CHAPTER ONE

# THE PHYSICAL FRAMEWORK

DECISION-MAKERS
FIELD CONFERENCE 2003
The Lower Pecos Region

San Andres Limestone at Six Mile Buckle on Highway 70/380 west of Roswell.

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# Regional Geology of the Pecos Country, New Mexico

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Water resources of the lower Pecos region are governed to a large extent by the geologic framework of southeastern New Mexico, which provides conduits and reservoirs for the ground water that is critical to this part of the state. The geology of the lower Pecos country is defined by its large sedimentary basins and mountain uplifts. Of these, the most important are the Delaware Basin to the south, and the Guadalupe and Sacramento Mountains to the west.

## REGIONAL GEOLOGY

The Delaware Basin is a large, sediment-filled depression of the earth's crust, occupying over 17,000 square miles in west Texas and southeastern New Mexico. The basin is one of the deepest in North America, containing more than 24,000 feet of sedimentary rock that provide reservoirs for the water, oil, and natural gas resources of the region. A thinner section of this sedimentary rock overlaps the northern edge of the basin, extending for more than 100 miles beyond the basin margin across the Northwest Shelf.

The Delaware Basin is rimmed by the Capitan reef, which is exposed as a steep limestone escarpment along the southeast flank of the Guadalupe Mountains. These mountains, which form some of the more prominent topography in southeastern New Mexico, stretch in a northeast direction for approximately 70 miles across western Eddy County. A southern prong of the mountains projects into Texas, rising to an elevation of almost 9,000 feet at Guadalupe Peak, the highest point in the state. The mountains decrease in prominence to the northeast, persisting as a range of low limestone hills west of Carlsbad. The Capitan reef limestone is an important aquifer in southern Eddy County, providing fresh water for the town of Carlsbad; it is also the host rock for many of the caves in this area, including Carlsbad Caverns and Lechuguilla Cave.

The Sacramento Mountains, together with Sierra Blanca and the Capitan Mountains at the northern end of the range, constitute one of the largest and most conspicuous mountain ranges in southern New Mexico. The profile of the Sacramentos is strongly asymmetric, with a bold, west-facing escarpment that rises abruptly for more than a mile above the desert floor of the Tularosa Valley. Eastward from the crest of the mountains, the land surface merges almost imperceptibly with the Pecos slope, a flat, nearly treeless plain that slopes gently downward toward the Pecos River, 80 miles away and 6,000 feet lower in elevation.

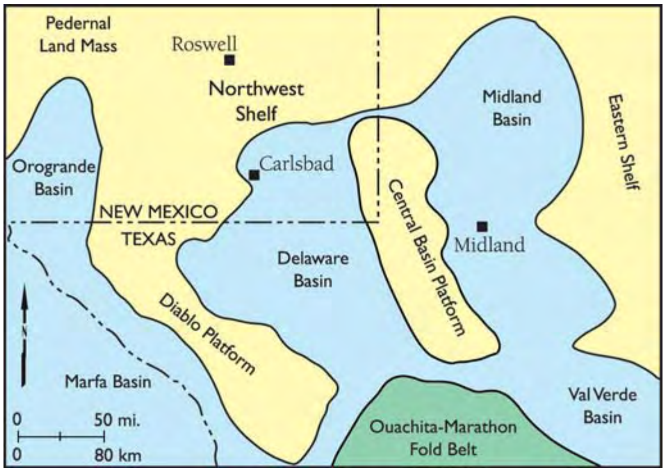
Most of the crest and eastern slope of the Sacramentos is capped by limestones of the San Andres Formation. San Andres limestones constitute most of the artesian aquifer that provides water for irrigation in the Roswell artesian basin of Chaves and northern Eddy Counties. Where it is exposed at the surface, the San Andres is charged with fresh water by rainfall and ephemeral streams flowing across the Pecos slope. Recharge of the aquifer is facilitated by the Pecos buckles, a series of parallel faults and folds that extend as far as 80 miles in a northeast direction across the slope. Fractures are commonly associated with the Pecos buckles, providing conduits for surface water to flow downward into the aquifer.

A few miles west of Roswell, near Six Mile Hill, the San Andres Formation dips into the subsurface and extends eastward beneath the Pecos River valley. At greater depths east of the Pecos River, the San Andres is an important oil and gas reservoir.

## GEOLOGIC HISTORY

Sedimentary strata in the Delaware Basin and surrounding areas range in age from a few thousand to more than 500 million years. However, that portion of the geologic column of most interest to us begins in the middle Permian Period, 250 million years ago. At that time, southeastern New Mexico and west Texas were occupied by a restricted ocean basin with water depths exceeding 1,500 feet, in a physiographic setting somewhat similar to the modern Persian Gulf or Black Sea. Sediments being deposited in the basin included fine sands, silts, and lime mud typical of a deep-water environment. These sediments eventually formed the rocks of the Delaware Mountain Group and Bone Spring Formation, which can be seen in outcrop on the road to El Paso, at the base of El Capitan.

In the warm, shallow waters of the shelf area that rimmed the basin, the skeletal remains of thousands



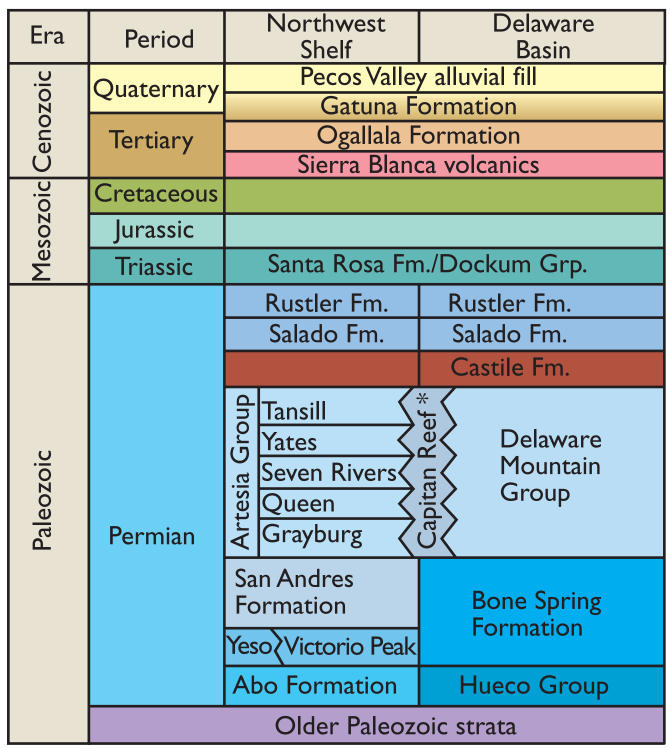

Paleogeographic map of southeastern New Mexico and west Texas in middle Permian time, about 250 million years ago. Areas occupied by ocean basins and relatively deep water are shown by blue shading. Tan shading indicates shelf and platform areas that were periodically flooded by shallow seas.

of marine organisms contributed to the accumulation of great volumes of lime sand and mud. Those sediments formed the thick limestone units now found at the surface and in the subsurface throughout southeastern New Mexico. The San Andres Formation is the lowermost and most extensive of these strata. San Andres limestones extend for hundreds of miles across eastern New Mexico, from the Guadalupe Mountains to the Roswell artesian basin and beyond. The San Andres is still present in the subsurface as far north as Santa Rosa, where it is the source of the spring water that feeds the lakes in that community.

Later, a great reef grew around the upper rim of the Delaware Basin, almost completely encircling it with a limestone escarpment hundreds of feet thick. This enormous structure, the Capitan reef, was constructed in very shallow water by a multitude of reef-building marine organisms including sponges, algae, and sea lilies, all animals and plants that thrived in the warm, tropical seas of the middle Permian Period. In its overall form and setting, the Capitan reef is similar to the Great Barrier reef of eastern Australia, although the organisms that formed it are not the corals of the modern south Pacific reefs. The Capitan reef can be seen today in the massive limestone outcrop that forms the east flank of the Guadalupe Mountains. Farther to the northeast, near Carlsbad, the reef plunges underground, but it can be traced in the subsurface around the northern and eastern margins of the Delaware Basin into west Texas.

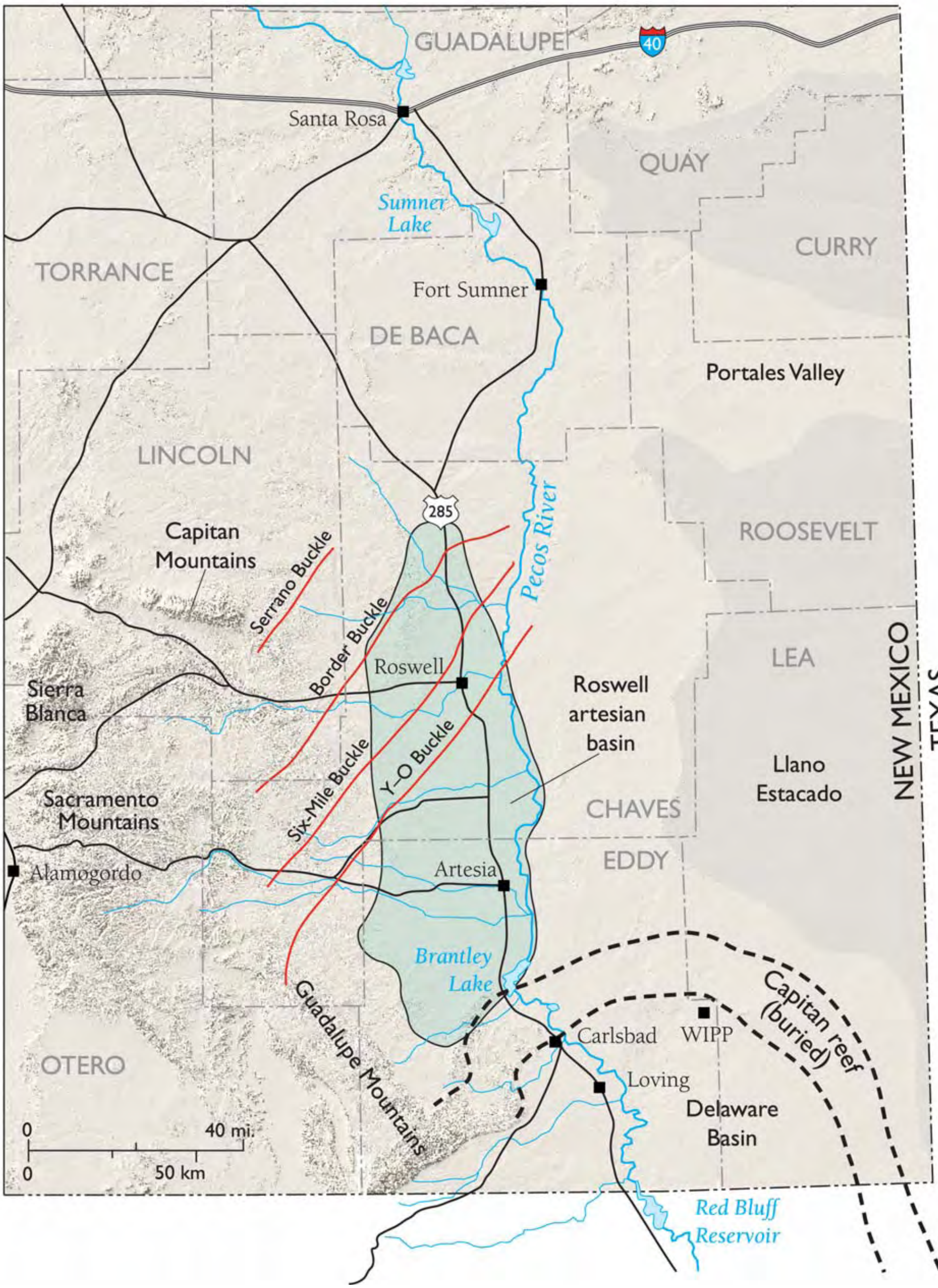
Behind the Capitan reef, a variety of sediments were deposited in the shallow waters of a broad lagoon that extended for many tens of miles across the Northwest Shelf. Immediately behind the reef, the sediments being deposited were mostly lime mud and sand, which now make up the limestone and sandstone beds of the Artesia Group. These rocks are exposed today throughout the Guadalupe Mountains west and north of the reef escarpment, and can easily be distinguished by their layered appearance from the massive, unstratified character of the Capitan reef.

As we follow the strata of the Artesia Group farther north, the environment in which they formed changed from the shallow waters of an open marine lagoon to an arid coastal region characterized by ephemeral streams and salt flats. Because of this change in depositional environment across the Northwest Shelf toward present-day Roswell, rocks of the Artesia Group undergo a remarkable transformation. The thin-bedded limestones found in the northern Guadalupe Mountains change over a short distance

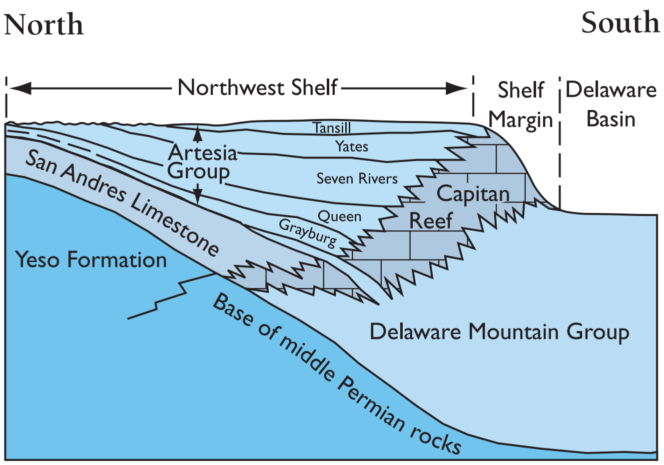



* lower portion of reef section includes the Goat Seep reef

Geologic column for southeastern New Mexico, showing geologic time periods (left) and corresponding rock formations (right).




Regional map of southeastern New Mexico. Pecos buckles are shown by the red lines trending northeast across the Pecos slope, east of the Sacramento Mountains.



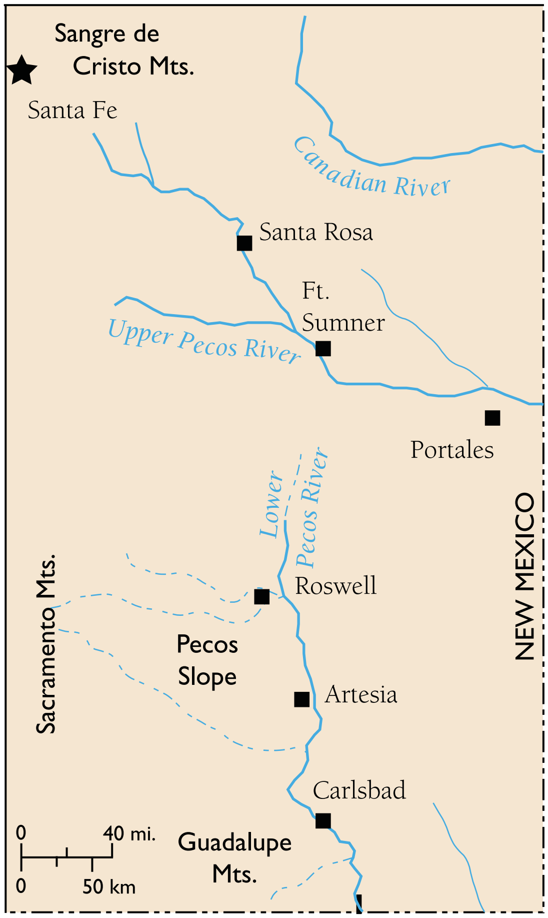

North-south cross section showing shelf-to-basin relationships of middle Permian strata of the Delaware Basin and adjacent shelf area. The section extends roughly from Roswell, New Mexico to Orla, Texas, just south of Red Bluff Reservoir.

into red mudstone, gypsum, and salt. These are the rocks exposed in the Seven Rivers escarpment east of Roswell, where they host the striking gypsum sinkholes of Bottomless Lakes State Park. Because of their very low permeability, mudstones and gypsum of the Artesia Group also serve as the confining unit for the artesian aquifer.

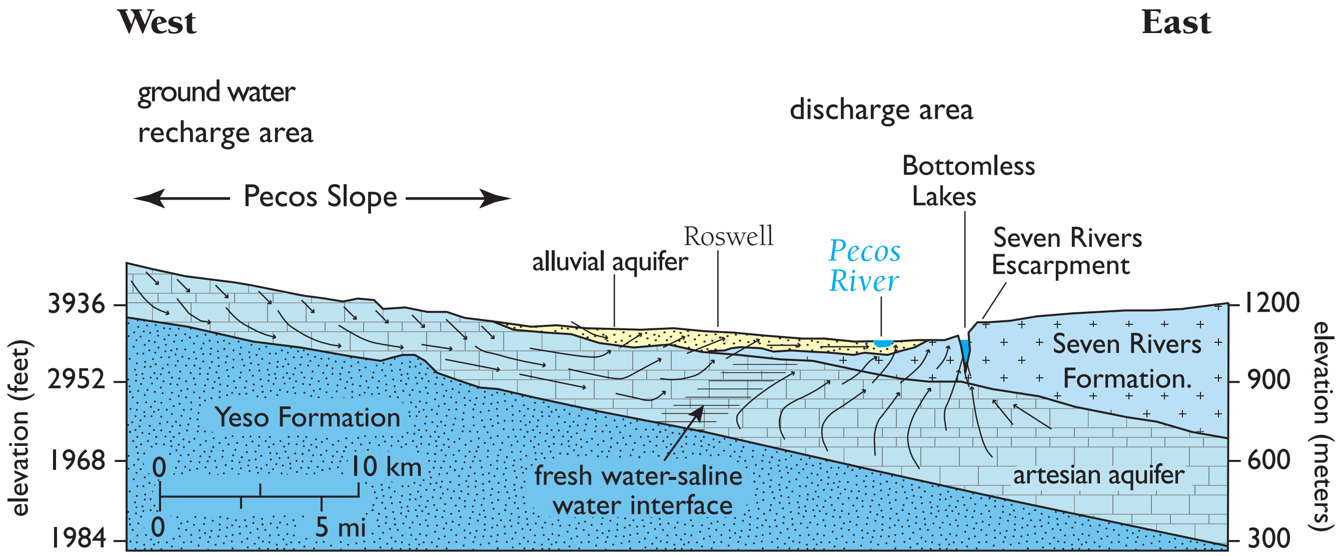
Toward the end of the Permian Era, sea level began to fall in the Delaware Basin, and the environment became increasingly hot and arid. As the waters of the basin and adjacent shelf area evaporated, their mineral content was left behind as thick accumulations of gypsum, anhydrite, and rock salt of the Castile, Salado, and Rustler Formations. Commercial potash deposits are mined east of Carlsbad from these evaporite rocks. In part because of their low permeability, the massive salts of the Salado Formation are now being used for disposal of radioactive waste at the Waste Isolation Pilot Plant (WIPP), which is located in the northern Delaware Basin a few miles south of the buried reef front. As one would expect, the water contained in these Upper Permian strata has a very high mineral content. Saline waters in the Rustler Formation discharge into the Pecos River near Malaga Bend, south of Loving, resulting in a dramatic increase in salinity of the river downstream.

