407500	C.7	2/25/2015	Pecos River at Red Bluff, N. Mex.	10	10.7	8.3	8,500	6.2
08412500	D.1	2/25/2015	Pecos River near Orla, Tex.	n/a	13.5	7.8	19,000	n/a
313256103294600	D.3	2/26/2015	Pecos River at Barstow Dam near Barstow, Tex.	5	9.2	7.8	18,500	10.4
08437710	D.5	2/24/2015	Pecos River at Farm to Market 1776 near Grandfalls, Tex.	−0.3	9.3	7.8	21,400	6.3
08437710	D.5	2/24/2015	Field blank (Tex.)	n/a	n/a	n/a	<5	n/a
311820102523900	D.6	2/24/2015	Pecos River at Highway 18 near Grandfalls, Tex.	2.6	12.1	8.1	21,400	7.2
311557102355600	D.7	2/25/2015	Pecos River at Old Crane Road near Imperial, Tex.	6.2	10.4	7.9	22,900	6.6
311402102285400	D.8	2/24/2015	Pecos River at Horsehead Road near Imperial, Tex.	1.1	12	8.0	23,400	6
08446550	D.10	2/24/2015	Pecos River near Girvin, Tex. (flood gage)	−2.8	10.1	7.9	24,000	4.4
310204102131500	D.11	2/23/2015	Pecos River at Ranch Road 1901 near McCamey, Tex.	−2.7	10.1	7.9	23,700	7.6
305849101582900	D.12	2/22/2015	Pecos River at State Highway 349 near Iraan, Tex.	7.3	8.1	7.8	21,900	16.4
305849101582900	D.12	2/22/2015	Pecos River at State Highway 349 near Iraan, Tex. (replicate)	n/a	8.4	7.9	22,400	16.1
304718101500600	D.13	2/23/2015	Pecos River at Crockett County Road 306 near Iraan, Tex.	−1.3	8.4	7.9	21,400	11.8
332430104235610	B.TRIB2	2/23/2015	Bitter Lake National Wildlife Refuge south weir inflow	−3	10.3	8.1	10,400	3.3
332218104242310	B.TRIB3	2/23/2015	Rio Hondo Spring Channel near Roswell, N. Mex.	−2	13.4	7.8	10,700	7.9
331856104195310	B.TRIB4	2/24/2015	Lea Lake outflow, N. Mex.	5	7.9	7.9	11,700	13.4
311418102432601	D.WELL1	2/25/2015	Artesian well MRK east near Imperial, Tex.	6.2	0.1	6.8	10,300	28.8
311323102435200	D.WELL2	2/25/2015	Artesian well southeast of Farm to Market 1053 near Imperial, Tex.	13.9	0.1	6.6	124,000	27.6
315300103550900	D.TRIB11	2/25/2015	Salt Creek at Red Bluff Lake Road near Orla, Tex.	12.6	9.9	7.9	31,500	6.7

Table 6. Selected water-quality data including quality-control data from sites sampled by the U.S. Geological Survey in February 2015 in the Pecos River Basin, New Mexico and Texas.—Continued

[USGS, U.S. Geological Survey; deg C, degree Celsius; mg/L, milligram per liter; std, standard; µS/cm, microsiemens per centimeter; n/a, not collected; <, less than; BLM, Bureau of Land Management; TRIB, tributary; MRK, Farm to Market 1053; $CaCO_3$, calcium carbonate; SiO_2, silica; H, hydrogen; O, oxygen; Sr, strontium; per mil, a unit expressing the ratio of stable-isotope abundances of an element in a sample to those of a standard material. Sites at which quality-control data were collected are shown in blue font]

USGS station number	Site identifier (figs. 6, 7, 8, 9)	Sample date	Dissolved solids, dried at 180 deg C (mg/L)	Dissolved solids load (tons per day)	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L)	Bromide (mg/L)	Carbonate (mg/L)	Chloride (mg/L)
08382650	A.1	2/22/2015	1,980	9.02	464	46	1.7	16.4	153	185	<0.15	0.6	9
08382650	A.1	2/22/2015	n/a	n/a	470	47	1.7	17.5	151	182	<0.15	0.6	9
345701104422710	A.2	2/22/2015	2,560	20.5	566	67	1.9	42.5	149	181	<0.15	0.6	42
345701104422710	A.2	2/22/2015	<20	n/a	<0.022	<0.011	<0.03	<0.06	n/a	n/a	<0.03	n/a	<0.02
08385522	B.2	2/25/2015	2,150	201	410	72	3.1	103	155	187	<0.15	1.2	106
08386000	B.4	2/23/2015	3,170	249	461	105	3.9	356	114	137	<0.6	0.9	517
08394033	B.7	2/24/2015	5,530	971	551	161	5.7	982	156	187	<0.75	1.2	1,560
08396500	B.8	2/24/2015	6,470	1,276	566	188	8.2	1,200	155	185	<0.75	1.8	2,060
08405200	C.4	2/24/2015	2,810	223	346	113	5	366	184	220	0.33	2	602
08406500	C.5	2/26/2015	4,700	890	450	169	8.4	673	160	192	<1.5	1.5	1,130
08407000	C.6	2/25/2015	5,550	972	452	185	22.5	948	160	190	<1.5	2.8	1,240
08407500	C.7	2/25/2015	6,300	1,212	441	179	25.9	1,080	156	186	<1.5	2.4	1,760
08412500	D.1	2/25/2015	13,400	280	803	342	27.8	3,100	173	208	6.11	1.6	4,930
313256103294600	D.3	2/26/2015	13,200	464	765	346	33.2	2,480	162	194	4.35	1.3	4,590
08437710	D.5	2/24/2015	15,000	899	809	413	37.7	3,230	153	184	3.97	1.1	5,120
08437710	D.5	2/24/2015	n/a	n/a	0.134	0.184	0.14	1	n/a	n/a	<0.030	n/a	1
311820102523900	D.6	2/24/2015	15,000	977	710	377	35	2,850	140	166	3.95	1.9	4,840
311557102355600	D.7	2/25/2015	16,200	1,178	830	451	40.8	3,620	145	175	4.38	1	6,110
311402102285400	D.8	2/24/2015	16,300	1,300	747	431	35.2	3,130	150	181	4.29	1.2	6,060
08446550	D.10	2/24/2015	16,800	1,423	788	502	42.8	3,490	177	214	4.76	1.2	6,410
310204102131500	D.11	2/23/2015	16,900	1,672	728	463	39.6	3,310	153	183	4.85	1.6	5,910
305849101582900	D.12	2/22/2015	16,100	2,104	804	511	44.4	3,520	135	162	4.29	1.3	6,100
305849101582900	D.12	2/22/2015	16,100	n/a	701	441	36.6	3,050	135	162	4.67	1.2	6,100
304718101500600	D.13	2/23/2015	15,100	1,571	691	448	39.2	3,110	149	179	4.03	1.3	5,140
332430104235610	B.TRIB2	2/23/2015	6,850	126	426	130	8.8	1,620	166	200	<1.5	1.5	2,450
332218104242310	B.TRIB3	2/23/2015	7,640	78.2	606	252	4.6	1,120	202	244	<1.5	1	2,730
331856104195310	B.TRIB4	2/24/2015	8,520	178	815	129	9.1	1,720	166	200	<1.5	0.9	2,590
311418102432601	D.WELL1	2/25/2015	7,530	n/a	640	193	17.7	1,130	627	763	4.12	0.8	1,840
311323102435200	D.WELL2	2/25/2015	91,600	n/a	2,000	395	50	35,200	369	448	<15	1	53,600
315300103550900	D.TRIB11	2/25/2015	22,000	137	921	410	41.8	6,440	127	152	15.5	1.3	8,190