After deposition of the Late Permian evaporites, very little younger sediment accumulated in the Pecos region until late Tertiary time, about 13 million years ago, when uplift of the Guadalupe and Sacramento Mountains began. Streams and rivers flowing eastward across the Pecos slope deposited large volumes of sand and gravel in a broad apron east of the rising mountains.

Backreef limestones of the Artesia Group in Slaughter Canyon, Guadalupe Mountains, New Mexico.




Drainage system of the ancestral Pecos River, approximately 5 million years ago.




West-east cross section of the Roswell artesian basin. Arrows show generalized patterns of ground water flow within the San Andres artesian aquifer and shallow alluvial aquifer. The Seven Rivers and Yeso Formations act as regional confining units.

These sediments now make up the Ogallala aquifer, the principal source of water for irrigated agriculture on the Llano Estacado, or southern High Plains.

Deposition of the Ogallala sands and gravels ceased about 5 million years ago when their source streams were diverted by an evolving system of valleys cut by the ancestral Canadian and Pecos Rivers. At this time the upper Pecos River occupied a separate drainage system flowing east/southeast through the Portales Valley in Roosevelt County. To the south, the lower Pecos Valley was forming by dissolution and subsidence of the limestone and gypsum bedrock across which the river flowed. As the lower Pecos River extended its reach farther to the north by headward erosion, it progressively captured streams flowing eastward from the Sacramento Mountains, culminating in capture of the upper Pecos River near Fort Sumner about one million years ago, at which time the modern drainage system was established.

The Pecos River originally flowed west of Roswell, but the channel has migrated eastward due to continued uplift of the Sacramento Mountains, and downtilting of the land surface to the east. Alluvial sediment deposited by the Pecos River over the past few million years constitutes most of the shallow surficial aquifer that is also used for irrigation in the Roswell–Artesia area.

As the river migrated eastward, it eroded and undercut east-tilting strata of the Artesia Group, a process that continues to this day, giving the Roswell-to-Carlsbad reach of the Pecos Valley a distinctly asymmetric character. Much of the eastern margin of the valley is defined by steep gypsum bluffs of the Seven Rivers Formation, in contrast to the gently sloping west side.

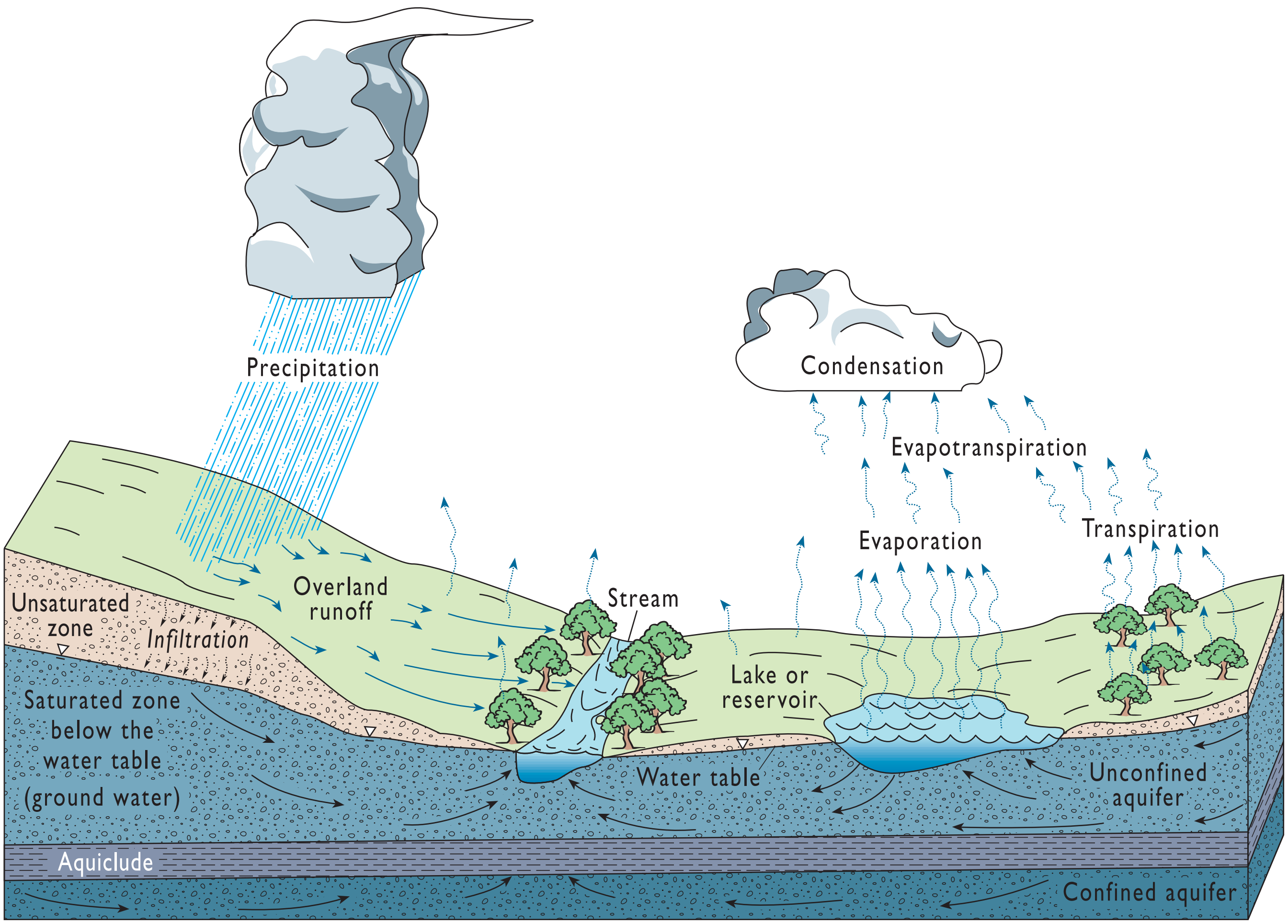
To a large extent, growth and economic development in the lower Pecos Valley have been determined by the geology and hydrology of southeastern New Mexico. The first European settlements in the area were established near surface water sources. The town of Eddy, now Carlsbad, was located near Carlsbad Springs, and settlers in the Roswell area built their homes on the north and south Spring Rivers. Subsequent development of ground water resources in the Roswell artesian aquifer stimulated the expansion of irrigated agriculture. Economic growth has continued with the discovery and exploitation of oil, gas, and potash deposits in Permian and older rocks. Recent developments include construction of the WIPP site east of Carlsbad, which provides deep geologic sequestration of radioactive waste in the thick Upper Permian salt deposits of the Delaware Basin. Future growth and development in the Pecos Valley will almost certainly continue to be driven by exploitation of the geologic and hydrologic resources of the region.

# A Primer on Water: Ground Water, Surface Water and Its Development

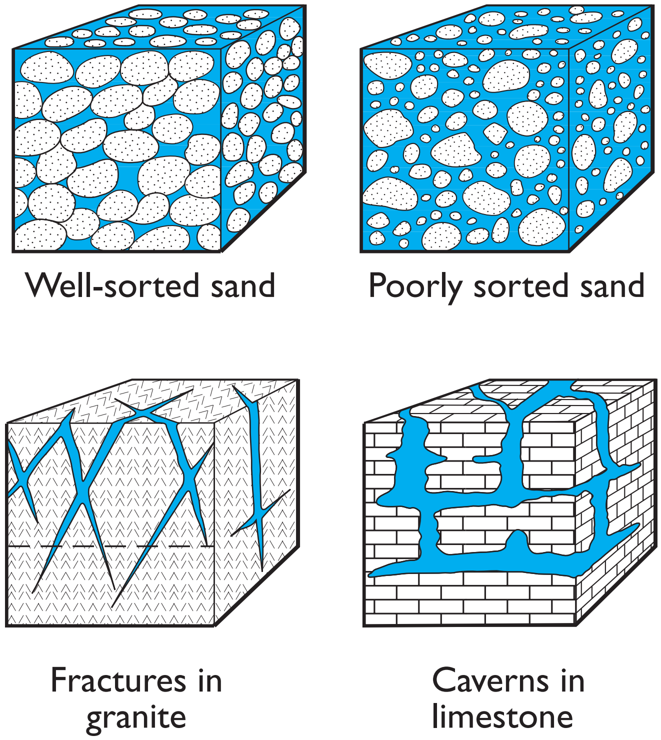
Peggy Johnson, *New Mexico Bureau of Geology and Mineral Resources*

Water is the primary factor in determining how New Mexico grows and looks in the future. Our water is limited in quantity, and in some places by its quality. Its availability is highly variable, and often uncertain or poorly defined. Initially, all of New Mexico's water comes from precipitation, and the principal constraint on our water supply is climate. This paper provides basic information on water in New Mexico: its nature and conditions of occurrence and fundamental issues surrounding its development.

Most of New Mexico is a desert. A desert is defined as a region with a mean annual precipitation of 10 inches or less, and so devoid of vegetation as to be incapable of supporting any considerable population. Precipitation in New Mexico ranges from 6.7 inches at Shiprock to a maximum of 26.2 inches at Cloudcroft, but much of New Mexico receives less than 10 inches of water per year. Most of the precipitation that falls evaporates within a short time of reaching the ground (or sometimes before). Of the precipitation that reaches




A hydrologic cycle for New Mexico.




Pore space in sand, gravel, and other unconsolidated deposits, fractures in crystalline and consolidated sedimentry rocks, and dissolution cavities in limestone provide storage for ground water aquifers.

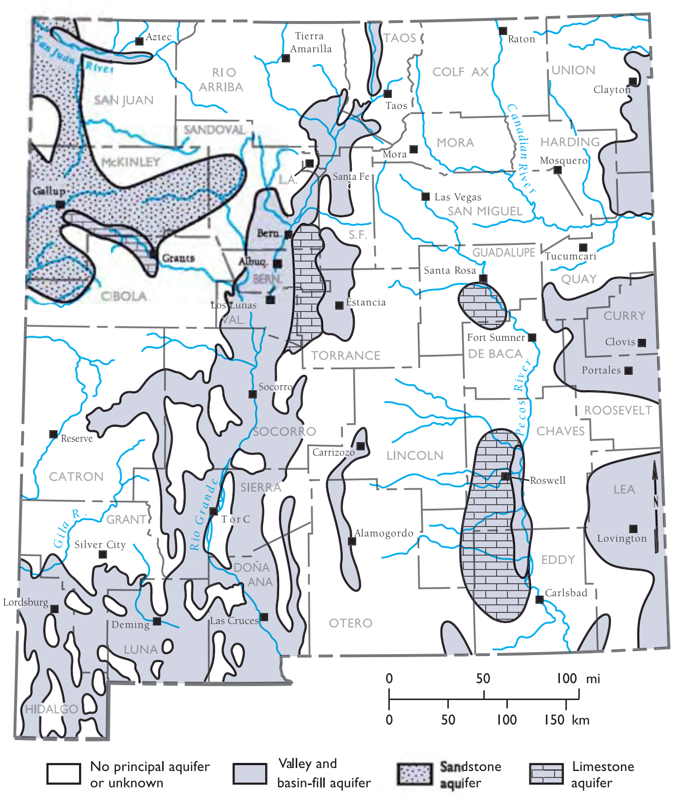
land without evaporating, much is taken up and used by plants (called transpiration). The rest either flows across the land surface into rivers and streams, or percolates into the ground, where it recharges underground aquifers. The portion of New Mexico where precipitation exceeds the combination of evaporation and transpiration (called evapotranspiration) is limited to a few areas of high elevation during the cool months of the year. The circulation of water through the physical environment, described by the hydrologic cycle, involves these and other physical processes.

Surface water refers to all water located on the surface of the land—rivers, lakes and streams. New Mexico's surface water supply originates as rain or melting snow, but 97 percent of that water evaporates or is transpired by plants. Surface water is renewable, but in our climate, flows are highly variable. Flows in the Pecos River are particularly erratic, and we are not very good at predicting ahead of time how much surface water will be available in a coming year or even coming months. A detailed description of surface water in the Pecos River basin is provided in the paper by John Longworth and John Carron (this volume) titled "Surface Water Hydrology of the Pecos River."

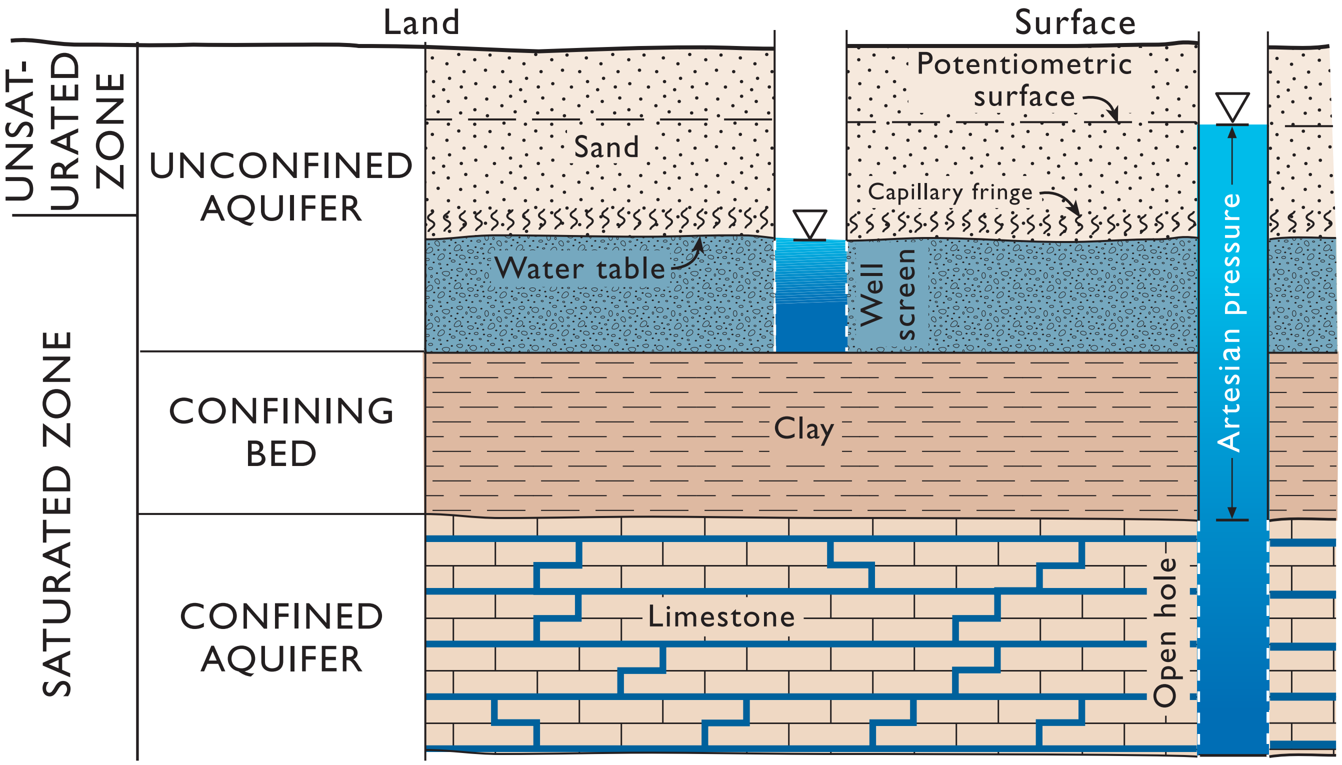
## GROUND WATER

Most of New Mexico's fresh water is stored in aquifers below the land surface, where it occupies small open spaces between grains of sand or gravel and small cracks or fractures in rock. These cracks and void spaces are referred to as the porosity of the rock or sediment. All rocks that underlie the earth's surface are classified as either aquifers or confining beds (also known as aquitards). An aquifer is a saturated rock unit or geologic formation that yields significant quantities of water to wells and springs. A confining bed (or aquitard) is a saturated geologic unit of less permeable material that is incapable of transmitting significant quantities of water, thus restricting the movement of ground water either into or out of adjacent aquifers.

Ground water occurs in aquifers under two different conditions. In places where water only partially fills an aquifer, the upper surface of the water table is open to the atmosphere and is free to rise and fall in response to atmospheric pressure and changes in aquifer storage. The water in these aquifers is said to be unconfined, and the aquifers are referred to as




Major aquifer types in New Mexico.