Table 6. Selected water-quality data including quality-control data from sites sampled by the U.S. Geological Survey in February 2015 in the Pecos River Basin, New Mexico and Texas.—Continued

[USGS, U.S. Geological Survey; deg C, degree Celsius; mg/L, milligram per liter; std, standard; µS/cm, microsiemens per centimeter; n/a, not collected; <, less than; BLM, Bureau of Land Management; TRIB, tributary; MRK, Farm to Market 1053; $CaCO_3$, calcium carbonate; SiO_2, silica; H, hydrogen; O, oxygen; Sr, strontium; per mil, a unit expressing the ratio of stable-isotope abundances of an element in a sample to those of a standard material. Sites at which quality-control data were collected are shown in blue font]

USGS station number	Site identifier (figs. 6, 7, 8, 9)	Sample date	Fluoride (mg/L)	Silica (mg/L as SiO_2)	Sulfate (mg/L)	Iron (mg/L)	Manganese (mg/L)	Strontium (mg/L)	Boron (mg/L)	H-2/H-1 (per mil)	O-18/O-16 (per mil)	Sr-87/Sr-86 ratio
08382650	A.1	2/22/2015	0.40	10.5	1,120	50.7	272	4,020	70	−73.6	−10.07	0.70782
08382650	A.1	2/22/2015	0.39	10.9	1,170	47.8	283	4,210	72	−73.1	−10.03	n/a
345701104422710	A.2	2/22/2015	0.60	13.0	1,470	168	122	6,670	100	−70.5	−9.64	0.70797
345701104422710	A.2	2/22/2015	<0.01	<0.018	<0.02	<4.0	<0.2	<0.2	<2.0	n/a	n/a	n/a
08385522	B.2	2/25/2015	0.48	9.88	1,120	11.9	47	5,500	146	−52.7	−6.74	0.70827
08386000	B.4	2/23/2015	0.46	8.12	1,450	24.9	53.8	6,720	216	−46.8	−5.12	0.70822
08394033	B.7	2/24/2015	0.81	9.15	1,490	<40	136	8,700	283	−49	−5.92	0.70780
08396500	B.8	2/24/2015	0.89	7.53	1,710	<40	38.1	9,090	396	−47	−5.86	0.70774
08405200	C.4	2/24/2015	0.64	13.4	970	20.8	6.8	4,490	209	−41.4	−5.27	0.70774
08406500	C.5	2/26/2015	0.67	12.4	1,360	<40	38.3	6,780	288	−41	−5.12	0.70767
08407000	C.6	2/25/2015	0.54	11.2	1,080	<40	51	7,180	365	−41.2	−5.04	0.70768
08407500	C.7	2/25/2015	0.69	9.69	1,300	<40	53	7,040	342	−40.9	−5.06	0.70769
08412500	D.1	2/25/2015	1.14	9.01	2,560	80.8	698	14,700	1,430	−31.7	−3.17	0.70759
313256103294600	D.3	2/26/2015	0.92	6.09	2,520	<80	207	13,500	993	−26.7	−2.31	0.70769
08437710	D.5	2/24/2015	1.23	11.1	2,570	<80	291	14,800	1,030	−28.9	−2.81	0.70791
08437710	D.5	2/24/2015	<0.01	<0.018	0.40	<4.0	0.23	2	<2.0	n/a	n/a	n/a
311820102523900	D.6	2/24/2015	1.21	8.83	2,450	<80	263	13,500	947	−29.1	−2.64	0.70792
311557102355600	D.7	2/25/2015	1.54	11.8	3,000	<80	384	15,500	1,160	−28.8	−2.47	0.70794
311402102285400	D.8	2/24/2015	1.58	10.1	3,020	<80	281	14,400	988	−28.8	−2.49	0.70799
08446550	D.10	2/24/2015	2.27	11.6	3,360	<80	199	15,600	1,140	−30	−2.7	0.70812
310204102131500	D.11	2/23/2015	1.69	8.00	3,070	<80	63.3	14,600	1,070	−27.5	−2.44	0.70812
305849101582900	D.12	2/22/2015	1.86	6.69	3,300	<80	60.9	16,400	1,210	−29.5	−2.65	0.70813
305849101582900	D.12	2/22/2015	2.10	5.84	3,300	<80	49.6	14,300	1,050	−29.2	−2.65	0.70813
304718101500600	D.13	2/23/2015	1.79	4.34	2,690	<80	29.6	14,200	1,050	−29.7	−2.83	0.70810
332430104235610	B.TRIB2	2/23/2015	1.30	6.02	1,310	33.1	18.6	6,690	259	−47.9	−6.23	0.70760
332218104242310	B.TRIB3	2/23/2015	0.77	14.3	1,190	<60	93.8	10,000	218	−52.9	−7.51	0.70763
331856104195310	B.TRIB4	2/24/2015	1.03	11.9	1,910	66.5	10.1	11,100	404	−54.1	−7.98	0.70739
311418102432601	D.WELL1	2/25/2015	2.05	12.6	2,020	<80	<4	10,400	735	−52.8	−7.69	0.70764
311323102435200	D.WELL2	2/25/2015	1.19	14.3	3,110	<200	15.3	34,300	7,800	−50.9	−7.59	0.70711
315300103550900	D.TRIB11	2/25/2015	1.60	2.22	3,110	<200	12	20,400	4,300	−34.9	−3.69	0.70759

In the Artesia (site B.8 in the lower section of reach B) to Carlsbad (site C.4 in the upper section of reach C) section of the Pecos River, all major-ion concentrations decrease downstream from Brantley Lake except for bicarbonate (figs. 7, 8, and 10, table 6). Sodium and chloride concentrations may be diluted in the Pecos River downstream from Brantley Lake by releases of relatively lower salinity water stored in Brantley Lake. Periodic releases of relatively fresh water from Sumner Dam are subsequently stored in Brantley Lake as a management strategy to reduce the salinity in Brantley Lake (Robertson, 1997; Miyamoto and others, 2007). In the section of the Pecos River between Artesia and Carlsbad, inflows of relatively fresh groundwater near Carlsbad may also help dilute the dissolved-solids concentrations (Robertson, 1997; Hoagstrom, 2009). Lake Avalon is downstream from Brantley Lake and may also be contributing to the reduction in salinity of the Pecos River in this section of the river by the process of dilution. Percent differences for sodium, chloride, and sulfate are greater than 5 percent between Artesia and Carlsbad on the Pecos River, indicating a relatively large decrease in concentrations (fig. 11). In addition, streamflow gain and loss measurements indicate that streamflow increases from 61.1 ft^3/s upstream from Dexter (site B.6) to 80.9 ft^3/s upstream from Brantley Lake (site B.9) (table 3), potentially from groundwater inflows, springs, or additional tributaries, thereby contributing to the dilution of major-ion concentrations.

Sodium and chloride concentrations appear to increase slightly through the section of the Pecos River between Carlsbad (site C.4) and Red Bluff, N. Mex. (site C.7) (fig. 8). Sodium concentrations increase from 366 to 1,080 mg/L, and chloride concentrations increase from 602 to 1,760 mg/L in this section of the Pecos River (fig. 10, table 6). As described in the “Previous Salinity Studies by Reach” section of this report, the Malaga Bend region of the Pecos River, which is downstream from Malaga, has been documented as historically contributing to salinity in the Pecos River. Saline groundwater near the Malaga Bend originates from the contact between the Rustler and Salado Formations and issues from springs that contribute to the Pecos River (Miyamoto and others, 2006). Historical water-quality data for this section of the Pecos River indicate that sodium, chloride, and sulfate concentrations have been greater than concentrations from samples collected by the USGS in February 2015 (Houston and others, 2019).

Downstream from Red Bluff Reservoir (within reach D) (fig. 9), major-ion concentrations increase substantially compared to those measured in reaches A, B, and C (table 6). The percent differences in sodium and chloride concentrations increase about 20 and 30 percent, respectively, from site C.7 to site D.1 (fig. 11). The combination of reduced flow in the Pecos River and evaporative processes could be contributing to the elevated concentrations of sodium and chloride downstream from Red Bluff Reservoir (Miyamoto and others, 2007; Hoagstrom, 2009). Hoagstrom (2009) noted that evaporation from the surface of Red Bluff reservoir and low inflows to the reservoir might cause dissolved-constituent concentrations to increase, resulting in relatively saline reservoir releases and seepage losses. Hoagstrom (2009) also stated that streamflow diversions, groundwater pumping, and flood control structures have reduced the amount of streamflow in the lower Pecos River downstream from Red Bluff Reservoir. Hoagstrom (2009) continued that periodic floods in the past, before reservoirs regulated the flow, helped dilute constituent concentrations throughout the Pecos River. The reservoirs along the Pecos River were constructed primarily for irrigation storage and flood control, and with increased water use and impoundment, streamflow in the Pecos River has decreased (Hoagstrom, 2009). This change in streamflow can be seen in the measurements of streamflow gains and losses. During 2015, streamflow decreased from 71.3 ft^3/s at site C.7 at Red Bluff, N. Mex. to 7.7 ft^3/s at site D.1 near Orla, Tex. (table 2). Salt Creek enters the Pecos River downstream from the Red Bluff Reservoir and upstream from Orla. Samples were collected from Salt Creek (site D.TRIB11) during the February 2015 water-quality sampling. Sodium (6,440 mg/L) and chloride (8,190 mg/L) concentrations were higher in the sample collected from the Salt Creek site than in samples collected by the USGS in February 2015 from all other sites on the Pecos River (table 6). Brune (1981) stated that the source of salinity in Salt Creek is the various springs that issue from faults and fractures in the Rustler and Castile Formations, whereas the Upper Rio Grande BBEST (2012) stated that the source of the salt in Salt Creek is Rustler Springs.

Downstream from Orla (site D.1) to Grandfalls, Tex. (site D.6) (fig. 9), sodium concentrations fluctuate between about 2,500 and 3,200 mg/L, and chloride concentrations fluctuate around 5,000 mg/L (table 6). Sulfate concentrations are around 2,500 mg/L in this section. From Imperial (site D.7) to Iraan (site D.12), sodium concentrations remain high at more than 3,000 mg/L, and chloride concentrations increase further to about 6,000 mg/L and sulfate concentrations to about 3,000 mg/L (fig. 10, table 6). Percent differences for sodium, chloride, and sulfate concentrations can increase more than 5 percent in some sections from Orla to Imperial (fig. 11). Few streams provide inflows in this section of the Pecos River, but irrigation return flows through groundwater seeps and springs can contribute to the salinity in the upper part of this section of the Pecos River (Ashworth, 1990; Hoagstrom, 2009; Upper Rio Grande BBEST, 2012). Historical chloride concentrations in groundwater near the Pecos River in this section of the basin can vary from 500 mg/L to more than 1,000 mg/L (Houston and others, 2019). Inflows of groundwater affected by oil field brines in the area may be a source of increased salinity to the Pecos River. In addition, several oil-test wells were historically converted to water use, particularly for irrigation, and could contribute to salinity in the Pecos River (Armstrong and McMillion, 1961). Several saltwater disposal and injection wells also are in the basin, particularly in Crane, Upton, and Crockett Counties, that could affect the salinity of the Pecos River through the seepage of groundwater (Railroad Commission of Texas, 2015). Streamflow gain and loss measurements indicate streamflow increases from 7.7 ft^3/s near Orla (site D.1) to 31.4 ft^3/s at Girvin (site D.10) (table 4). With no known tributary streamflow inputs to this section, the gains in streamflow along this section of the Pecos River are thought to be from groundwater sources.

No water-quality data were collected during the February 2015 sampling downstream from Iraan (site D.12) to Independence Creek (site D.HIST17) on the Pecos River. Historical data for this subreach of the Pecos River indicate that all major-ion concentrations likely decrease relative to sites upstream, possibly from groundwater interacting with the Pecos River in this area. Downstream from Girvin, the Pecos River receives freshwater inflow from groundwater and surface-water sources (Jenson and others, 2006). In this subreach of the river, sodium concentrations in historical samples decreased from 3,000 mg/L at Sheffield (site D.14) to 500 mg/L downstream from Independence Creek (site D.HIST17), similarly chloride concentrations decreased from 6,000 to 1,000 mg/L, and sulfate concentrations decreased from 2,500 to 1,000 mg/L (fig. 10). Additional data are needed to better understand surface-water and groundwater interactions and changes in water quality in the section of the Pecos River from Iraan to Independence Creek and further downstream to the Rio Grande.

Dissolved-Solids Concentrations and Loads

Dissolved-solids concentrations are a measure of the amount of dissolved constituents in a sample (Hem, 1985). Constituents such as sodium, chloride, and sulfate contribute to the dissolved-solids concentrations and salinity. In addition to the individual major-ion concentrations, dissolved-solids concentrations (fig. 12) and instantaneous dissolved-solids loads (fig. 13) were analyzed and computed for the samples collected by the USGS in February 2015. Instantaneous dissolved-solids loads were estimated by using the following equation:

$$Load = Conc \times Streamflow \times CF \tag{6}$$

where

Load is the instantaneous dissolved-solids load, in tons per day;

Conc is the dissolved-solids concentration, in milligrams per liter;

Streamflow is the instantaneous streamflow, in cubic feet per second; and

CF is a conversion factor of 0.00269684 used to compute instantaneous daily dissolved-solids load, in tons per day.

Dissolved-solids concentrations increase from about 2,100 mg/L at Fort Sumner (USGS station 08385522 Pecos River below Taiban Creek near Fort Sumner, N. Mex. [site B.2]) to about 6,500 mg/L at Artesia (USGS station 08396500 Pecos River near Artesia, N. Mex. [site B.8]) (fig. 12, table 6). Dissolved-solids concentrations then decrease from about 6,500 mg/L at Artesia to about 2,800 mg/L at Carlsbad (USGS streamflow-gaging station 08405200 Pecos River below Dark Canyon at Carlsbad, N. Mex. [site C.4]) (fig. 12, table 6). This increase and subsequent decrease in dissolved-solids concentrations match the increase and subsequent decrease in both sodium and chloride concentrations in the same section of the Pecos River, indicating that sodium chloride is a large component of the dissolved-solids concentration (fig. 10). Similar to the increases observed in dissolved-solids concentrations, the instantaneous load for dissolved solids increases from about 200 tons per day at Fort Sumner (site B.2) to about 1,300 tons per day at site B.8 near Artesia (fig. 13). The instantaneous load for dissolved solids also then decreases at Carlsbad (siteC.4) to about 200 tons per day (fig. 13).