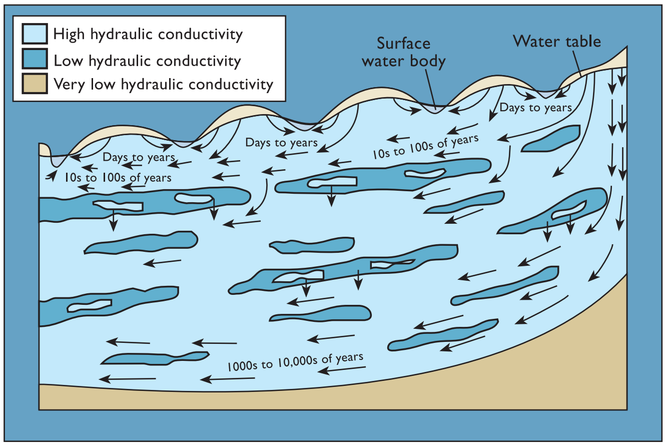



A typical relationship between an unconfined aquifer, confining bed, and confined aquifer, as occurs in the Roswell artesian basin, and the occurence of water-table and artesian wells. Note that the hydraulic head is higher in this instance in the artesian aquifer than the water-table aquifer; hence ground water will leak upwards from the limestone, artesian aquifer through the confining clay bed and into the shallow unconfined aquifer.

unconfined aquifers or water-table aquifers. Where water completely fills an aquifer that is overlain by a confining bed, the water in the aquifer is confined under pressure and the aquifer is referred to as a confined or artesian aquifer.

The elevation of water standing in wells that are completed below the water table and open to the aquifer reflects the hydraulic head, which is the sum of elevation and water pressure in the aquifer. Hydraulic head is used to describe the potential energy field in ground water flow systems. Water levels in wells open to unconfined aquifers, referred to as water-table wells, indicate the position of the water table in the surrounding aquifer. Wells drilled into confined aquifers are referred to as artesian wells. The water level in artesian wells stands at some height above the top of the aquifer because the water is under confining pressure, but does not necessarily rise above the land surface. If the water level in an artesian well stands above the land surface, water will discharge and flow freely if the well is not capped, and the well is called a flowing artesian well. Both artesian and flowing artesian wells are common to the Roswell artesian basin.

Large supplies of ground water occur in different categories of aquifers that include sand and gravel (alluvial) aquifers, sandstone aquifers, and limestone or fractured rock aquifers. Alluvial aquifers produce large amounts of water along the state's major river valleys, in the closed basins of central and southwest New Mexico, and from the Ogallala Formation in eastern New Mexico. Sandstone aquifers can also be productive, but mineral cements that partially fill the open spaces between sand grains may reduce the original porosity of sandstone aquifers and limit their storage capacity. Limestone forms the major aquifers in the Roswell artesian basin, along the north flank of the Zuni Mountains, in the Sandia and Manzano Mountains, and in parts of San Miguel and Guadalupe Counties. Because cracks and caverns in limestone make up a relatively small portion of the total rock volume, limestone aquifers like the Roswell artesian aquifer possess relatively small storage capacity, but transmit water very rapidly.




Regional ground water aquifers are complex, three-dimensional systems, where ground water moves at vastly different time scales.

Ground water is not strictly speaking a nonrenewable resource like a mineral deposit or a petroleum reserve, but neither is it renewable on an annual or seasonal basis like surface water. Factors that govern "renewability" of ground water include the permeability, complexity, and connectivity of the aquifer and the sources and rates of recharge. Ground water resources may appear ample, but availability actually varies widely and only a portion of the ground water stored in the subsurface can be withdrawn economically or without adverse consequences. Prudent development of ground water requires an understanding and appreciation of the dynamic and complex nature of aquifers.

Aquifers are dynamic. Ground water moves through aquifers, from recharge areas to discharge areas, under the driving force of a hydraulic gradient, or the change in hydraulic head per unit distance in the aquifer. Under natural, pre-development conditions, aquifers are in a state known as dynamic equilibrium, where recharge or replenishment of the aquifer approximately equals discharge. Ground water moves along flow paths from areas of recharge such as mountains, rivers, or arroyos, to areas of discharge, like springs, wetlands, and streams. Pumping from a well diverts ground water that was moving slowly to its natural, possibly distant, area of discharge. The source of water pumped from wells is initially aquifer storage, but eventually that diversion will decrease the ground water discharge to streams, springs, and wetlands.

Recharge from precipitation continually replenishes ground water, but much more slowly than withdrawal rates of pumping. In New Mexico, the amount of recharge from precipitation is both small and relatively fixed, with estimates ranging from 0.03 percent to 20 percent of mean annual precipitation, depending on soil or rock type, topography, vegetation, and climate. Significant recharge is extremely localized along rivers, streams, arroyos, mountain fronts, and some faults. Excessive ground water use in limited aquifers with negligible recharge can cause widespread declines in ground water levels and a significant decrease in ground water storage.

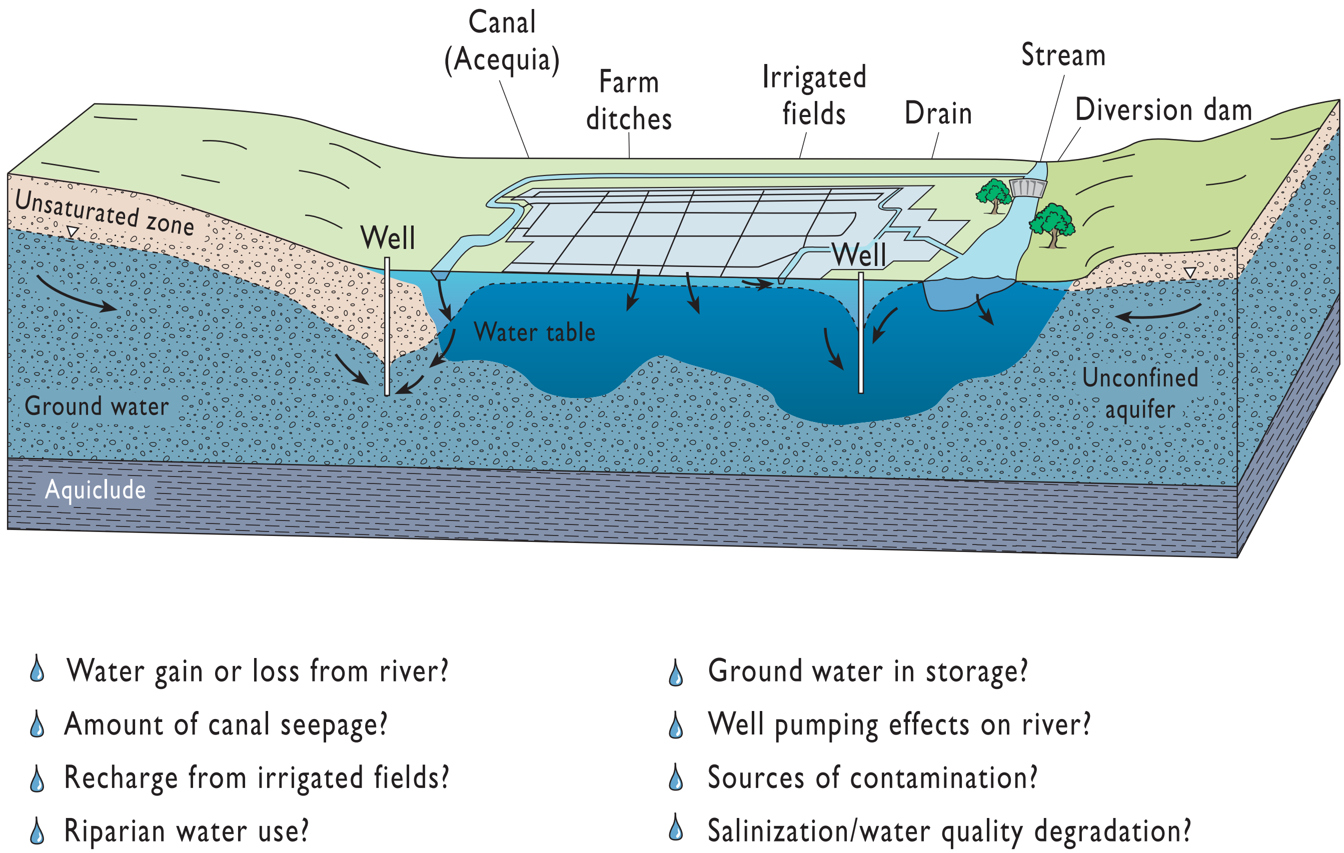
Aquifers are complex three-dimensional flow systems, with subsystems that occur at local, subregional, and regional scales. Faults, low permeability rocks, and differences in the thickness and character of water-bearing beds over short distances can form barriers to ground water flow and partition the aquifer into compartments analogous to an egg carton.

The various compartments of an aquifer system can operate on scales varying from tens of feet to hundreds of miles and in time frames of days to hundreds, thousands, or tens of thousands of years. The rate of ground water flow through an aquifer ranges from one foot per day or greater, to as little as one foot per year, or even one foot per decade. Because development of regional aquifers may take place over many years and the effects of ground water pumping tend to manifest slowly over time, the full impacts of ground water development may not become obvious until undesirable effects are evident.

## INTERACTIONS OF GROUND WATER AND STREAMS

Surface water and ground water are components of the same system. There is a direct hydrologic link between almost all surface water sources and the adjacent aquifer. Ground water contributes to surface water in many settings, and infiltration of surface water replenishes our aquifers. Withdrawals from an aquifer drain not only the aquifer, but also deplete the associated stream. Where aquifers and surface streams are connected, management of the water supply must recognize that fact.

Pumping ground water near streams alters the natural interchange between stream and aquifer. Pumping from wells in a stream-connected aquifer intercepts water that would otherwise have discharged to a stream, and may also cause water to flow directly from the stream into the aquifer (a process called induced recharge). The combination of the two is termed *capture*. Pumping also depletes the amount of ground water in storage. The allocation between stream

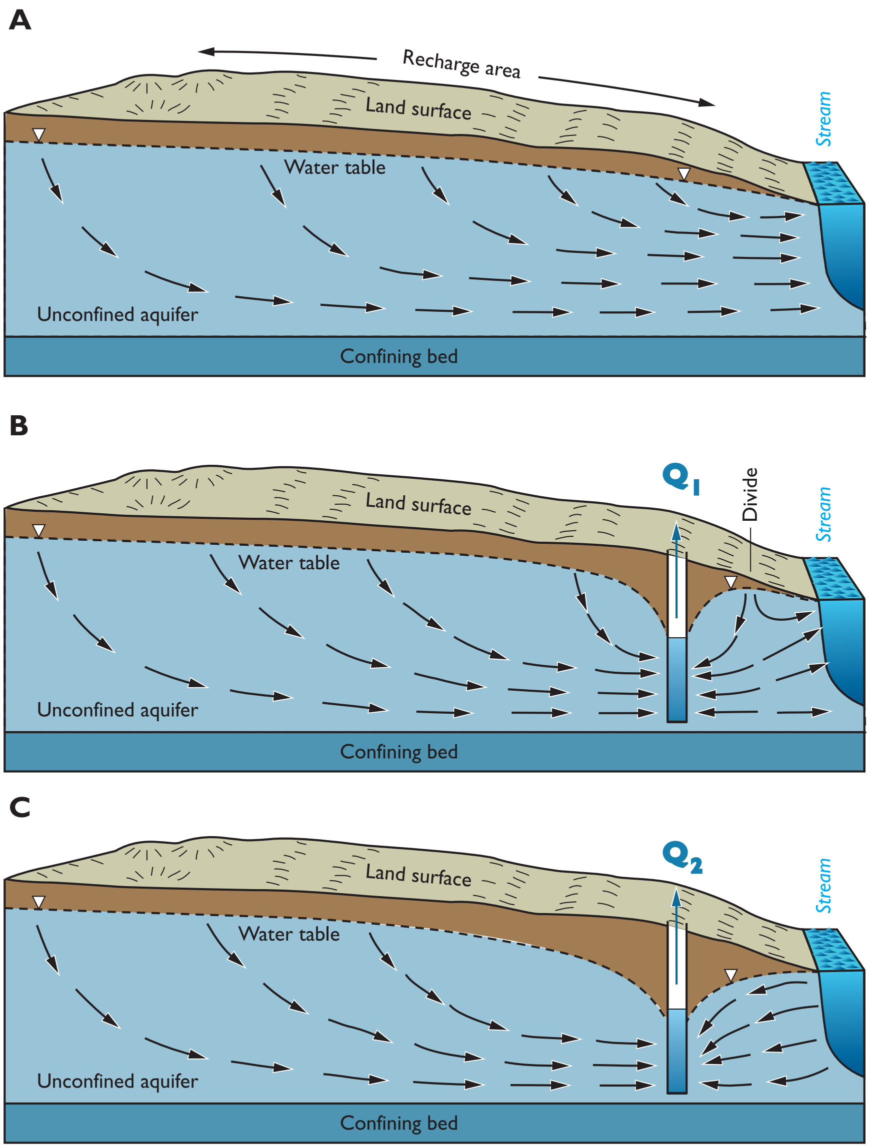



This cross section of a typical irrigated river valley where the stream and aquifer are connected illustrates some of New Mexico's prevalent hydrologic and water management issues.

capture and reduction of ground water storage varies greatly and changes with time, depending on the distance from well to stream, and the characteristics of the aquifer. Eventually, a new dynamic equilibrium is reached, where capture supplies all of the water being pumped, and no more is taken out of storage. When pumping stops, stream depletions continue until all of the ground water storage previously depleted by pumping is replaced at the expense of flow in the stream. In complex regional aquifers, the amount of time it takes to reach a new equilibrium between pumping and stream depletion can be many decades or longer.

Historically, hydrologists and planners have relied on a concept known as the safe yield of an aquifer to guide water management decisions. The safe yield equals the amount of naturally occurring ground water that can be economically and legally withdrawn from an aquifer on a sustained basis without impairing the native ground water quality or creating other undesirable effects. Safe yield is generally equivalent to capture and is quantified by estimating the increase in recharge and decrease in discharge that is due to a decline in water levels caused by pumping. One of the eminent figures in ground water hydrology, John Bredehoeft, has referred to this concept as the "water-budget myth" and summarizes it as follows:

- The recharge, and certainly the change in recharge due to ground water development (induced recharge), is difficult if not impossible to quantify. Usually the recharge is fixed by rainfall and does not change with development.
- Commonly a change in virgin discharge (capture) is what makes it possible to bring a ground water system into balance. Capture from natural discharge is usually what determines the size of a sustainable development.
- Pumping does not have to exceed recharge for streams to be depleted. Pumping is an additional stress on the system. The water pumped will usually be supplied both from storage and from reduced natural discharge.




Ground water discharges to a stream under natural conditions. Recharge at the water table equals discharge to the stream.

A well pumping near the stream will intercept part of the water that would have discharged to the stream.

A higher pumping rate reverses hydrologic conditions and induces water to flow from the stream to well.

The effects of ground water withdrawals on surface water (after Winter et al., 1999).

- Equilibrium is a state in which there is no more change in ground water storage with time—water levels are stable in time. If no new equilibrium can be reached, the aquifer will continue to be depleted. Once a new equilibrium is reached, the natural discharge is reduced by an amount equal to the development—capture equals development. This has nothing to do with recharge. Often streams are depleted long before pumping reaches the magnitude of recharge.

Many of New Mexico's cities and some irrigation districts that rely on stream-connected ground water have postponed dealing with impacts to the river until some time in the future. But eventually the debt to the river must be paid.

## SUGGESTED READING

Leopold, L. B., 1997, Waters, rivers and creeks: University Science Books, Sausalito, California, 185 pp.

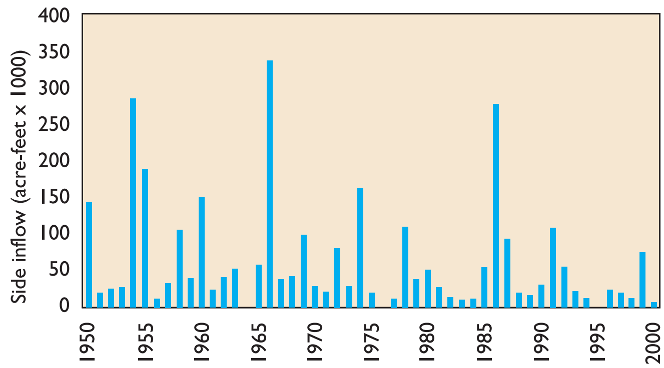
Winter, T. C., Harvey, J. W., Franke, O. L., and Alley, W. M., 1999, Ground water and surface water, a single resource: U.S. Geological Survey, Circular 1139, 79 pp.

Alley, W. M., Reilly, T. E., and Franke, O. L., 1999, Sustainability of ground-water resources: U.S. Geological Survey, Circular 1186, 79 pp.

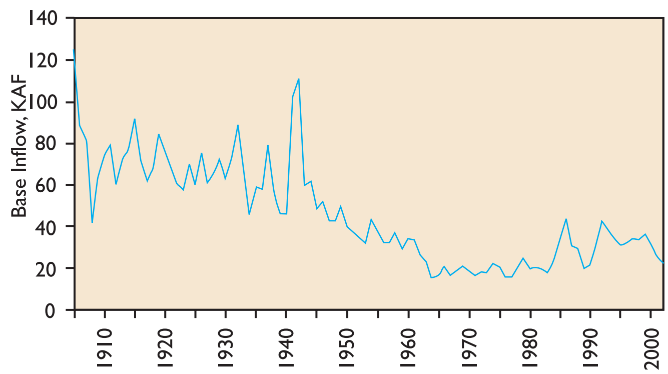
# Surface Water Hydrology of the Pecos River

John Longworth, *New Mexico Interstate Stream Commission*
John Carron, *Hydrosphere Resource Consultants, Inc*

The Pecos River is typical of many western U.S. rivers, originating in high alpine mountains—in this case the Sangre de Cristo Mountains of northern New Mexico—whose snowmelt runoff is one source of the river's reliable water supply. The river then travels through desert or semi-desert regions where ephemeral tributary inflows generated by unpredictable (and highly variable) precipitation events provide additional flows. The Pecos River drains much of southeastern New Mexico and continues south from New Mexico into southwestern Texas before merging with the Rio Grande near Del Rio, Texas.




Annual side inflow (flood inflow) volumes to the Pecos River.




Base inflows to the Pecos between Roswell and Artesia. Notice the systematic decline in base inflows starting in approximately 1945, believed to reflect the impacts of ground water withdrawals.