Downstream from Carlsbad (site C.4), dissolved-solids concentrations steadily increase to about 13,000 mg/L near Orla (site D.1), including an approximate 7,000 mg/L increase from site C.7 at Red Bluff, N. Mex., where the dissolved-solids concentration was about 6,000 mg/L, to site D.1, where Red Bluff Reservoir is located (figs. 9 and 12, table 6). The large increase in dissolved-solids concentrations, downstream from Red Bluff Reservoir is consistent with the large increases in sodium and chloride concentrations in this section of the Pecos River (fig. 10). The load for dissolved solids in this section of the Pecos River follows the same pattern as dissolved-solids concentrations, where instantaneous load increases from about 200 tons per day at site C.4 to about 1,200 tons per day at site C.7 (fig. 13). The dissolved-solids load then decreases downstream from site C.7 to about 280 tons per day at site D.1 because of the decreased streamflow between these two sites even though dissolved-solids concentrations increased between the two sites (figs. 12 and 13, table 6).

Dissolved-solids concentrations increase again downstream from 13,000 mg/L at site D.1 near Orla to 16,900 mg/L at site D.11 Pecos River at Ranch Road 1901 near McCamey, Tex. (fig. 12, table 6). Increased dissolved-solids concentrations downstream from Orla may be from groundwater inflow from aquifer units with saline water. Downstream from McCamey, dissolved-solids concentrations decreased in the Pecos River to about 15,000 mg/L at site D.13 downstream from Iraan (fig. 12, table 6). Historical data collected at sites D.14, D.HIST16, and D.HIST17 downstream from Sheffield indicate that dissolved-solids concentrations continue to decrease as the Pecos River nears the Rio Grande, with concentrations decreasing to between 2,500 and 3,500 mg/L for dissolved solids, following the same pattern for decreases in sodium, chloride, and sulfate concentrations in this subreach of the Pecos River (Houston and others, 2019). The instantaneous dissolved-solids load steadily increases downstream from Orla to Iraan with the highest load value around 2,100 tons per day (fig. 13, table 6).

Hydrogen and Oxygen Stable Isotopes

The relation between the ratios of hydrogen-2 to hydrogen-1 (δD) and of oxygen-18 to oxygen-16 ($\delta^{18}O$) can aid in understanding changes in water chemistry and in identifying areas of groundwater inflows to a stream because changes in δD and $\delta^{18}O$ provide useful indicators of regional recharge (Clark and Fritz, 1997; Eddy-Miller and Wheeler, 2010). The δD and $\delta^{18}O$ values were plotted in downstream order to determine where changes in water chemistry are occurring and possible areas of recharge to the river (fig. 14). Hydrogen and oxygen isotopic analyses from multiple rainfall samples collected around the world were compared, and a linear regression line referred to as the "global meteoric water line" (GMWL) was computed as $\delta D = 8 \times \delta^{18}O + 10$ (Craig, 1961). Changes from the GMWL can be attributed to multiple factors including variations in elevation, storm intensity, latitude, seasons, and continental climate (Fontes, 1980). Uliana and others (2007) sampled springs and wells in the Trans-Pecos region of Texas and had the samples analyzed for δD and $\delta^{18}O$ values. The δD and $\delta^{18}O$ values for those samples plot close to the GMWL, thereby supporting the use of the GMWL for comparison to samples collected in the Pecos River in February 2015. The samples collected from the Pecos River in February 2015 were used to develop a linear regression line to represent the Pecos River evaporation line for that period and were compared to the GMWL (fig. 15). Evaporation can cause preferential loss of water molecules containing the lighter, stable isotopes of hydrogen and oxygen. Therefore, ratios of hydrogen to oxygen isotopes will deviate from the GMWL if evaporation is occurring.

The δD and $\delta^{18}O$ values become isotopically heavier going downstream from site A.1 (Pecos River above Santa Rosa Lake, N. Mex.) in reach A to site B.4 (Pecos River near Acme, N. Mex.) in reach B, with δD values increasing from −73.6 to −46.8 per mil and $\delta^{18}O$ values increasing from −10.07 to −5.12 per mil (fig. 14, table 6). The values for the δD and $\delta^{18}O$ from site A.1 to site B.4 plot below the GMWL (fig. 15), indicating that the water in the Pecos River from site A.1 to site B.4 is likely a mixture of different types of water, with older evaporitic water or other saline water entering the Pecos River because saline water is generally isotopically heavier compared to freshwater (Plummer and others, 1993; Kendall and McDonnell, 1998). The δD and $\delta^{18}O$ values become isotopically lighter from site B.4 near Acme to site B.7 near Dexter (reach B); the δD values decrease to −49.0 per mil, and the $\delta^{18}O$ values decrease to −5.92 per mil. These changes in δD and $\delta^{18}O$ values indicate the addition of isotopically different water to the Pecos River in this area and are consistent with the increasing sodium and chloride concentrations in this same section of the Pecos River. During the gain-loss measurements in February 2015, streamflow generally increased in the Pecos River from Santa Rosa to Artesia (table 6); the increase in streamflow might be from saline springs and groundwater inflows and other saline inflows in this section of the Pecos River. Likely sources of saline inflow to the Pecos River near Acme include spring flow and underflow from the BLNWR, inflow from the Rio Hondo, and outflow from Lea Lake (Reimus and others, 2012). The δD and $\delta^{18}O$ values measured in samples from sites at the BLNWR south weir inflow (site B.TRIB2), the Rio Hondo spring channel (site B.TRIB3), and the Lea Lake outflow channel (site B.TRIB4) indicate slightly lower isotopic ratios compared to those measured in samples collected from nearby sites on the Pecos River (fig. 15) and are similar to isotopic ratios measured in historical groundwater samples collected from nearby wells in the Artesia Group (Houston and others, 2019). The slightly lower δD and $\delta^{18}O$ values measured in samples from sites at the BLNWR south weir inflow, the Rio Hondo spring channel, and the Lea Lake outflow channel could help cause δD and $\delta^{18}O$ values to decrease in the Acme (site B.4) to Dexter (site B.7) section of the Pecos River.

Downstream from site B.7 to site C.7, the δD and $\delta^{18}O$ values in the Pecos River remain relatively stable (δD about −50 per mil and $\delta^{18}O$ about −6 per mil) (table 6). Compared to the δD and $\delta^{18}O$ values measured in reach C, larger (less negative) δD and $\delta^{18}O$ values were measured in the samples collected in reach D, which is downstream from reach C (table 6). At site D.1 near Orla and site D.3 near Barstow, δD values were −31.7 and −26.7 per mil, respectively, and the $\delta^{18}O$ values −3.17 and −2.31 per mil, respectively (table 6). This increase in isotopic values in reach D compared to the isotopic values measured in the upstream reaches is likely caused by several factors including the relatively saline releases and seepage losses from Red Bluff Reservoir as described in the "Major-Ion Concentrations" section of this report and inflows of older evaporitic water entering the Pecos River (Kendall and McDonnell, 1998) (fig. 14). Salt Creek enters the Pecos River between Red Bluff and Orla and could be contributing to the increasing δD and $\delta^{18}O$ values because the δD and $\delta^{18}O$ values of Salt Creek (site D.TRIB11) are isotopically heavier than those in reach C (fig. 9). From site D.3 near Barstow to site D.5 near Grandfalls, the δD and $\delta^{18}O$ values decrease slightly, with δD values decreasing from −26.7 to −28.9 per mil and $\delta^{18}O$ values decreasing from −2.31 to −2.81 per mil, indicating mixing of isotopically different water. The δD and $\delta^{18}O$ values in the Pecos River again remain relatively stable (δD about −29 per mil and $\delta^{18}O$ about −2.5 per mil) downstream from site D.5 near Grandfalls to sites D.12 and D.13 near Iraan. No samples collected by the USGS in February 2015 were analyzed for δD and $\delta^{18}O$ downstream from Sheffield.

Strontium Isotopes

Strontium isotopic ratios, specifically the ratio of strontium-87 to strontium-86 ($\delta^{87}Sr$), are useful in describing the source of water as defined by changes in the composition of the salts dissolved in the water (Kendall and McDonnell, 1998). When there is an increase or decrease in $\delta^{87}Sr$ values from one site to the next downstream site (fig. 16), water in the river is potentially mixing with a geochemically different source of water. Strontium can substitute for calcium especially in carbonate rocks that are commonly found in subsurface geologic units in the basin (Hem, 1985; Banner, 2004; Musgrove and others, 2009; Bumgarner and others, 2012). As a result of this rock-water interaction, $\delta^{87}Sr$ values can be used to evaluate sources of dissolved constituents to groundwater and possible groundwater mixing (McNutt and others, 1990; Musgrove and Banner, 1993; Banner and others, 1994; Uliana and others, 2007; Musgrove and others, 2009). Water in a specific geologic unit should have $\delta^{87}Sr$ values that reflect the isotopic ratio of minerals in that unit. Because strontium concentrations are a negligible part of the salt balance, $\delta^{87}Sr$ values are useful as a geochemical tracer of source waters originating from different geologic units (Kendall and McDonnell, 1998). By using information obtained from previous studies, Bumgarner and others (2012) summarized $\delta^{87}Sr$ values for several geologic units in the Pecos River Basin in Pecos County, Tex. The $\delta^{87}Sr$ values measured in the samples collected in February 2015 can be compared to other $\delta^{87}Sr$ values measured in groundwater within the basin including comparing $\delta^{87}Sr$ values measured at different sites along the Pecos River to evaluate the potential of groundwater mixing or mixing with isotopically different water.

In the upper part of the Pecos River, the most notable changes in $\delta^{87}Sr$ values determined from samples collected in February 2015 are from Santa Rosa (site A.1) to Fort Sumner (site B.2) and from Acme (site B.4) to Dexter (site B.7) (fig. 16). The $\delta^{87}Sr$ values increase from 0.70782 at Santa Rosa (site A.1) to 0.70827 at Fort Sumner (site B.2) (table 6), indicating the possible mixing of isotopically different water with the Pecos River in this area. Several streams enter the Pecos River in this area that could contribute to the changes in the $\delta^{87}Sr$ values; however, it is not known whether surface-water or groundwater inflows predominately account for the observed water-quality changes in this section. The $\delta^{87}Sr$ values decrease from 0.70822 at Acme (site B.4) to 0.70780 at Dexter (site B.7). This decrease in $\delta^{87}Sr$ values is paired with a change in δD and $\delta^{18}O$ values, confirming the potential of isotopically different water entering the Pecos River between Acme (site B.4) and Dexter (site B.7) either from groundwater or from different surface-water features. The $\delta^{87}Sr$ values for the sampling sites where the Rio Hondo spring channel (0.70763 at site B.TRIB3) and the Lea Lake outflow (0.70739 at site B.TRIB4) were measured are less than the $\delta^{87}Sr$ value measured in the samples collected at Acme (site B.4); therefore, Rio Hondo inflow and Lea Lake outflow could be contributing to the decrease in $\delta^{87}Sr$ values measured in the sample collected from Dexter (site B.7). Although sodium and chloride concentrations continue to increase from Dexter (site B.7) to Artesia (site B.8), both δD and $\delta^{18}O$ values and the $\delta^{87}Sr$ values remain relatively unchanged. Because the differences in isotopic signatures are small, it is difficult to determine from isotopic analyses the effects on the Pecos River of the three surface-water features—the BLNWR south weir inflow, Rio Hondo inflow, and Lea Lake outflow.

Additional changes in $\delta^{87}Sr$ values occur in the section of the Pecos River from the sampling site at Red Bluff (site C.7) downstream to the sampling site near Orla (site D.1) and further downstream to the sampling site near Barstow (site D.3), with $\delta^{87}Sr$ values decreasing from 0.70769 at site C.7 to 0.70759 at site D.1 and then increasing to 0.70769 at site D.3. Salt Creek enters the Pecos River downstream from Red Bluff Reservoir, and the $\delta^{87}Sr$ value of 0.70759 at Salt Creek (site D.TRIB11) was less than the $\delta^{87}Sr$ value of 0.70769 at Red Bluff (site C.7), which may contribute to changes in $\delta^{87}Sr$ values. Although these changes in $\delta^{87}Sr$ values are not appreciable and are within measurement uncertainty limits (plus or minus 0.00002) (Bullen and others, 2006), the increase of δD and $\delta^{18}O$ from site C.7 to site D.3 indicates that evaporative processes may be occurring. The $\delta^{87}Sr$ values increase from 0.70769 at site D.3 to 0.70791 at Grandfalls (site D.5), likely indicating the addition of isotopically different water mixing with the Pecos River between these two sites. The changes in the isotopic signatures for both δD and $\delta^{18}O$ values and for $\delta^{87}Sr$ values from Orla (site D.1) to Grandfalls (site D.5) indicate that the salinity in this part of the Pecos River is no longer largely affected by inflows from Red Bluff Reservoir or Salt Creek; other sources such as groundwater inflows may be affecting the salinity. The $\delta^{87}Sr$ values again increase slightly from 0.70794 at Imperial (site D.7) to 0.70812 at Girvin (site D.10). Because most major-ion concentrations appear to decrease downstream from Girvin (site D.10), this change in $\delta^{87}Sr$ values may be a result of groundwater contributing to the Pecos River in this area. Downstream from Girvin (site D.10) to Iraan (site D.13) (the most downstream main stem water-quality sampling site), $\delta^{87}Sr$ values remained relatively constant, ranging from 0.70810 to 0.70813.

Saturation Indices for Selected Minerals

Saturation indices for calcite, dolomite, halite, and gypsum were determined by using the PHREEQC program (Parkhurst, 1995; Parkhurst and Appelo, 2013) for the samples collected in February 2015 (table 7). PHREEQC computes the distribution of aqueous species, along with the state of saturation of each water sample with respect to a variety of commonly occurring rock-forming minerals. The saturation index is computed by using the following equation:

$$SI = log(IAP/K_{sp}) \tag{7}$$

where

SI	is the saturation index;
log	is the base 10 logarithm;
IAP	is the ion activity product based on chemical concentrations; and
K_{sp}	is the solubility product, a thermodynamic constant in PHREEQC.

Table 7. Major-ion balance and saturation indices computed from the geochemical sample results in the Pecos River Basin study area in New Mexico and Texas, February 2015.