**PHYSIOGRAPHY**

The Pecos River begins at an altitude of 12,000 feet in the Sangre de Cristo Mountains of north-central New Mexico, east of Santa Fe. The landscape there is dominated by steep mountain valleys and coniferous forests. As the Pecos descends out of the Sangre de Cristos, it is generally confined between limestone escarpments through the Fort Sumner area. South of Fort Sumner, it becomes wide and meandering as it crosses the semi-arid high plains of southeastern New Mexico. From the area just north of Roswell to Carlsbad, the basin is bounded on the west by a series of mountain ranges, including the Sacramento and Capitan ranges. To the east, the land rises slowly from the river, terminating in a low-elevation escarpment that forms the eastern boundary of the drainage. In this region, the Pecos is located east of the populated areas of Roswell and Artesia. Below its headwaters, most of the major tributaries of the Pecos originate in the ranges west of the river. The Pecos River basin drains an area within New Mexico of approximately 19,500 square miles.

**HYDROLOGY—SOURCES**

Pecos River water has three primary sources. The first is snowmelt and runoff from the headwaters in the Sangre de Cristo Mountains. The drainage area that generates these flows is approximately 10 percent of the total New Mexico drainage. The average annual runoff over the past 30 years has been approximately 50,000–60,000 acre-feet.

The second source is overland flow, or flood inflow, generated by precipitation either from storms from the Pacific Ocean or from the monsoons originating in the tropics. These flood events can occur anywhere in the basin, and on average provide most of the surface water supply. They are the source of the largest recorded flow events in the basin (e.g., the floods of 1919 and 1941) and can provide hundreds of thousands of acre-feet of water to the Pecos River. When such floods are abundant, they can fill all the major storage facilities in a short period of time. Conversely, the absence of these storm systems coincides with some of the most significant historic droughts. It is these flood inflow events that largely define the variable nature of the Pecos River hydrology.

The third source of Pecos River water is ground water inflow, commonly referred to as base inflow. Although there is the potential for base inflow throughout the basin, there are three primary locations in the basin where significant amounts of base inflow occur. The uppermost source is the springs located in the area in and around Santa Rosa (including the well-known Blue Hole Spring in Santa Rosa). Regionally, the springs contribute 36,000–60,000 acre-feet per year to the Pecos River. The source of these springs has not been intensively studied, but the water is believed to originate in the upper watershed, entering the ground water aquifer through direct percolation or via seepage from the Pecos River.

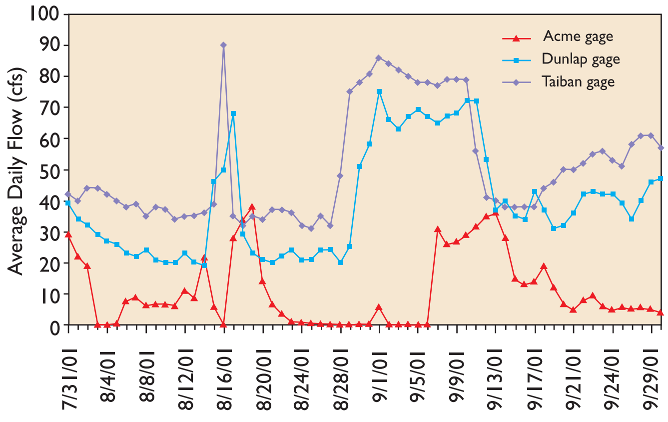
Farther south, significant ground water inflow occurs in the Roswell–Artesia area. Here base inflow originates from the artesian and shallow aquifers of the Roswell artesian basin. These aquifers are recharged from the mountains and tributaries west of the Pecos River. This base inflow has been as high as 120,000 acre-feet and as low as 15,000 acre-feet per year over the period of record (1905–1998). It is important to note how dramatically the base inflow has changed since the early 1900s, due in large part to the growth of ground water use for irrigation. Additionally, it is widely reported that before the development of the artesian basin there were many perennial streams originating in the Sacramento Mountains that fed the Pecos River.

The final location of significant ground water inflow is the Carlsbad area. Here are two primary sources of water. The first is discharge from the Capitan aquifer. Historically this aquifer discharged to the Pecos River in Carlsbad through Carlsbad Springs. Precipitation in the Guadalupe Mountains, and possibly other sources of water, recharge the Capitan aquifer. Ground water diversions from this aquifer have now largely eliminated the base inflow to the Pecos River originating from the Capitan aquifer. The second source of base inflow to this reach of the Pecos is seepage from Lake Avalon and return flows from irrigation in and around the Carlsbad area, primarily by the Carlsbad Irrigation District (CID). CID irrigators divert an average of 75,000 acre-feet of Pecos River water each year. Of this amount, approximately 60 percent is consumed by crops and evapotranspiration. The remaining 40 percent returns to the Pecos River, either as surface runoff or, predominately, as base inflows from percolation into the underlying aquifer.

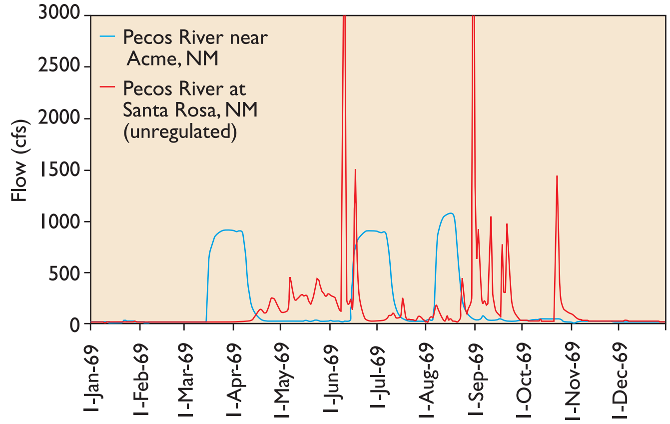
## HYDROLOGY—LOSSES AND CONSUMPTIVE USES

There are primarily three processes that contribute to the reduction of flows in the Pecos River: natural evapotranspiration, seepage of water into the underlying ground water system, and human-induced consumptive use, mainly from irrigation. Natural evapotranspiration is the process of water being vaporized into the atmosphere. This process occurs either through transpiration from plant leaf surfaces or evaporation directly from the water surface itself. Evapotranspiration is thought to result in significant losses; many thousands of acres of salt cedar have been cleared in the Pecos River basin in an attempt to reduce water losses from the river. Direct evaporation from water surfaces is also a significant component of this process. Annual evaporation rates in the Pecos River basin range from 5.5 feet near Fort Sumner to nearly 8 feet at Lake Avalon. Evaporation is a function of weather conditions and storage levels, but the four major storage reservoirs in the basin can expect a total evaporation, on average, of 40,000–50,000 acre-feet of water each year

Seepage of water from the river into underlying alluvium or shallow aquifer systems is thought to occur in several reaches of the Pecos River, most notably in the reaches between Taiban and Acme, just above Brantley Reservoir, and from Lake Avalon itself. It is unclear (and very difficult to quantify) how much of this seepage either returns to the river at points downstream or is permanently lost. In the case of losses above




Losses in the Pecos River between Sumner Dam and Acme gage. The distance from Taiban to Acme gage is approximately 70 river miles.




Example hydrographs from the Pecos River, 1969. The impact of reservoir storage and regulated releases for irrigation is clearly illustrated by the pattern of block releases for CID irrigators.

Brantley Reservoir, it is thought that the water "lost" into the alluvium actually re-enters the surface water system at Brantley. Lake Avalon seepage is thought to contribute to base flows below the dam.

A combination of seepage and evapotranspiration causes the river to become intermittent at times in the area around Acme. Studies of losses in the river reaches between the U.S. Geological Survey gages near Taiban and near Acme—a distance of approximately 70 miles—indicate that during summer months the river will typically lose 30 cubic feet per second (cfs) at flows of 100 cfs or less. These losses are critically important to water managers and biologists, because much of this stretch of river is designated critical habitat for the environmentally threatened Pecos bluntnose shiner.

Consumptive use by irrigation is the third significant process that directly reduces Pecos River flows. On average, approximately 110,000–120,000 acre-feet of Pecos River water is diverted for irrigation of crops. Approximately 85 percent of this is used by two large irrigation districts, the Carlsbad Irrigation District and the Fort Sumner Irrigation District. The remaining usage is by the many irrigators who pump water directly from the river, and by small acequias.

### HYDROLOGY—IMPACTS OF WATER DEVELOPMENT

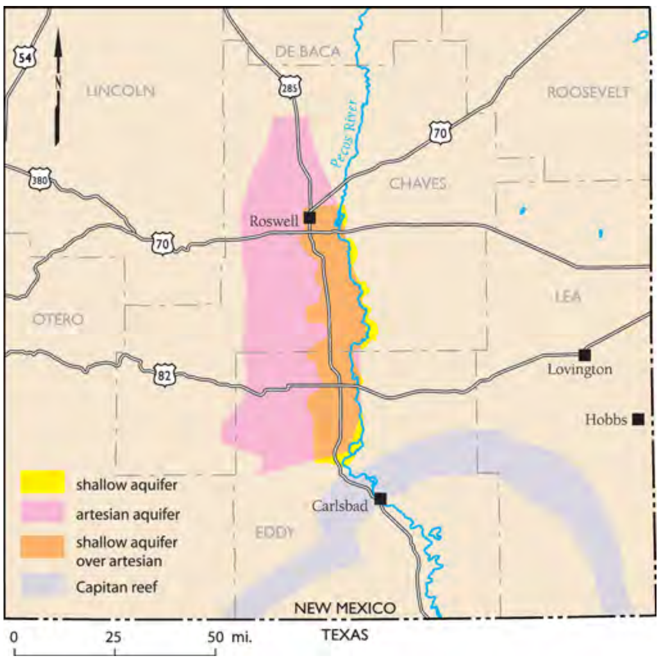
Storage, diversion, and consumption of the surface waters of the Pecos River have affected the natural hydrology of the basin. This is particularly true for those sections of the river regulated by the four large main-stem reservoirs. Although these reservoirs play a critical role in flood control, the Carlsbad Irrigation District (CID) uses them primarily for storage. The variable nature of the Pecos River results in an unreliable supply, in terms of both quantity and timing. By capturing snowmelt runoff and overland flow throughout the year and re-regulating these flows, water from the Pecos can be used to meet irrigation demands in the CID. When the demand for water is needed in the district, CID releases water from Sumner Lake and Santa Rosa Lake in "blocks" of water. These block releases are typically 14–20 days in duration at a flow rate of 1,000–1,400 cfs. By releasing water in blocks, only when downstream storage levels are low, CID minimizes evaporative and seepage losses that occur both in the river reaches and in downstream reservoirs.

Brantley Dam.

# Regional Hydrology of the Roswell Artesian Basin and the Capitan Aquifer

Peggy Barroll, *New Mexico Office of the State Engineer*
John Shomaker, *John Shomaker & Associates, Inc.*

The Roswell artesian basin consists of an extremely productive artesian (confined) aquifer that is overlain by a thick confining unit, and topped off by a shallow alluvial aquifer. In the early part of the twentieth century, the artesian aquifer was famous for supporting high-capacity artesian wells, from which water flowed freely at the surface without the need for pumps. Large ground water diversions from the two aquifers support irrigation of approximately 100,000 acres. This use of ground water has since depressurized the artesian aquifer, so that, with few exceptions, wells no longer flow freely at the surface (especially during the irrigation season), and the large springs that once supplied surface water irrigation in the Roswell area have largely gone dry.




Map showing the limits of the shallow and artesian aquifers of the Roswell basin, and the Capitan reef aquifer near Carlsbad.

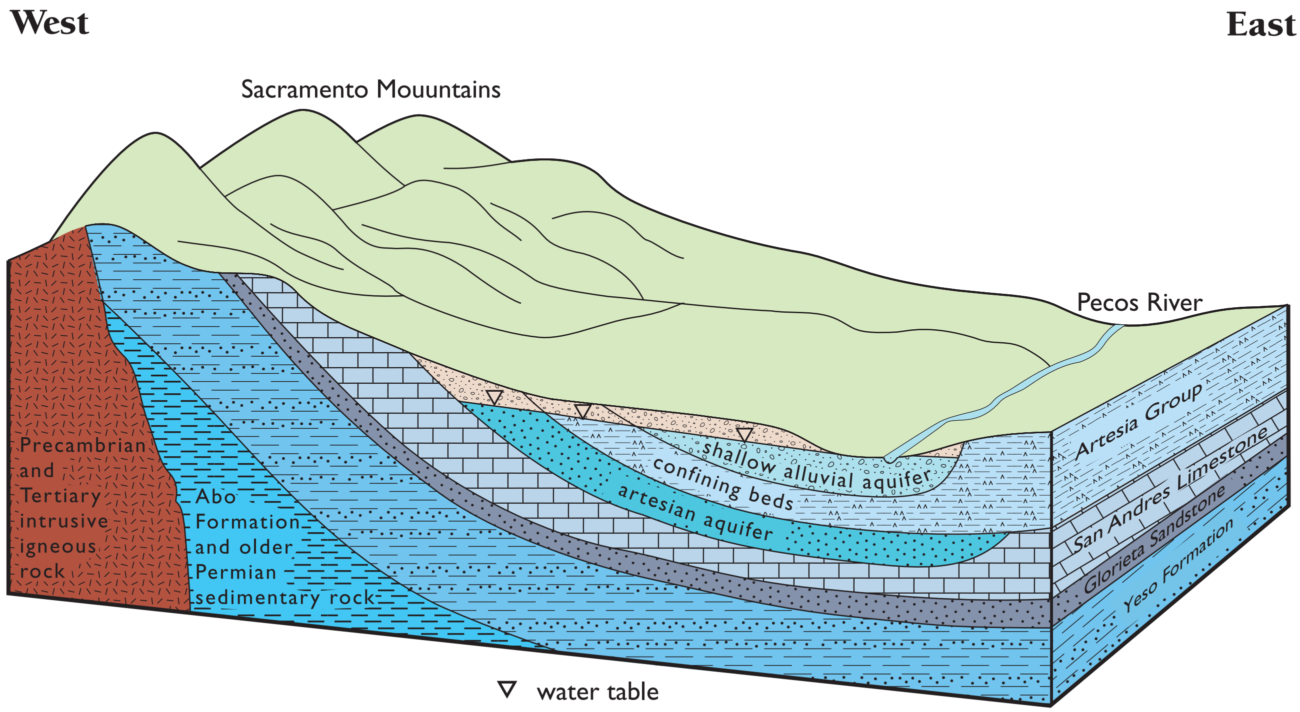
### HYDROGEOLOGY

The artesian aquifer is located within a sequence of east-dipping carbonate rocks (dolomite and limestone) belonging to the Permian-age San Andres Formation. These rocks are being dissolved by slightly acidic rainwater as it infiltrates and flows through them, so that small cracks are eventually enlarged into openings through which water passes very freely. In a sense the aquifer was created, and continues to be enhanced, by the water that passes through it. The artesian aquifer extends farther to the north, west, and south than the shallow aquifer, but the eastern boundary of each lies just east of the Pecos River.

Discharge from an artesian well into the Hagerman canal.

The shallow alluvial aquifer is composed of sand, gravel, and lesser amounts of clay and silt that partly fill the Pecos Valley. The shallow aquifer underlies the Pecos River from near the northern boundary of the basin, just north of Roswell, to the vicinity of Brantley Dam. The aquifer extends 10–15 miles west of the Pecos River and is generally less than 250 feet thick.

The artesian aquifer is dissected by several northeast-trending structural zones of faults and folds that cut across the Pecos slope, which is the recharge area for the aquifer. The land surface along these zones is dotted with sinkholes and open fractures, both of which provide avenues for rainwater to move down

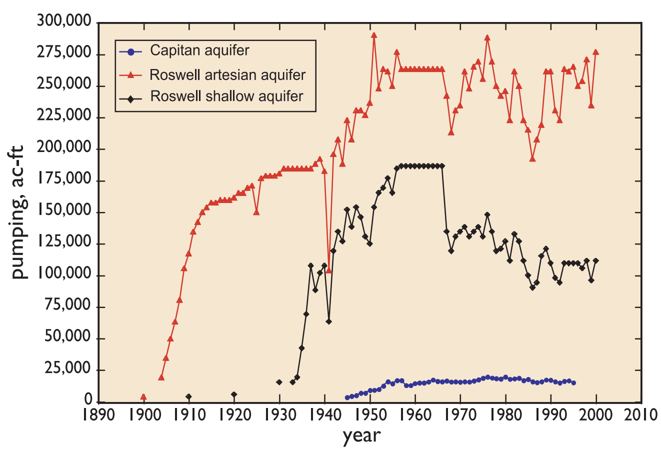



Schematic west-to-east cross section illustrating the relationships between the shallow aquifer, confining beds, and carbonate aquifer in the Roswell–Artesia area.

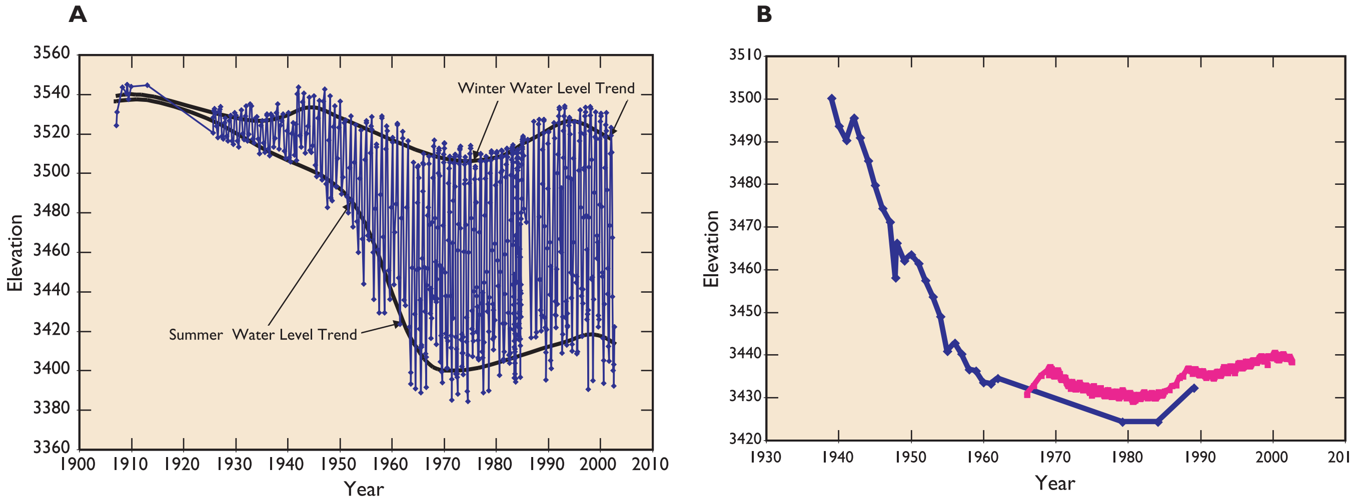
into the aquifer. The artesian aquifer is 300–500 feet thick. Near the Pecos River, the top of the aquifer lies at a depth of about 1,100 feet.