[USGS, U.S. Geological Survey; SI, saturation index; BLM, Bureau of Land Management]

Site identifier (figs. 6, 7, 8, 9)	USGS station name	Major-ion balance percent error	SI calcite	SI dolomite	SI halite	SI gypsum
A.1	Pecos River above Santa Rosa Lake, N. Mex.	2.39	0.70	0.45	−8.47	−0.13
A.2	Pecos River above Santa Rosa, N. Mex.	1.83	0.63	0.41	−7.39	0.00
B.2	Pecos River below Taiban Creek near Fort Sumner, N. Mex.	3.04	0.95	1.21	−6.59	−0.19
B.4	Pecos River near Acme, N. Mex.	0.11	0.78	0.94	−5.39	−0.11
B.7	Pecos River south boundary (BLM wetlands) near Dexter, N. Mex.	3.78	0.86	1.20	−4.49	−0.13
B.8	Pecos River near Artesia, N. Mex.	−0.47	0.98	1.58	−4.30	−0.12
C.4	Pecos River below Dark Canyon at Carlsbad, N. Mex.	2.34	0.89	1.42	−5.30	−0.38
C.5	Pecos River near Malaga, N. Mex.	1.95	0.98	1.65	−4.79	−0.23
C.6	Pecos River at Pierce Canyon Crossing, N. Mex.	15.10	1.16	2.02	−4.61	−0.33
C.7	Pecos River at Red Bluff, N. Mex.	2.96	1.00	1.68	−4.40	−0.28
D.1	Pecos River near Orla, Tex.	1.77	0.76	1.30	−3.56	0.00
D.3	Pecos River at Barstow Dam near Barstow, Tex.	−3.09	0.75	1.30	−3.68	−0.01
D.5	Pecos River at Farm to Market 1776 near Grandfalls, Tex.	3.80	0.65	1.08	−3.52	0.00
D.6	Pecos River at Highway 18 near Grandfalls, Tex.	0.23	0.84	1.50	−3.60	−0.05
D.7	Pecos River at Old Crane Road near Imperial, Tex.	−0.24	0.76	1.35	−3.41	0.04
D.8	Pecos River at Horsehead Road near Imperial, Tex.	−6.63	0.82	1.48	−3.47	0.02
D.10	Pecos River near Girvin, Tex. (flood gage)	−4.78	0.77	1.39	−3.40	0.07
D.11	Pecos River at Ranch Road 1901 near McCamey, Tex.	−3.48	0.76	1.42	−3.46	0.00
D.12	Pecos River at State Highway 349 near Iraan, Tex.	−1.65	0.73	1.51	−3.43	0.01
D.13	Pecos River at Crockett County Road 306 near Iraan, Tex.	0.94	0.80	1.59	−3.54	−0.07

Saturation indices measure departures from thermodynamic equilibrium and usually can be used to determine reactivity of minerals in an aquifer or stream. If a saturation index is negative, the mineral is undersaturated and more likely to dissolve; if the saturation index is positive, the mineral is saturated and more likely to precipitate. If the saturation index is zero, the mineral is at equilibrium with the water (Parkhurst, 1995; Langmuir, 1997; Parkhurst and Appelo, 2013). The saturation indices for minerals also are based on the solubility of the minerals in water. If the concentration of ions is increasing from one site to another, rock-water interactions might be contributing to the ionic concentrations in the stream. Therefore, changes in saturation indices along the Pecos River could indicate groundwater inputs to the stream. For groundwater inputs to streams from aquifer systems or surface-water inputs in contact with geologic units, the saturation indices can indicate the extent to which minerals in the aquifer systems or surface-water inputs are likely to become sources of mineral-derived constituents in stream water (Langmuir, 1997).

Saturation indices for calcite, which is the principal mineral in limestone, are positive in all samples collected in the basin (table 7), indicating that the mineral (consisting of calcium and carbonate) is more likely to precipitate and probably would not be contributing appreciably to the dissolved-solids load. The saturation indices for dolomite also are positive in all samples collected in the basin. Dolomite is composed of calcium, magnesium, and carbonate. Similar to the way the minerals in limestone are more likely to precipitate than to dissolve into solution, the minerals in dolomite are also more likely to precipitate than to dissolve into solution (Langmuir, 1997). Bicarbonate can be a major component of the dissolved solids concentrations and is formed when carbonate minerals interact with water (Drever, 1997). Magnesium and bicarbonate have the two lowest concentrations of the dissolved constituents of interest in the Pecos River samples collected in February 2015, and calcium has the third lowest concentrations of dissolved constituents of interest (fig. 10).

Saturation indices for halite are negative in all samples collected in the basin (table 7), indicating that the mineral would be more likely to dissolve into solution than to precipitate. Among the constituents of interest for their effects on salinity, sodium and chloride have the highest concentrations in most of the samples collected in February 2015 (fig. 10). Most of the saturation indices for gypsum are slightly negative in the basin upstream from Red Bluff Reservoir (as measured in samples collected from site A.1 downstream through site C.7) (table 7). The saturation indices for gypsum are generally close to zero in the rest of the basin downstream from Red Bluff Reservoir, indicating that the amount of gypsum in solution is more or less at equilibrium in this part of the basin (table 7). The results for all of the saturation indices primarily show changes near Red Bluff Reservoir with calcite, dolomite, and gypsum minerals more prominent in the geologic units in the upper part of the basin upstream from Red Bluff Reservoir, indicating possible interactions with groundwater that is in contact with calcite, dolomite, halite, and gypsum minerals in the geologic units (Miyamoto and others, 2006). Halite is prominent in the geologic units in the lower part of the basin downstream from Red Bluff Reservoir, which is consistent with the most saline sections of the Pecos River (Miyamoto and others, 2006).

Higher Salinity Areas in the Pecos River Basin

Elevated salinity in reaches of the Pecos River was found to be caused by a combination of natural (geologic) and anthropogenic sources. Figure 17 shows a conceptual model of the changes in water quality along the main stem of the Pecos River. Two indicators of salinity inputs to the Pecos River are increases in major-ion concentrations (particularly sodium and chloride) and changes in isotopic values. Changes in these two indicators highlight areas of salinity concern, such as the subreach from Acme (site B.4) to Artesia (site B.8), where sodium concentrations increased from 356 mg/L to 1,200 mg/L and chloride concentrations increased from 517 mg/L to 2,060 mg/L (table 6). Values for δ^{87}Sr also decreased in this subreach, indicating a likely inflow of isotopically different water compared to the water in the Pecos River. Groundwater in contact with evaporite deposits and increased evaporation in this area can cause salinity to increase in the Pecos River. The gain-loss measurements showed that streamflow increased from 29.2 ft^3/s at Acme (site B.4) to 73.0 ft^3/s at Artesia (site B.8), indicating possible groundwater input to the Pecos River, but not all surface-water tributary inputs were clearly defined in this subreach. In general, groundwater inputs, increased evaporation, and surface-water inputs from spring inflow and underflow from the BLNWR, inflow from the Rio Hondo, and outflow from Lea Lake are thought to be key factors increasing salinity in the Acme to Artesia subreach of the Pecos River as indicated by changes in major-ion concentrations and δ^{87}Sr values. Downstream from Brantley Lake (reach C), major-ion concentrations continue to increase with dissolved solids increasing from about 2,800 mg/L to 6,300 mg/L upstream from Red Bluff Reservoir. Isotope concentrations are relatively stable in this subreach, but shallow groundwater and inflows from tributaries may be contributing to the salinity of the Pecos River in this area. Evaporative processes may also play a role, especially because streamflow is generally low (less than 75 ft^3/s) in the Pecos River, as indicated by the streamflow measurements made during 2015 as part of this study (table 2).