Although the carbonate rocks of the artesian aquifer are present farther east in the subsurface, they are much less permeable here because the pattern of ground water circulation ends with discharge to the Pecos River. Clay-rich rocks of the Permian-age Artesia Group (the confining beds) lie above the eastern portion of the artesian aquifer and form a seal (although a leaky one) that keeps water in the aquifer under pressure.

Surface runoff from the eastern slopes of the Sacramento Mountains disappears through the fractures and sinkholes in the carbonate rocks to recharge the artesian aquifer in the area west of the confining bed boundary. Ground water continues to flow eastward through fractures and solution openings, but also flows upward to the shallow alluvial aquifers, particularly north of Roswell, where the confining unit is thin, absent, or partially dissolved. This upward leakage from the artesian aquifer originally discharged through springs into tributaries of the Pecos River, and into the shallow river-connected aquifer itself, augmenting flow in the river. The confining beds in the southern Roswell Basin (in the vicinity of Hagerman and Lake Arthur) reach a thickness of almost 1,000 feet, and connection between the shallow and artesian aquifers in this area is thought to be extremely poor.




Estimated and metered pumping from the Roswell artesian aquifer, the Roswell Basin shallow aquifer, and the Capitan aquifer, 1900–2000.




Hydrographs from selected wells in the Roswell artesian basin: A) artesian aquifer - T12S R25E Section 23. B) shallow alluvial aquifer - T12S R25E Sections 22 and 23.

### WATER BUDGET AND GROUND WATER HYDROLOGY

It is estimated that approximately 300,000 acre-feet per year of natural recharge water enters the aquifers of the Roswell artesian basin from the Sacramento Mountains to the west, and from infiltration of rainfall and tributary streamflow within the basin. Before development of the basin's ground water resources, this same amount of water discharged from the aquifer either through large springs in the Roswell area, or directly into the Pecos River, or through evapotranspiration by native plants. Although estimates of discharge are difficult to make, modeling studies suggest that each of these discharges—spring flow, discharge to the Pecos River, and evapotranspiration—may originally have been about 100,000 acre-feet per year, although a wide range of estimates exists.

Since the advent of large-scale ground water development, the water budget has changed considerably. Natural recharge, as far as we know, remains at about 300,000 acre-feet per year. But now approximately 350,000 acre-feet per year is diverted from wells, mostly for irrigation but also for municipal supply and other uses. About one-third of that water returns to the aquifer system as return flow, but the rest—over 200,000 acre-feet per year—is depleted, or used up. Under the current development scheme, the ground water system now discharges only about 30,000 acre-feet per year to the Pecos River. Native plants are estimated to consume about 60,000 acre-feet per year of water from the aquifer. A large volume of water is stored in the aquifers, but the stored water cannot be withdrawn without affecting the flow of the Pecos River. The recharge that enters the aquifers goes partly to replenish storage depleted by ground water pumping, and is therefore not available to contribute to the flow of the river.

Ground water development began around 1900, shortly after the discovery of flowing wells. Pumping increased rapidly from 1940 through 1957. Water levels in both the shallow and artesian aquifers fell significantly over that time. In the mid- to late 1960s, state engineer administration and policies of the Pecos Valley Artesian Conservancy District (including metering of irrigation wells in the basin) led to a decline in pumping, but total ground water diversions still approached 400,000 acre-feet per year. Since 1977 annual pumping has been less than it was in 1947, the benchmark year for administration of the Pecos River Compact, and less than in most years between 1947 and 1957.

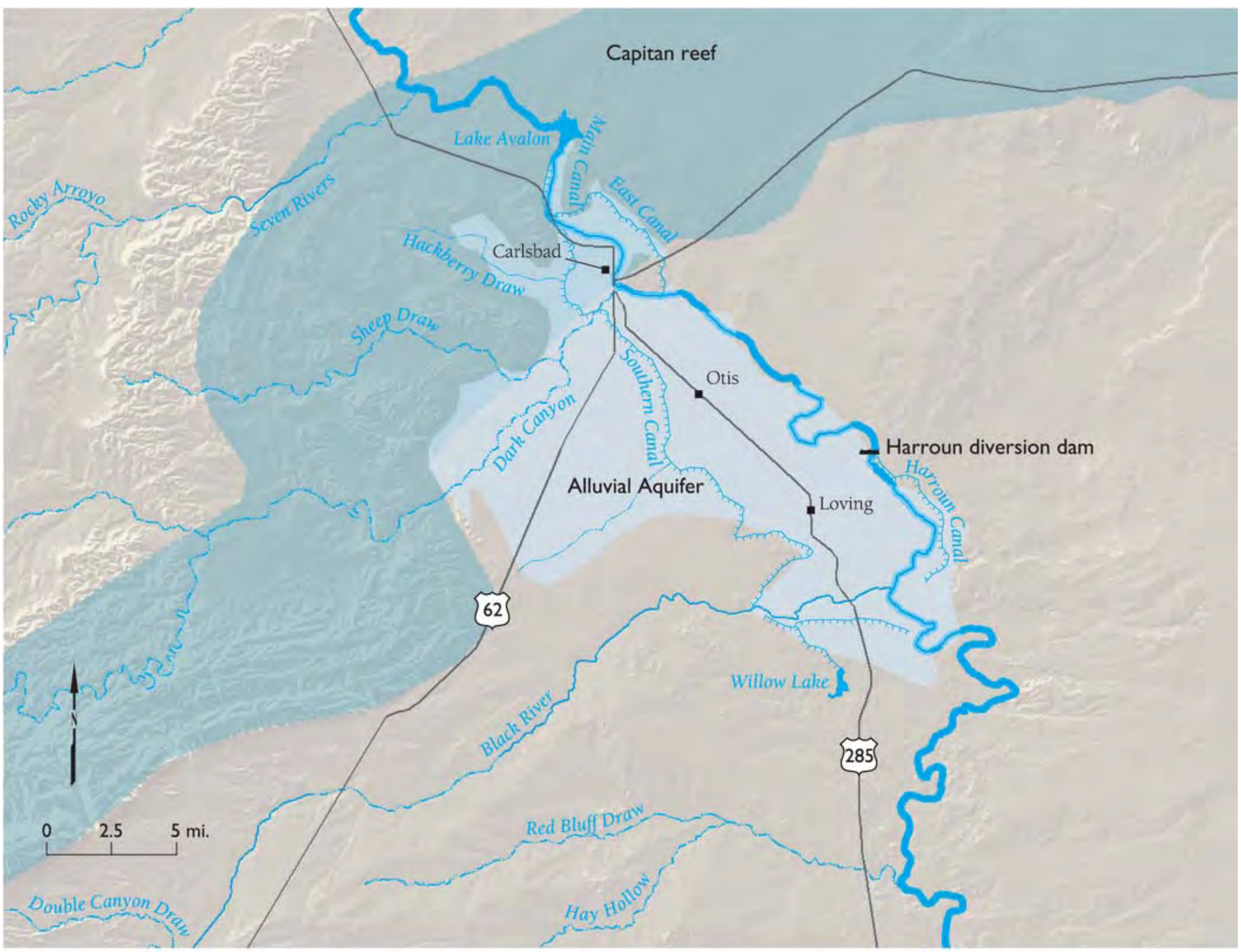
Water levels in the Roswell artesian basin show the effect of ground water development. In general, water levels declined rapidly from the mid-1930s to 1965, were roughly stable until about 1985, rose until the mid-1990s, and now appear to be declining again. Water levels in the artesian aquifer show a very strong winter-summer seasonal effect. In some locations, artesian water levels are more than 120 feet lower during the summer irrigation season than during the non-pumping winter season. This fluctuation reflects the confined conditions of the artesian aquifer.

The quality of water in both the artesian aquifer and the shallow aquifer is good, although the artesian aquifer does contain saline water along its eastern fringe, east of the Pecos River and beyond the zone in which water circulates rapidly from the recharge area to the river discharge area. Pumping in the vicinity of Roswell had led to some westward movement of the saline water and encroachment upon the active ground water development area, but the situation has stabilized as pumping has decreased.

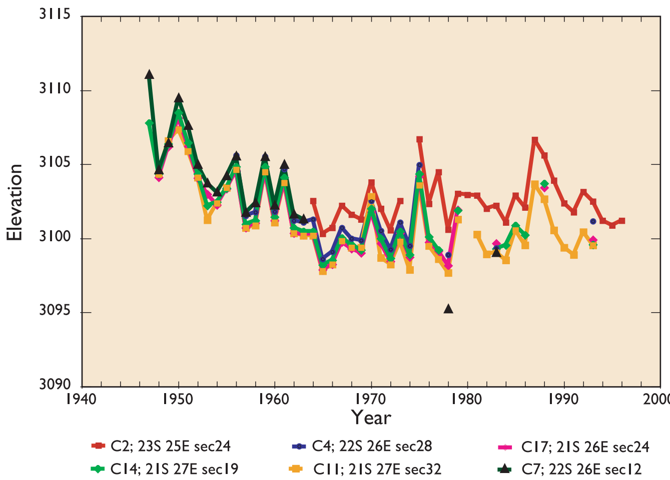
## CAPITAN AQUIFER

The cavernous limestone of the Capitan reef forms another important aquifer near Carlsbad, from which high capacity wells can produce good quality water. The Capitan reef is a thick accumulation of Permian-age massive limestone beds, the same rocks in which Carlsbad Caverns formed. It is present in the subsurface in an 8- to 12-mile-wide band, beginning in the Guadalupe Mountains on the west, and passing just north of Carlsbad and out of the Pecos Basin on the east. The Capitan reef ranges in thickness from several hundred to 2,000 feet, although not all of this thickness is equally productive. At Carlsbad, the Capitan aquifer is about 1,600 feet thick and lies immediately below the alluvium in the valley.

There is an extremely transmissive segment of the Capitan aquifer extending from the Guadalupe Mountains to just east of the Pecos River. Wells drilled into this part of the Capitan have extremely high yields, and some have encountered cavernous zones. Water levels in all wells completed in this segment of the reef are at the same elevation and rise and fall in unison in response to recharge events (such as floods in Dark Canyon) and ground water withdrawals. Ground water pumping from this part of the Capitan




Map showing extent of Capitan reef and alluvial aquifer in the Carlsbad area.




Hydrograph from wells in Capitan reef aquifer.

varies from 15,000 to 20,000 acre-feet per year, and historically water levels have dropped 10–15 feet.

From 10,000 to 20,000 acre-feet per year of natural recharge enters the Capitan aquifer in the Guadalupe Mountains and in Dark Canyon, through fractures and solution openings. The original discharge point of the Capitan aquifer was Carlsbad Springs, which discharges into and near the bed of the Pecos River. Ground water pumping now intercepts much of this natural discharge. Pumping from the Capitan aquifer is rapidly reflected in depletions of spring flow and flow of the Pecos River. Artificial recharge associated with leakage from Lake Avalon enters the Capitan aquifer near the city of Carlsbad and is now a large component of the present flow of Carlsbad Springs.

Carlsbad Spring, 1910.

Water quality in the Capitan aquifer is generally excellent southwest of Carlsbad, with concentrations of total dissolved solids less than 700 mg/L; here, water is moving rapidly from the recharge area toward natural discharge into the Pecos. West and north of Carlsbad, Capitan ground water mixes with poorer quality water from the bedrock aquifers in the Pecos Valley, and lower quality river water seeping in from Lake Avalon. The Capitan aquifer provides some of the best water in the vicinity, and the city of Carlsbad diverts its municipal water from this aquifer. Originally Carlsbad diverted water from the Capitan aquifer using a well field near the Pecos River. Degradation of water quality caused the city to drill a new well field closer to the Guadalupe Mountains, and thus closer to the source of natural recharge. Any increase in ground water pumping from the Capitan aquifer may lead to farther decrease in water quality.

East of the river, water quality in the Capitan aquifer declines sharply. The Capitan reef continues to the east and southeast in the subsurface, eventually passing into Texas at a depth of about 4,000 feet near the southeastern corner of New Mexico. It is still permeable relative to surrounding rocks of other formations, but the water it contains is highly saline; much of the water in the eastern Capitan reef can be described as a "brine." The portion of the reef east of the Eddy–Lea county line is relatively isolated from the reef aquifer in the Carlsbad area. Large-scale petroleum operations in this part of New Mexico and Texas have withdrawn large quantities of fluid from the reef, locally dropping water levels by hundreds of feet.

Pecos Valley alluvium is also an important shallow aquifer in the Carlsbad area and provides supplemental supplies to farms in the Carlsbad Irrigation District (CID) and for primary supplies outside the CID. Most of the recharge to the alluvial aquifer comes from seepage of irrigation water applied to fields. The aquifer discharges water to the Pecos River. Much of the water in the alluvial aquifer is slightly to strongly saline, but useable for irrigation purposes.

## SUGGESTED READING

Barroll, P., 2002, The Carlsbad area ground water flow model: New Mexico Office of the State Engineer, technical report, 143 pp.

Kelley, V. C., 1971, Geology of the Pecos Country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 24, 75 pp.

Welder, G. E., 1983, Geohydrologic framework of the Roswell groundwater basin, Chaves and Eddy Counties, New Mexico: New Mexico Office of the State Engineer, Technical Report 42, 28 pp.

# The Biohydrology of the Middle Pecos Region, New Mexico

Paul L. Tashjian, *U. S. Fish and Wildlife Service*

The valley of the Pecos River from Fort Sumner, New Mexico, to the Texas state line contains some of the most diverse and interesting aquatic habitats in the southwestern United States. In the heart of this apparently barren landscape is the sand-dominated Pecos River, used and enjoyed by farmers, ranchers, oil and gas seekers, hawks, falcons, coyotes, foxes, and a respectable population of native fish. This river is at its wildest north of Roswell, where one must drive appreciable distances on back-numbing washboard roads to visit its wide, sandy habitat. This region also contains a complex system of ground water-derived habitats including sinkholes and springs. These features are home to unique and diverse creatures that have evolved with and rely upon the salt-rich waters. The salt in these waters derives from the bedrock in which local ground water resides and through which it moves. These rocks were formed in ancient salt-rich environments, including shallow evaporitic ocean basins, coral reefs, and coastal rivers. These springs contain a phenomenal diversity of life; the springs and sinkholes of Bitter Lake National Wildlife Refuge near Roswell are home to over 50 species of dragonflies, one of the most diverse assemblages of dragonflies in North America.

In this overview, I discuss the interplay between aquatic habitat, human development, and the ecological communities of the middle Pecos River. In regions like the middle Pecos where water resources are limited, biologic resources and human development are often pitted against one another. I hope that the reader will walk away from this discussion with an appreciation for the aquatic habitats of the region. There is no doubt that the natural resource and biological issues of this region are complex, but through an exchange of information, ideas, and viewpoints, solutions may be found that will neither impair important industries and interstate agreements nor deteriorate the homes and populations of the region's aquatic wildlife.

## THE MIDDLE PECOS RIVER

The middle Pecos River between Sumner Lake and Brantley Lake is a classic western river, dramatically altered by humans during the past century. With the best intentions, twentieth century society has disrupted the natural flows of the river, which in turn has altered the physical habitat of the river. Add to this the introduction of tamarisk or salt cedar, intentionally planted in the 1930s to stabilize river banks, and the result is yet another western river on the verge of losing its pre-twentieth century physical characteristics and associated fauna.

There are three large reservoirs on the middle Pecos: Santa Rosa, Sumner (formerly called Alamogordo), and Brantley (which replaced McMillan in 1988). Fort Sumner Dam was built in the mid-1930s and operational by 1937. The primary purpose of Sumner Lake was (and is) the control and management of natural upstream flows to meet farming and interstate compact needs downstream. Historically, Pecos River flows were sent downstream to Lake McMillan (now Brantley Lake) in "blocks." In this kind of release, discharge goes from base flow (generally 0–100 cubic feet per second or cfs) to 1,000 cfs in a single day, stays at 1,000 cfs until the necessary amount of water is released, and then returns again to base flow. Essentially, under this regime the reservoir is operated like a spigot: open the tap when you need water, shut it off when you don't. Before 1937 flows north of Roswell dropped as low as 60 cfs on a bad day; from 1937 to 1990 they approached 0 cfs (a dry river) on a bad day. Santa Rosa and Sumner Lakes serve a secondary purpose, as well: flood control. Reservoir operations have dramatically altered flows in the Pecos River by reducing both base flows and flood peaks. Minimum base flows are necessary to support fish populations, and peak flows (floods) are necessary to create and maintain river habitat.

Primary components of the physical habitat of the middle Pecos River include channel shape, sediment, and the floodplain. Like the middle Rio Grande, the historic middle Pecos River before development was a wide, sediment-laden, braided river. River flows interacted with the channel to create a diversity of habitats, ranging from low-velocity backwaters to swift main-channel settings. Floods are necessary to maintain these habitats. They recycle sediment between the channel and the floodplain. They sculpt a wide channel, move sediment from the floodplain back into the channel, and form new floodplains with channel sediment. Today the most intact remaining habitat on the middle Pecos exists between Fort Sumner and Roswell. Here the channel is wide and relatively dynamic. Unfortunately, this reach is also the portion of the middle Pecos most likely to go dry, because its primary source of base flow is return flow from the Fort Sumner Irrigation District. South of Roswell, the Pecos River quickly degenerates from a wide, dynamic channel to a narrow, incised channel, lined and anchored with dense stands of salt cedar. Here the channel shape is similar to an irrigation ditch and contains very little backwater habitat, especially at higher flows. River flows are supported by ground water discharge from the Roswell artesian aquifer, which prevents this portion of the middle Pecos River from going dry. In short: Development and management of the Pecos River have resulted in good habitat above Roswell, degraded habitat below Roswell, an increased threat of a dry river above Roswell, and a lesser threat of a dry river below Roswell.

The Pecos River east of Roswell. The Pecos River from Roswell south is typified by poor habitat that includes an incised channel and river banks that are frozen in place by salt cedars. This portion of the Pecos receives base inflows from the Roswell ground water basin.

## THE BIOLOGY OF THE MIDDLE PECOS RIVER

The Pecos bluntnose shiner is the Pecos River minnow that has been at the center of much controversy. This fish, like the silvery minnow of the middle Rio Grande, has a pelagic spawning behavior: A pelagic spawning minnow typically reproduces when the flows in a river are increasing, usually as the result of spring runoff or a summer thunderstorm. The eggs are semi-buoyant and float downstream with the current of the river. In order for the spawn to be successful, the river must provide sufficient backwater settings into which the eggs can drift and settle, and these backwaters must remain connected to the river as flows recede. The Pecos River north of Roswell provides this type of habitat; the Pecos River south of Roswell does not. The fish populations reflect this very pattern: North of Roswell the minnow community is self sustaining and contains diverse species, and the population of each species contains both reproducing adults and younger, next-generation fish. South of Roswell the minnow community is almost entirely composed of sub-adult, pelagic-spawning minnows and red shiners. Red shiners lay a sticky egg and are more capable of surviving in degraded habitat. The sub-adult fish of the pelagic-spawning minnows originate north of Roswell and, because little backwater exists in the reach south of Roswell, the fish are flushed through the narrow channel into Brantley Lake before they are able to grow into reproducing adults.

Pecos bluntnose shiner.

The analogy of the "canary in a coal mine" is often used in reference to instances where the decline of single species reflects the decline of the overall health of an ecosystem. The Pecos bluntnose shiner is such a species: its well-being depends upon a wide, active river with some sort of natural flow pattern. Historically, the Pecos River was a wide, sand-bed river with an active floodplain. The river had a consistent base flow, a defined spring runoff peak from snow melt in the Sangre de Cristo Mountains, and flash floods in the summer resulting from monsoonal rains. The ecosystem of the middle Pecos evolved in response to this hydrologic pattern, and many native species of the middle Pecos have life support and reproduction behaviors keyed into both the habitat and the flow of the native river. On the simplest level, all fish require water for survival as do certain turtles, frogs, insects, and plants. On a more complex level, the reproductive behavior of many of these species is tied to the same cues from the hydrograph, whether that be spring runoff or runoff from summer storms. A wide, active sand bed supports a great diversity of native fish, healthy riparian woodlands, good habitat for turtles, and shallow water for wintering ducks and other migratory birds. An incised, channelized river lined with salt cedar is poor habitat for all of these species. By protecting the flow and habitat requirements for the Pecos bluntnose shiner, the positive repercussions are felt throughout the web of life within the middle Pecos River. Likewise, when the habitat of the Pecos bluntnose shiner is degraded, the negative repercussions of this are felt throughout the system.

The real question, then, becomes: How much is enough? Returning the river to its unadulterated natural state by removing reservoirs and banning diversions is not a realistic or equitable solution, given the farmers' reliance on this water and the interstate delivery requirements. The U.S. Bureau of Reclamation and the New Mexico Interstate Stream Commission are currently working on an environmental impact statement for the operation of Sumner Lake that addresses this very issue. The key to the future survivability of all species of the middle Pecos River is maintaining adequate flows north of Roswell and improving habitat throughout the middle Pecos River with an emphasis south of Roswell.

## SPRINGS OF THE MIDDLE PECOS RIVER

From just north of Roswell to the Texas border, the geology and hydrology of the Pecos region lends itself to ground water-derived spring features. These features, which include sinkholes, springs, and spring creeks, are associated with discharge from the regional ground water aquifer. The geology of these aquifers is karstic, formed within limestone and other evaporite rocks. The largest of these karst aquifers in New Mexico is in the Roswell Basin, which has been the focus of many hydrologic investigations and modeling studies since the early 1900s. It is a very important source of water for New Mexican cities, farmers, wildlife, and compact deliveries. Perhaps the most exciting news from the Roswell basin is that water levels and spring flows have stabilized or risen since the mid-1960s. This rise can be attributed to several factors including regulation of water rights by the State of New Mexico, starting in the 1960s, and purchasing of Roswell basin water by the State of New Mexico in 1990s to assist with Interstate Compact compliance. The resulting rise in ground water levels has been dramatic; in some places springs that had been dry since the early 1950s are flowing today. This is good news for the local biota that are reliant on the springs for habitat.

The biodiversity associated with the springs of the Roswell basin is outstanding. Hot spots of diversity include Bitter Lake National Wildlife Refuge (NWR) and Bottomless Lakes State Park, both near Roswell. Bitter Lake NWR is home to 26 fish species, 50 dragonfly species, 52 amphibian and reptile species, and 357 bird species, making it one of the most biologically significant wetlands in the southwestern United States and northern Mexico. Three extremely rare invertebrates that are found nowhere else on Earth rely on springs in the national wildlife refuge for survival: the Roswell springsnail, a tiny aquatic snail that once inhabited a wider area in the Roswell area; the Koster's springsnail, also tiny, which is found at scattered springheads on the refuge; and the Noel's amphipod, a small shrimp-like crustacean that is found at only four separate sites on the refuge. Another even tinier snail, *Pecos assiminea*, lives adjacent to springs in the refuge and at only one or two other sites hundreds of miles away in west Texas and Mexico. These rare invertebrates are herbivores, and they in turn support the rare predatory fish of the refuge—Pecos gambusia, Pecos pupfish, and the greenthroat darter. These fish, along with more abundant

A small sinkhole at Bitter Lake National Wildlife Refuge. The sinkholes and springs associated with the Roswell basin are home to an amazing diversity of native fish and invertebrates.

Fish seining in the Pecos River north of Roswell. The Pecos north of Roswell is typified by quality habitat that includes a wide, sandy channel that is dynamic. This portion of the River has the highest threat of intermittency.

species, provide food for the endangered interior least tern. The refuge hosts the only breeding population of these small birds in New Mexico. Clearly, these rare and unique spring communities, and the habitats that support them, deserve and require our attention and protection.

### THREATS AND PROMISING OPPORTUNITIES FOR AQUATIC NATURAL RESOURCES OF THE REGION

The middle Pecos River offers a myriad of complex issues regarding wildlife habitat and natural resources. The following list of threats and promising opportunities for the Pecos region's aquatic biota are presented to facilitate balanced decision making. By no means am I promoting a "wildlife before industry" philosophy. These points can be used as starting points for making complex and creative decisions regarding the long-term sustainability of both the region's industries and its aquatic wildlife.

### THREATS

- Drying of the Pecos River north of Roswell: The Pecos River north of Roswell is susceptible to drying, placing the fish community in this reach at risk.
- Prolonged reservoir releases from Sumner Lake: Studies of the fish communities on the Pecos River have shown that prolonged block releases from Sumner Lake flush eggs, larvae, and fish from the quality habitat north of Roswell into the poorer habitat south of Roswell.
- Pollution of the Roswell Basin ground water aquifer: Any pollution of this important aquifer system threatens both wildlife and humans who rely on these waters. Potential pollution sources include poor management of oil and gas development and septic systems associated with residential developments.
- Introduction of non-native aquatic species: Non-native species can rapidly disrupt the balance of an ecosystem. As with tamarisk (salt cedar), this disruption often affects human needs as well as wildlife. Other non-native species threatening the middle Pecos River include golden algae, sheepshead minnow, crayfish, and bullfrogs.
- Salt cedar proliferation north of Roswell: Salt cedar proliferation has caused extensive damage to the Pecos River habitat south of Roswell. Though common north of Roswell, continued proliferation in this area will degrade the habitat in this reach.

### PROMISING OPPORTUNITIES

- The State of New Mexico continues to purchase water rights to improve water delivery to Texas. This effort could be joined with an effort to conserve the biologic spring resources of the middle Pecos Valley. Water rights could be purchased from willing sellers in areas where the ground water rebound associated with the retirement of pumping could benefit both the flows in the Pecos River and the flows of Roswell basin springs.
- Efforts to reduce salt cedar can be joined with efforts to restore the physical functioning of the Pecos River and improve flood management. By implementing sound restoration, water salvage efforts can be enhanced, improving both habitat and flood control. This type of restoration has been designed for Chaves County by the U.S. Army Corps of Engineers. A similar design has been developed by the U.S. Fish and Wildlife Service and the U.S. Bureau of Reclamation for the Pecos River at Bitter Lake NWR.

The author wishes to thank Jim Brooks, U.S. Fish & Wildlife Service, for his comments on the fish of the Pecos River; Gordon Warrick, Bitter Lake National Wildlife Refuge, for his comments and text on the biology of the refuge; and Danny Katzman, Los Alamos National Laboratory, for his comments on the technical clarity of the manuscript.

# Overview of Water Operations in the Pecos River Basin

John Longworth, *New Mexico Interstate Stream Commission*
John Carron, *Hydrosphere Resource Consultants, Inc*

Water operations in the Pecos River basin are dominated by agricultural demands. Small-scale acequias, some of which date back over 200 years, are predominant in the northern part of the basin. Large irrigation districts dominate water use in the central and southern sections of the Pecos Basin, drawing on both surface and ground water supplies. Four main stem reservoirs provide flood control for the basin and irrigation water supply for the Carlsbad Irrigation District (CID). These reservoirs store and re-regulate Pecos River flows that are otherwise too unreliable to support significant agricultural production.

### WATER OPERATIONS NEEDS ON THE PECOS RIVER

The natural flows of the Pecos River vary considerably from year to year and from season to season (see second paper by Longworth and Carron in this volume). Runoff from snowmelt occurs early in the spring, after which there is typically a dry period before the summer monsoons begin. Summer monsoons (and other storms) can produce large inflows of water (tens of thousands to hundreds of thousands of acre-feet) in a very short period of time, although the timing and magnitude of these events is variable and unpredictable.

In a typical year not enough water flows into the Pecos to supply the surface water needs of the basin. Furthermore, the erratic flows and lengthy dry periods between flood inflows would make it impossible under natural conditions to support large amounts of irrigation. Reservoirs have been constructed on the Pecos River in order to store and redistribute the erratic flows of the Pecos. These reservoirs provide communities along the Pecos with much-needed flood control as well as providing water through the entire irrigation season.

### HISTORY OF WATER OPERATIONS

The Pecos River has had a long history of water development and associated water operations. This paper will review the historical operations in the northern portion of the basin, Fort Sumner Irrigation District, the Pecos Valley Artesian Conservancy District, and the Carlsbad Project.

### THE NORTHERN BASIN

In the late 1700s the first Spanish settlers developed acequia (community irrigation ditch) systems in the upper reaches of the Pecos watershed. These systems required a coordinated diversion and apportionment of the waters from the Pecos. Other than improvement of irrigation methods, this method of water use has remained essentially unchanged for over 200 years.

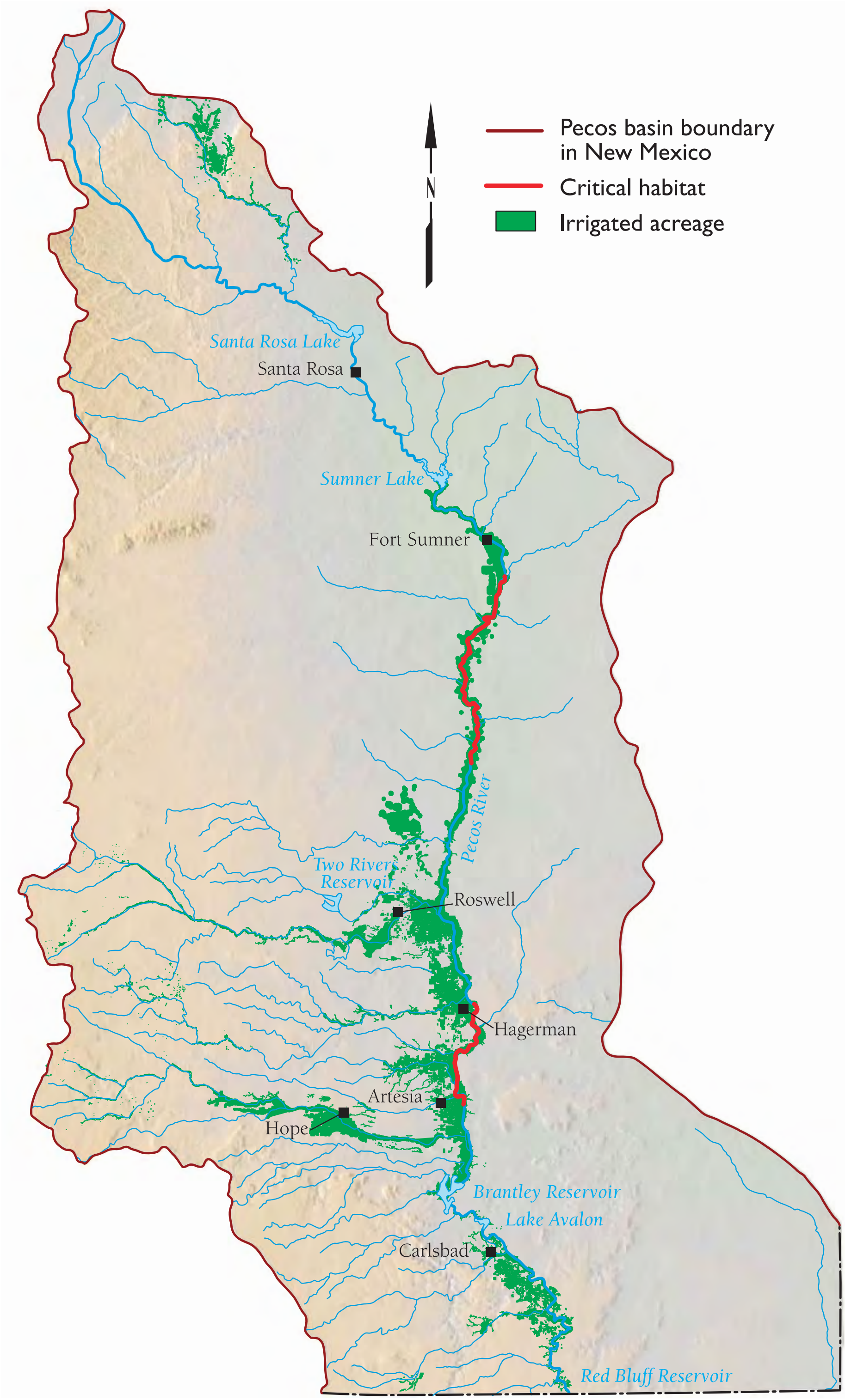
### FORT SUMNER IRRIGATION DISTRICT

In 1863 the first development in the vicinity of the Fort Sumner irrigation project began. This project was developed to support the soldiers occupying the fort. This early irrigation project ultimately failed, and the irrigation diversion ceased around 1868.

Continuous irrigation began in 1907 when private interests began irrigating in the Fort Sumner area. This established the current diversion right and formed the basis for operations today. These initial private attempts did not succeed, and in 1919 the Fort Sumner Irrigation District was formed and took over the irrigation works. This marked the beginning of a focused attempt to develop and maintain a diversion structure on the Pecos River near Fort Sumner. This effort continued until 1941 when the diversion structure suffered major flood damage. The district did not recover financially from this event, and in 1949 the president of the United States approved the Bureau of Reclamation's rehabilitation plan for the district. In 1950 construction of a concrete diversion dam, improvements to the main canal, and a new lift station for the high line canal were completed. These improvements remain in place today.

### THE ROSWELL–ARTESIA AREA

Most water development in the Roswell–Artesia area is based on ground water extraction. These pumping operations affect the Pecos River main stem operations




Pecos River basin—irrigated acreage

by depleting waters that would otherwise have reached the Pecos in the form of subsurface inflows. The primary surface water users in the Roswell—Artesia area are river pumpers, who have rights to pump Pecos River water directly from the river channel to their fields. Currently, these operations are relatively small (no more than 5,000 acre-feet total diversion rights). Historically, however, these rights totaled over 10,000 acre-feet.

Another surface water right in this area is the Hagerman Irrigation Company (HIC). These are some of the most senior rights on the Pecos; historically they were obtained from the Rio Hondo. However, as ground water development progressed in this region, the surface flows of the Rio Hondo ceased. Currently the HIC primarily obtains its water from return flows from the Roswell wastewater treatment plant and supplemental wells constructed along its main canal.

## CARLSBAD AND THE CID

Surface water development in the Carlsbad area began in the late 1880s with the formation of privately funded irrigation companies. These early efforts resulted in the construction of Avalon Dam and McMillan Dam. From the late 1880s through the early 1900s, a series of devastating floods washed out these dams and the irrigation improvements. Around 1906 the United States Reclamation Service (which later became the Bureau of Reclamation) purchased what is currently the Carlsbad Irrigation District. After this

The original wooden flume on the Pecos River in Carlsbad was destroyed in the flood of 1893.

purchase, the Bureau of Reclamation began rehabilitation of the project and rebuilt both Avalon and McMillan Dams. The construction of Sumner Dam (formerly Alamogordo Dam) provided much-needed upstream storage for snowmelt and overland precipitation events. The primary function of Santa Rosa Dam (a.k.a. Los Esteros Dam, completed in 1980) was to provide additional flood protection for the lower Pecos Valley, and it also provided for additional upstream storage for the CID.