The salinity of the Pecos River reaches its highest levels downstream from Red Bluff Reservoir (reach D), where dissolved-solids concentrations are more than twice as large compared to sites upstream from the reservoir (table 6). Major-ion concentrations, as well as dissolved-solids concentrations, increase downstream from Red Bluff Reservoir and remain relatively high (dissolved-solids concentrations greater than 14,000 mg/L) on the Pecos River to Iraan (figs. 10, 12, and 17, table 6). The Pecos River at Sheffield was not sampled in February 2015, but historical samples collected at that site indicate that major-ion concentrations decrease appreciably (sodium and chloride concentrations less than 2,000 mg/L) from Sheffield (site D.14) to the Pecos River confluence with Independence Creek (site D.HIST.17). As noted in the “Major-Ion Concentrations” and “Red Bluff Reservoir to Confluence of Rio Grande and Pecos River—Reach D” sections of this report, dissolved salts might be concentrating in Red Bluff Reservoir because of evaporation losses and low inflows to the reservoir. Therefore, increased salinity downstream from the reservoir may result from reservoir releases and seepages from the reservoir (Hoagstrom, 1989; Miyamoto and others, 2007; Ewing and others, 2012); however, δ^{87}Sr values increase downstream from Red Bluff Reservoir, indicating that other sources of isotopically different water may be mixing with the Pecos River.

Progressing from upstream to downstream in the basin, δD and δ^{18}O values generally increase, indicating that evaporation is an important process that could be contributing to the increased salinity. Both the δD and δ^{18}O values plot farther from the GMWL progressing downstream along the Pecos River, indicating that additional chemical changes such as mixing with isotopically different water may be occurring in the lower part of the basin. Any increases or decreases in δ^{87}Sr values along the Pecos River indicate possible mixing of isotopically different water with the Pecos River. There are several areas along the main stem of the Pecos River where mixing of different water may be occurring as indicated by changes in δ^{87}Sr values, such as in the upper part of the basin from Santa Rosa to Fort Sumner and in the lower part of the basin from Orla to Grandfalls (fig. 17). The groundwater and surface-water tributaries in these areas may need further investigation to determine if and where the mixing of water may be occurring and whether that is a factor affecting salinity in the Pecos River.

Base modified from U.S. Geological Survey 1:500,000-scale digital data
Albers Equal-Area projection, Texas State Mapping System
North American Datum of 1983

Site ID (table 6)	Nearby city	Change in water-quality parameter at site compared to water-quality parameter at nearest upstream site			
		Combined concentration of sodium and chloride (milligrams per liter)	Dissolved-solids load (tons per day)	Ratio of hydrogen and oxygen stable isotopes	Strontium isotope ratio
A.1	Santa Rosa Lake, N. Mex.	N/A	N/A	N/A	N/A
A.2	Santa Rosa, N. Mex.	—	—	↑	↑
B.2	Fort Sumner, N. Mex.	—	↑	↑	↑
B.4	Acme, N. Mex.	↑	↑	↑	↓
B.7	Dexter, N. Mex.	↑	↑	↓	↓
B.8	Artesia, N. Mex.	↑	↑	—	↓
C.4	Carlsbad, N. Mex.	↓	↓	↑	—
C.5	Malaga, N. Mex.	↑	↑	—	↓
C.6	Pierce Canyon Crossing, N. Mex.	↑	↑	—	—
C.7	Red Bluff, N. Mex.	↑	↑	—	—
D.1	Orla, Tex.	↑	↓	↑	↓
D.3	Barstow, Tex.	↓	↑	↑	↑
D.5	Upstream from Grandfalls, Tex.	↑	↑	↓	↑
D.6	Grandfalls, Tex.	↓	↑	—	—
D.7	Imperial, Tex.	↑	↑	—	—
D.8	Downstream from Imperial, Tex.	—	↑	—	—
D.10	Girvin, Tex.	—	↑	—	↑
D.11	McCamey, Tex.	—	↑	—	—
D.12	Iraan, Tex.	—	↑	—	—
D.13	Downstream from Iraan, Tex.	↓	↓	—	—

Note: Table depicts changes in water quality along the main stem of the Pecos River in samples collected by the U.S. Geological Survey in February 2015 (see table 6). Increases and decreases for sodium and chloride concentrations and dissolved-solids loads were +/– at least 2 percent difference. Increases and decreases for hydrogen and oxygen stable isotopes were +/– 1 per mil for hydrogen and +/– 0.1 per mil for oxygen. Increases and decreases for strontium isotope ratio were +/– 0.00002.

[ID, identifier; N/A, not applicable]

EXPLANATION

Pecos River Basin study area

Pecos River Basin boundary

B.2 — Site sampled by the U.S. Geological Survey in February 2015 and site identifier—See table 1

— No substantial change compared to nearest upstream site

↑ Increase compared to nearest upstream site

↓ Decrease compared to the nearest upstream site

0 25 50 75 100 MILES

0 25 50 75 100 KILOMETERS

Figure 17. Changes in water quality along the main stem of the Pecos River, New Mexico and Texas, in samples collected by the U.S. Geological Survey in February 2015.

Summary

The elevated salinity of the Pecos River throughout much of its length is of paramount concern to water users and water managers. Dissolved-solids concentrations in the Pecos River exceed 3,000 milligrams per liter (mg/L) in many of its reaches in the study area, from Santa Rosa Lake, New Mexico, to the confluence of the Pecos River with the Rio Grande, Texas. In this report, "salinity" and "dissolved-solids concentrations" are considered synonymous; both terms are used to refer to the total ionic concentration of dissolved minerals in water. Throughout the course of the Pecos River in New Mexico and Texas, the salinity of the river increases as a result of the addition of dissolved salts or the removal of fresher water by diversion for irrigation or by evapotranspiration. The high salinity in the Pecos River affects the availability of useable water for agriculture, livestock, and recreation. The sources of salinity in the Pecos River Basin are natural (geologic) and anthropogenic, including but not limited to groundwater discharge, springs, and irrigation return flows. Past studies have been completed in the Pecos River Basin by many local, State, and Federal agencies to gain a better understanding of salinity and water-quality issues. However, most of these studies were project specific and designed to address salinity issues in specific parts of the Pecos River Basin. In 2015 the U.S. Geological Survey (USGS) in cooperation with the U.S. Army Corps of Engineers, New Mexico Interstate Stream Commission, Texas Commission on Environmental Quality, and Texas Water Development Board assessed the major sources of salinity throughout the extent of the basin where elevated salinity in the Pecos River is well documented (that is, in the drainage area of the Pecos River from Santa Rosa Lake to the confluence of the Pecos River and the Rio Grande). The goal was to gain a better understanding of how specific areas might be contributing to the elevated salinity in the Pecos River and how salinity of the Pecos River has changed over time. This assessment includes a literature review and compilation of previously published salinity-related data, which guided the collection of additional water-quality samples and streamflow gain-loss measurements in the Pecos River Basin. Differences in water quality of surface-water and groundwater samples, streamflow measurements, and geophysical data were assessed to gain new insights regarding sources of salinity in the Pecos River Basin and a more detailed assessment of potential areas of elevated salinity in the basin. The datasets that were compiled for this assessment are available in a companion data release.

The literature review identified several potential sources of salinity inputs to the Pecos River in New Mexico and Texas. In New Mexico, sources of salinity inputs included sinkhole springs discharging into El Rito Creek, the Bitter Lake National Wildlife Refuge inflow to the Pecos River, inflow from the Rio Hondo, outflow from Lea Lake at Bottomless Lakes State Park, and springs discharging into the Pecos River in the Malaga Bend region. In Texas, sources of salinity inputs included Salt Creek downstream from Red Bluff Reservoir and the area near the Horsehead Crossing ford on the Pecos River.