The most recent major improvement was Brantley Dam, which in 1988 replaced McMillan Dam. McMillan Dam had a long history of problems, including lost storage capacity resulting from the siltation during the 1941 flood, and leakage around the dam structure itself. Ultimately McMillan was declared unsafe. These factors and the need for flood protection for the greater Carlsbad area were the impetus for the construction of Brantley Dam. It increased the CID's ability to store floodwater originating south of Sumner Dam, provided more terminal capacity for the project, and created a recreation opportunity for the Carlsbad area.

The CID storage system operates as a whole to store and redistribute the highly variable flows of the Pecos. CID diverts approximately 75,000 acre-feet annually from these four reservoirs. The area south of Avalon Dam, which controls main stem flows, includes the dams within Carlsbad and relatively minor irrigation diversions. The dams within the city limits create the Carlsbad lakes that are used primarily for recreational activities.

## WATER OPERATIONS ON THE PECOS RIVER

As stated above, there are four primary reservoirs on the Pecos River that regulate the flow of the Pecos River. The following provides the total physical storage, the total storage as allowed by the Office of the State Engineer permit. These values are from 2002.

The most frequent operations of the main stem system are for irrigation in the Fort Sumner Irrigation District (FSID) and CID. The flood control operations are used on an infrequent, if not rare, basis. The historic operation of these reservoirs with respect to CID's water is based upon the need to maximize water conservation. Generally, the water is kept upstream as long as possible (in Santa Rosa Lake and Sumner Lake), where evaporative losses are relatively low. Water from these upstream reservoirs is delivered downstream to Brantley and Avalon only when it is need. This provides two benefits: the first is a reduction in evaporation losses, which are about 30 percent less at Sumner than at Brantley. The second is a reduction in transport

| Reservoir | Year completed | Storage capacity (acre-feet) | Conservation storage (acre-feet) | Minimum pool (acre-feet) | Uses |
|---|---|---|---|---|---|
| Santa Rosa Lake | 1980 | 439,900 | 92,237 | 0 | Irrigation storage, flood control, and sediment control |
| Sumner Lake | 1937 | 40,397 | 94,750 | 2,500 | Irrigation storage and flood control |
| Brantley Lake | 1988 | 1,008,000 | 40,000 | 2,000 | Irrigation storage, flood control, sediment control, fish and wildlife enhancement, and recreation |
| Lake Avalon | 1907 (Initially 1890) | 4,466 | 3,866 | 600 | Irrigation storage, regulating CID diversion |

Physical and OSE-permitted storage capacities based on 2002 values.

Sumner Dam.

losses. This second savings is realized by delivering upstream water in blocks. These "block releases" are high volumes of water (over 1,000 cfs) released at a constant rate for 14–20 days. These block releases occur two to three times per year, depending on supply and demand within the CID.

Sumner Dam has an additional standard bypass operation, which serves the FSID. From March 1 through October 31 and for two 8-day periods from November 1 through the end of February, FSID has the right to divert as much as 100 cfs of the natural flow of the Pecos River. The Office of the State Engineer staff sets this allotment every two weeks.

## PECOS RIVER COMPACT AND AMENDED DECREE

The Pecos River Compact between New Mexico and Texas was intended to provide a means for dividing the surface waters of the river. However, differences in interpretation of the compact resulted in U.S. Supreme Court litigation between Texas and New Mexico. The result of this litigation included the U.S. Supreme Court's Amended Decree, which appointed a River Master who determines New Mexico's annual obligation and compliance.

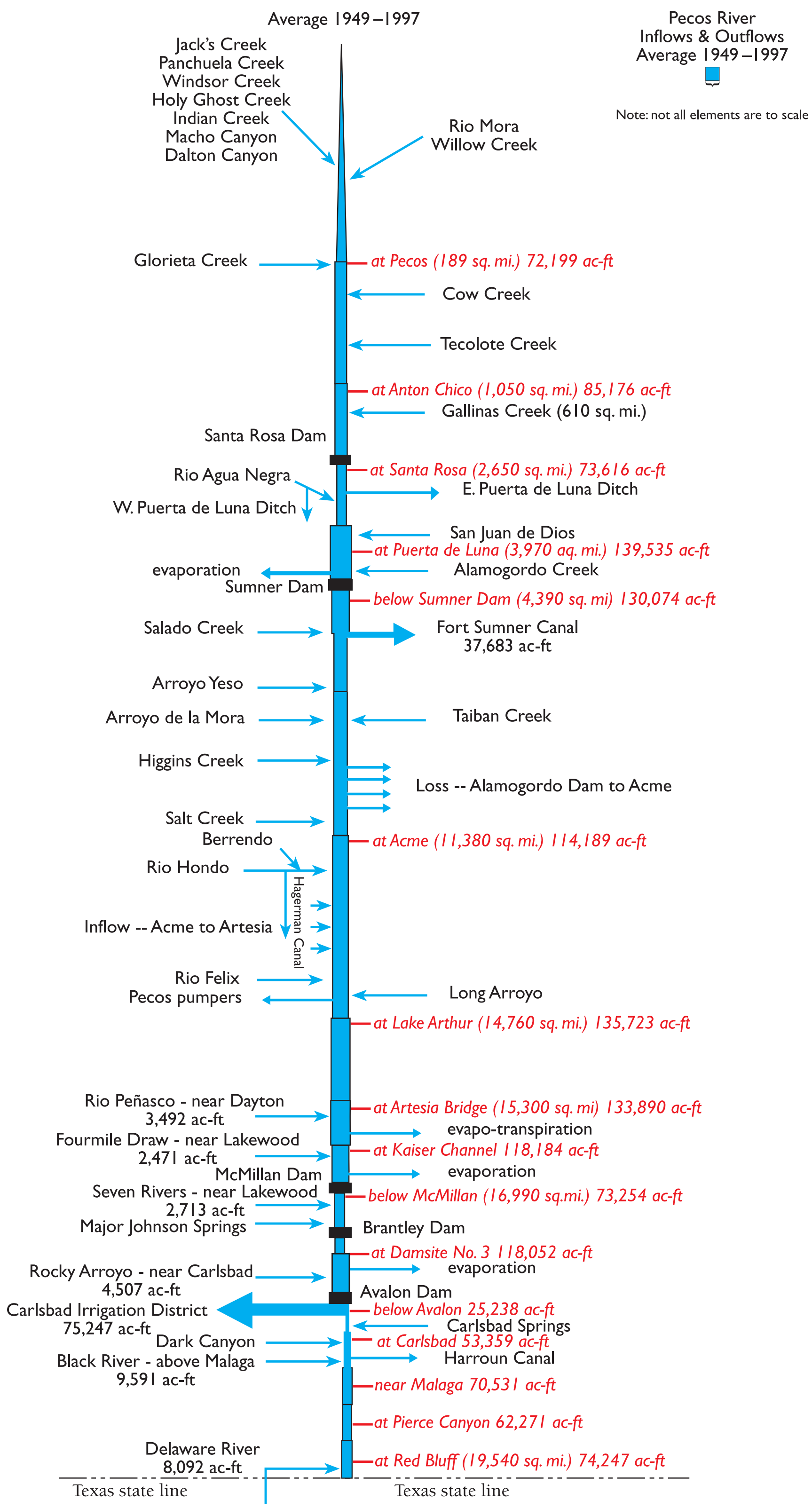
New Mexico's obligation is determined by a complex set of instructions called the River Master's Manual. The primary factor in determining New Mexico's obligation is flood inflow. Flood inflow is determined from an examination of river gage records combined with a series of hydrologic calculations. It includes releases from Sumner Dam and the total overland and tributary flows accumulating to the Pecos from Sumner Dam to the Texas state line. The manual provides that roughly 50 percent of the flood inflow to the basin must be delivered to Texas over a three-year period. Therefore, each year, New Mexico is required to deliver one-sixth of each of the current and previous two-year's flood inflows.

Over the last 10 years the New Mexico Interstate Stream Commission has been leasing water from CID members and has purchased water rights throughout the basin for the purpose of meeting New Mexico's compact obligations. Water leased from CID is released from Avalon Dam directly to the river, and hence to the state line. Generally, the water leased from CID is released twice each year, once in the summer and once again in the fall. These releases have averaged approximately 15,000 acre-feet per year over the last 11 years.

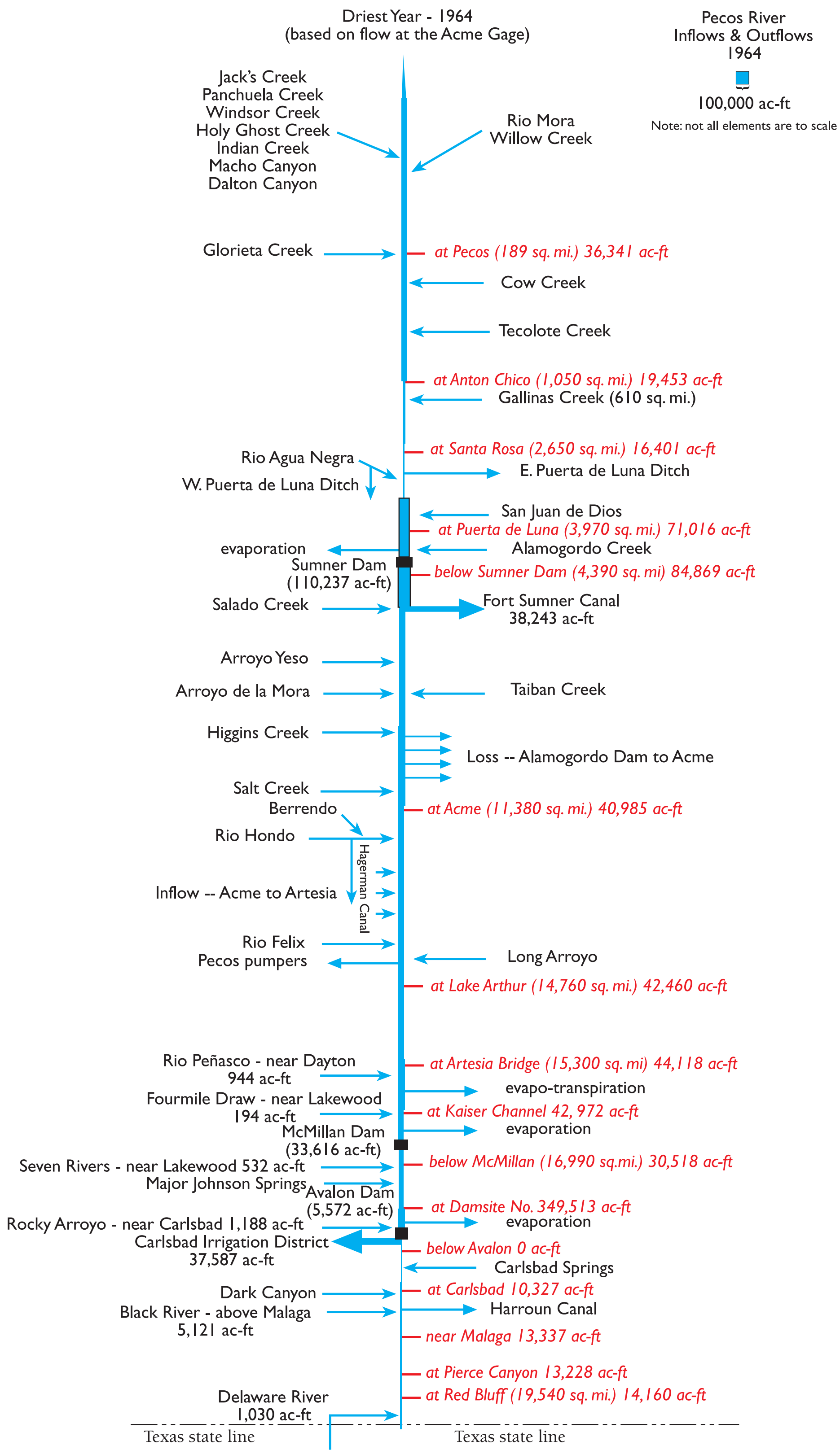
## THE ENDANGERED SPECIES ACT

Since 1989 the Endangered Species Act (ESA) has affected operations on the Pecos River more than any other issue. The primary subject of the ESA actions has been the Pecos bluntnose shiner. This fish is listed as a threatened species under the ESA and is afforded special protections under the ESA. Historic CID operations have provided for the maximum practical efficiency of the water resource for purposes of irrigation; these operations have been ongoing since the construction of Sumner Dam. Additionally, the FSID diversions that first began in the 1860s have been continuous since at least 1907. Fisheries biologists believe that these long-standing operations are the cause of the decline of the shiner, and they believe that modified river operations are necessary to recover the species. Unfortunately, any modified water operations will negatively impact agriculture in the basin. It is this dilemma that causes much of the friction between existing uses and the ESA proponents.

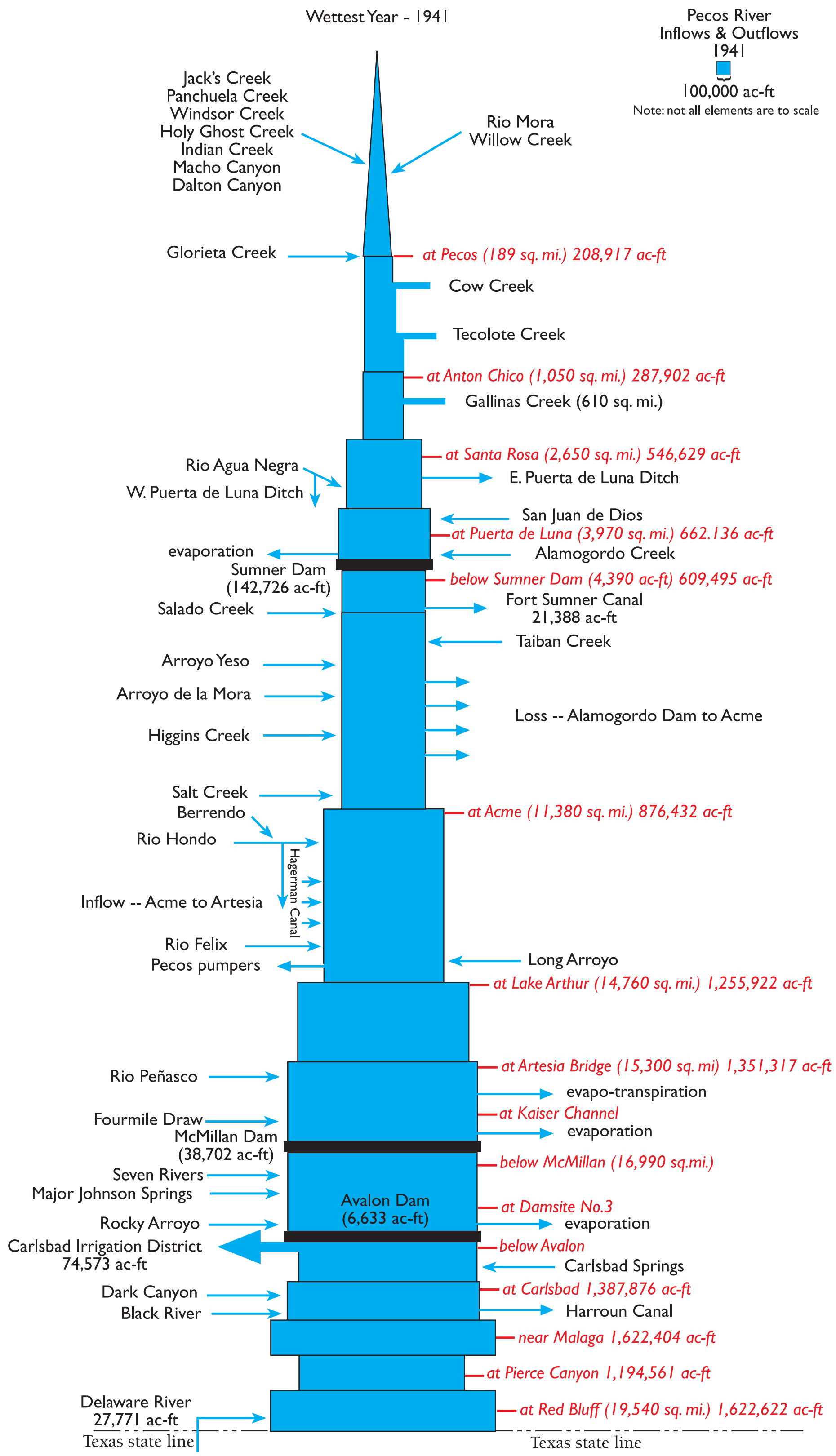
The most recent modifications that have been implemented by the Bureau of Reclamation to support the fish include changes to the block release operations, bypass of water through Sumner Dam, and retirement of irrigated agriculture to offset the effects of the changed operations. The modification of block releases has included a maximum limit of release to 15 days, a minimum restriction of timing between releases of 14 days, and a total of no more than 65 days of block releases in any one irrigation season. The bypass of water through Sumner Dam is intended to maintain 35 cfs of flow at the Acme gage. The Bureau of Reclamation has also implemented water depletion offset operations in recognition of the negative effects the ESA operations have had on water supply. These operations have been primarily in the Roswell artesian basin and consist of water lease arrangements between willing sellers and willing buyers. These leased waters are used to augment surface water downstream.




The inflow-outflow diagrams on these next three pages were originally created by Josh Nims of John Shomaker & Associates, Inc. in Albuquerque for the Pecos Valley Artesian Conservancy District. They were provided courtesy of John Shomaker. They have been recreated here in order to fit the page. Not all elements are to scale. This page: Pecos River inflow and outflow diagram (average inflows and outflows, 1949–1997).




Pecos River inflow and outflow diagram (driest year, 1964).




Pecos River inflow and outflow diagram (wettest year, 1941).