The compilation of historical water-quality data resulted in a considerable amount of data; however, not all the constituents measured in samples collected by agencies in the Pecos River Basin are relevant to salinity. The lack of consistent sampling of the same constituents at the same sites along the main stem of the Pecos River results in data gaps that hinder the ability to effectively analyze long-term changes in water quality that may help with the understanding of how salinity changes in different parts of the basin and over time and the understanding of sources of salinity in the Pecos River Basin. To help fill in these data gaps, water-quality and streamflow data were collected in the study area in February 2015 by the USGS.

Streamflow gains and losses were computed in two reaches of the Pecos River: reach B, from Lake Sumner to Brantley Lake, N. Mex., and part of reach D, from Orla to Sheffield, Tex. The subreach with the largest verifiable gain in reach B (14.87 ft^3/s) was subreach B.5–B.6, between the Pecos River at Highway 380, N. Mex. (site B.5) and the Pecos River at the north boundary of the BLM wetlands near Dexter, N. Mex. (site B.6). The Rio Hondo spring channel (site B.TRIB3) flows into this subreach. This is also the subreach in which 40 percent of the dissolved-solids concentrations and 75–80 percent of the sodium chloride concentrations that reach Brantley Lake originate. The subreach with the largest verifiable gain in reach D (12.49 ft^3/s) was subreach D.11 to D.12, between the Pecos River at Ranch Road 1901 near McCamey, Tex. (site D.11), and the Pecos River at State Highway 349 near Iraan, Tex. (site D.12).

Water-quality data from both historical and February 2015 samples were evaluated for selected major-ion concentrations, dissolved-solids concentrations, and deuterium, oxygen, and strontium isotopes. Analysis of the data indicated several areas of increasing salinity in the Pecos River. Most notable increases were in two subreaches of the river: between Acme and Artesia, N. Mex., and between Orla and Grandfalls, Tex. Sodium and chloride concentrations increase in the Acme to Artesia subreach, which is the same subreach in which the isotopic ratio of strontium-87 to strontium-86 decreases, indicating a likely inflow of water to the Pecos River from an isotopically different source of water such as groundwater or other surface-water features. Dissolved-solids concentrations increase from about 2,000 mg/L at Fort Sumner to 6,000 mg/L at Artesia in this subreach of the Pecos River. The subreach between Orla and Grandfalls shows a substantial increase in dissolved-solids concentrations and a shift in isotope values, indicating that neither evaporative processes in Red Bluff Reservoir nor inflow from Salt Creek likely solely influences the salinity of the Pecos River in this reach. In the study area, the salinity of the Pecos River is highest downstream from Red Bluff Reservoir. Major-ion concentrations increase downstream from Red Bluff Reservoir and remain relatively high (dissolved solids greater than 14,000 mg/L) to Iraan.

Mixing of different waters along two subreaches of the Pecos River may be occurring as indicated by changes in the three isotopic values (deuterium, oxygen, and strontium) in the upper part of the Pecos River Basin from Santa Rosa to Dexter in New Mexico and in the lower part of the Pecos River Basin from Orla to Girvin in Texas. The spatial distribution of the areas of interest from the literature review and the water-quality data are available in the companion data release.

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Appendix 1. Recommendations From the Literature

As part of the literature review for the salinity assessment, the U.S. Geological Survey (USGS) documented scientific recommendations that were made by researchers working in the Pecos River Basin, such as salinity control options, water-quality sampling suggestions, and locations of data gaps. Recommendations were documented from reports that were reviewed during the preparation of this report and may not include all recommendations made by researchers in the basin.

Water Quality

Belzer and Hart (2007) suggest redoing a sediment analysis on the intermittent tributaries that feed the Pecos River in Texas.

Gregory and others (2014) suggest towing a Global Positioning System (GPS) linked fiber optic temperature sensor, in conjunction with a water-quality monitor downstream on the Pecos River, to potentially identify areas where water is entering the river. The changes in water temperature can be an indicator of inflowing water.

Goodbar and Goodbar (2014) suggest that a water tracer study be done in the Nash Draw, N. Mex. to better understand the flow paths of the karstic system.

Miyamoto and others (2006) suggest that a detailed study on groundwater inflow is needed on the Pecos River between Grandfalls and Girvin, Tex. to assess feasibility of salt control measures there.

Partey and others (2011) suggest a detailed geochemical study of individual sinkholes to model the rock-water interaction at Bitter Lake National Wildlife Refuge (BLNWR), N. Mex. The authors suggest long-term monitoring to look at seasonal changes in water chemistry to study mechanisms controlling groundwater chemistry.

Reimus and others (2012) suggest that the study area inflow and dissolved-solids/halite flux estimates could be further refined by more focused sampling in the Acme to Artesia subreach, N. Mex.

Reimus and others (2012) suggest the continuation of continuous specific conductance logging in the Acme to Artesia subreach; however, the authors recommended using better quality biofoul-resistant probes than the ones used in their study.

Reimus and others (2012) suggest adding periodic sampling at the following locations in New Mexico to allow closure of dissolved-solids balance computations:

- Pecos River at the Highway 70 Bridge (this sampling could possibly be done at USGS streamflow-gaging station 08386000 Pecos River near Acme, N. Mex.)
- Pecos River at scout camp in BLNWR (including inflow and just upstream from inflow if flowing)
- Pecos River upstream from the BLNWR south weir
- BLNWR south weir inflow to Pecos River
- Pecos River at the Highway 380 Bridge
- Rio Hondo at lower crossing in BLNWR unit south of Highway 380
- Pecos River one-quarter to one-half mile south of confluence with Rio Hondo
- Pecos River at a location referred to as “BLM N” or USGS streamflow-gaging station 08394024 Pecos River north boundary (BLM wetlands) near Dexter, N. Mex.
- Lea Lake inflow to Pecos River (and river just upstream from inflow)
- Pecos River at a location referred to as “BLM S” (likely near the south boundary of the BLM wetlands (this sampling could possibly take place at USGS streamflow-gaging station 08394033 Pecos River south boundary [BLM wetlands] near Dexter, N. Mex.)
- Pecos River at N. Mex. 409 Bridge in Dexter

Reimus and others (2012) recommend a more evenly spaced sampling schedule on the Pecos River to provide better representation of inflow at different times of the year.

Tachovsky (2005) recommends sampling groundwater sites near the Pecos River while the Texas Commission on Environmental Quality (TCEQ) Clean Rivers surface-water sites are sampled. Data collected during the same time period and as nearby as possible could be used along with short-term estimates of base flow obtained from USGS streamflow-gaging station data to estimate the flux from groundwater to surface water.

Water Quantity

Upper Rio Grande Basin and Bay Expert Science Team (BBEST) (2012) suggests conducting a study to determine a total water balance from Red Bluff Reservoir to Iraan, Tex.

Species Diversity/Habitat/Environmental Flows

Upper Rio Grande BBEST (2012) recommends establishing subsistence flow for the upper Pecos River by releasing water from Red Bluff Reservoir and monitoring it at Iraan until the flow has enough dissolved oxygen (DO) and calling this subsistence flow. However, in the Texas Parks and Wildlife (2012) review comments of the Upper Rio Grande BBEST (2012) report, the authors respond that DO alone should not be used to determine subsistence flows and that there are other factors that should be included like temperature and habitat.

Upper Rio Grande BBEST (2012) suggests constructing the geomorphic history for the Pecos River Basin for the past 100 years.

Upper Rio Grande BBEST (2012) suggests that comprehensive flow history be developed by using available streamflow-gaging data from the lower Pecos River.

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