# Modeling Hydrologic and Water Operations in the Pecos River Basin

Peggy Barroll and Eric Keyes, *New Mexico Office of the State Engineer*
John Longworth and Bhasker Rao, *New Mexico Interstate Stream Commission*

The New Mexico Office of the State Engineer (OSE) and Interstate Stream Commission (ISC) now have a functional suite of models, a "Decision Support System" that can simulate much of the ground water and surface water hydrology and operations associated with the Pecos River from Santa Rosa Reservoir to the New Mexico–Texas state line. The need for these models arose from OSE administration of ground water resources, negotiations involving the adjudication of the Pecos River, ongoing environmental impact statement (EIS) processes, and the State's need to determine how the Pecos River system can be managed to ensure our compact obligations to Texas are met. The model suite consists of:

- RiverWare™ surface water model of the Pecos River
- Carlsbad Area Ground Water Model (CAGW)
- Roswell Artesian Basin Ground Water Model (RABGW)
- Data Processing Tool (DPT)
- Red Bluff Accounting Model (RBAM)

**Model Components of the Pecos Hydrology Decision Support System**

| Model | Principal model developers |
|---|---|
| RiverWare™ Pecos Model | John Longworth (ISC), Sean Bohlman (USBOR), Craig Burroughs (Tetratech), John Carron (Hydrosphere) |
| RABGW | Eric Keyes (OSE), Amy Lewis (then D B Stephens & Assoc.), Steve Larson and staff (S S Papadopulos & Assoc.) |
| CAGW | Peggy Barroll (OSE), Amy Lewis (then OSE), David Jordan and Greg Ruskauff (Intera) |
| DPT | Peggy Barroll (OSE), John Carron and staff (Hydrosphere) |
| RBAM | John Carron and staff (Hydrosphere) |

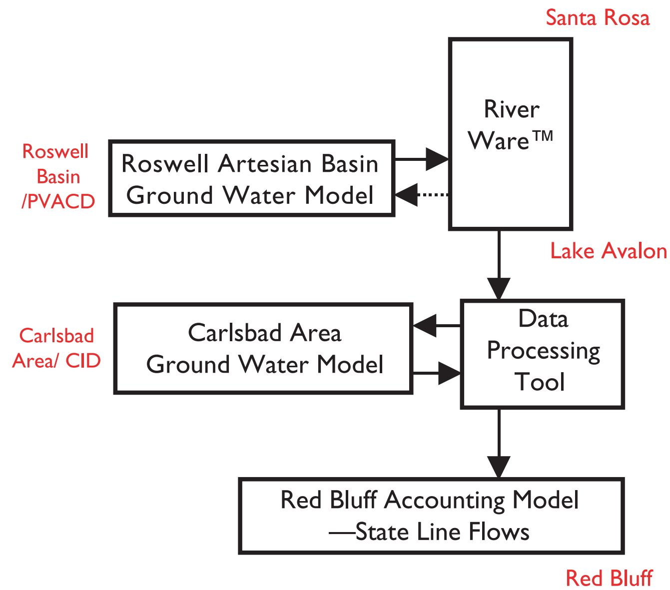



Diagram of model interaction.

These models have been extensively tested. As part of these tests, the models were calibrated, which means they were used to reproduce the hydrologic history of the Pecos River system and did so successfully. The models are based on the best available scientific data and standard, well-accepted methods. These tools should provide reasonable and useful estimates of the effects of management changes contemplated for the Pecos.

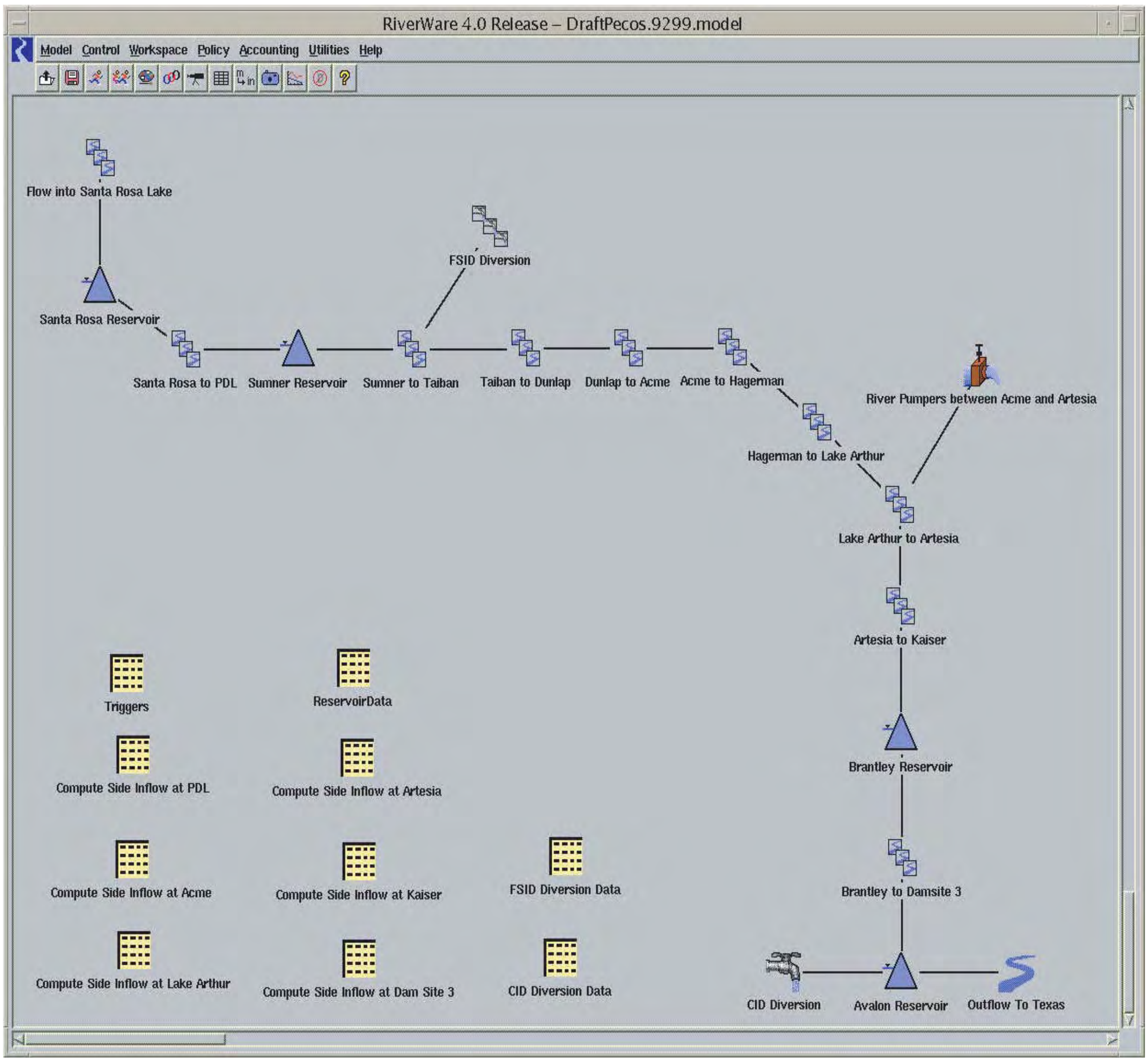
## INTRODUCTION TO MODELING

In general terms, a model is a simplified representation of a complex real system. Because it is very expensive and time consuming to test the effects of management changes on the real Pecos River hydrologic system, we take a shortcut and develop a model of each aspect of the system that we need to understand. Each model must be complex enough to include all the phenomena and structures that are important to us, but not so complex as to be mathematically insolvable.

The structure of a model is developed using basic information about the system we are simulating—for example, the length and width of the streambed for surface water models, and the nature of the rocks that make up the aquifer system for ground water models. The system is divided up into grid cells or nodes, each of which represents a small chunk of the system.

Input to a ground water or surface water model includes the inflow of water (aquifer recharge in the case of a ground water model, and flow from upstream and from tributaries to a surface water model), as well as diversion of water from the system. A model uses basic equations that govern the flow and conservation of water (like Darcy's Law) to keep track of this water and move it along at the proper velocity, from cell to cell or node to node, and determine its fate.

A ground water model calculates what the water levels in the aquifers will be, and how much ground water will discharge into adjacent streams. A surface water model calculates how much river water makes it downstream, how fast it gets there, and in the case of




Pecos River RiverWare™ Diagram.

complex, rule-based models, how much is diverted from reservoirs for irrigation, how much is released from the reservoir into the stream bed, and how much remains in reservoir storage.

### RIVERWARE™ SURFACE WATER MODEL

The backbone of the Decision Support System (DSS) is a surface water model developed by ISC and U.S. Bureau of Reclamation (BOR) staff and consultants using standard RiverWare™ software. The Pecos River RiverWare model simulates the flows of the Pecos River from Santa Rosa Lake to Lake Avalon. Inflows from tributary streams and from ground water discharge are input to RiverWare, and the model calculates the resulting flows downstream based upon the routing and loss coefficients that affect those flows. In addition to simulating the physical system, this model also simulates the rules by which the reservoirs on the Pecos River are managed and can test the effect of changing these rules. RiverWare™ can simulate a wide range of operating policies, including flood operations, conservation storage, irrigation district operations, Pecos River Compact under-delivery contingencies, and endangered species needs. The model structure of the RiverWare™ model, in which various "objects" are programmed to simulate the physical processes and rules that govern a particular stretch of river, or a particular reservoir, is illustrated on the opposite page.

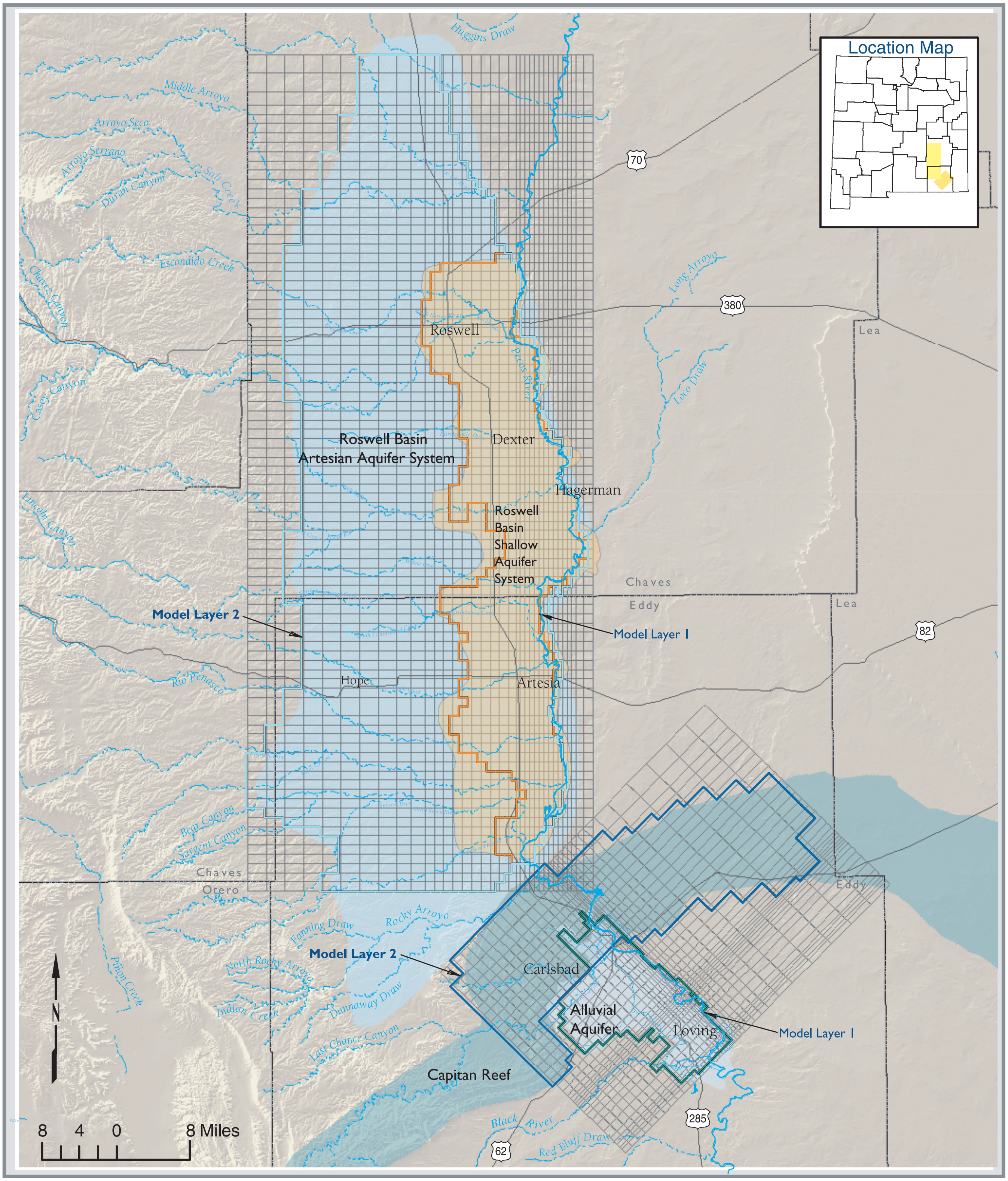
### ROSWELL AND CARLSBAD GROUND WATER MODELS

An important input to the RiverWare™ model is the inflow of ground water from the Roswell artesian basin into the Pecos River. These inflows are related to ground water pumping in the basin (which intercepts water that would otherwise have discharged to the river or to springs). Because these inflows could be modified by changes in the management of the basin (such as retirement of irrigated acreage or use of augmentation wells to supplement the flows of the Pecos River), the ISC decided to use a ground water model to simulate these inflows explicitly. The Roswell Artesian Basin Ground Water Model (RABGW) was developed by staff of the OSE and by ISC consultants, using standard USGS MODFLOW software. The model is based upon decades of geologic and hydrologic investigation of the Roswell basin, a huge set of water-level and stream-gage data, and has been in development by a number of modeling groups over the past 10 years. The RABGW model simulates the Roswell artesian aquifer, the overlying confining unit and shallow alluvial aquifer, and the interaction of this aquifer system with the Pecos River.

Inputs to the model include recharge of water to the basin from the mountains west of the basin, from tributary streams, and from irrigation seepage, as well as discharge of water from the basin to ground water pumping. Model outputs include water levels at any location within both aquifers and the discharge of ground water into the Pecos River. During model calibration it was found that the model could simulate historically observed water levels and base inflows to the Pecos River to a reasonable degree of accuracy. When using the model for projection or prediction, the model inputs can be modified, and the model will then simulate the effect of these changes (for example, ground water pumping) on water levels in the aquifers and on the inflow of ground water to the Pecos River. One key prediction of the RABGW model is that the effects of changes in artesian aquifer pumping will not reach the Pecos River for many years.

The Pecos River RiverWare™ model ends at Lake Avalon, at the top of the Carlsbad Irrigation District (CID). The final act of the RiverWare model is to calculate how much water CID would divert out of Lake Avalon into its main canal (based upon the amount of surface water available and the needs of CID), and to calculate how much water leaks out of Lake Avalon or is released into the bed of the Pecos River. Historically, there were many years when no water was released from the lake into the bed of the river, and almost all of the waters of the Pecos River that made it to Avalon were diverted into the CID main canal for irrigation of lands in the Carlsbad Basin. Return flow associated with this irrigation makes up a large component of New Mexico's state-line delivery to Texas. Because this return flow must first travel through the Carlsbad basin ground water system, where it can be intercepted by wells before reaching the Pecos River, it was decided to use a ground water model to simulate the hydrologic system below Avalon.

The Carlsbad Area Ground Water Model (CAGW) was developed by OSE staff and by ISC consultants, using standard USGS MODFLOW software. The model is based upon substantial geologic and hydrologic investigations published by the OSE and USGS, and upon a large set of water level and stream gage data from the 1940s to the present day. This model simulates the shallow alluvial aquifer and the reef aquifer in the Carlsbad area, as well as natural and man-made sources of water to (and discharge of water




Roswell basin and Carlsbad ground water model grids from) those aquifers. The model calculates the outflow of ground water into the Pecos River, and also calculates water levels in both aquifers. The operations of the CID surface water irrigation system are simulated on a year-by-year basis, including supplemental irrigation well pumping, which is activated when the surface water supply is insufficient. During model calibration it was found that the CAGW model could simulate the historically observed water levels and base inflows to the Pecos River in this area with reasonable accuracy.

### DATA PROCESSING

The inputs to the CAGW model are numerous and complex, as they vary from year to year based upon surface water supply and other factors. A data processing tool (DPT) was developed to take output from the RiverWare™ model, and other kinds of data, and produce appropriate input files for the CAGW model. The DPT also takes output from the CAGW model: it takes model-calculated discharge of ground water into the Pecos River, combines this outflow data with releases from Lake Avalon calculated by RiverWare, and feeds this information into a spreadsheet model: the Red Bluff Accounting Model (RBAM), which routes this water, along with any side inflows, to the state line.

### MODEL APPLICATION

These models are best used to calculate the effects of a change in the system. Although the models will not be able to tell us what the flow in the Pecos River will be in ten years time (because we cannot predict the weather), the models can give us a good estimate of the difference in the flow of the Pecos River between one management option and another.

The best use of the model suite involves two different runs: one run with one set of management rules and ground water pumping, and a second run with a different set of rules and/or pumping. All other model inputs (precipitation, inflow from recharge or tributaries) are kept the same in the two runs and are typically based on historical natural conditions. The difference in the output between the two runs, such as the difference in the flow of the Pecos River at Red Bluff, should be the result of the management and pumping differences we imposed upon the model runs. Typically we compare a number of model outputs (water levels, surface flows at various locations) that reflect various hydrologic resources: these are some of the “resource indicators” of an EIS process.

Each complete run of the model suite generates sufficient information to allow us to calculate what New Mexico’s delivery obligation to Texas would be, under the Pecos River Compact, for each year of that model run. The state-line flows generated by the RBAM model constitute New Mexico’s delivery to Texas for each year of that model run. The simulated obligation and deliveries can be readily compared for each run, giving us an idea of how likely actual compact compliance is for each scenario that we model.

The model suite has been used to evaluate the Pecos River consensus plan and the terms of settlement between the major parties to the Lewis adjudication. These evaluations involve testing of a complex set of rules involving ground water pumping restrictions, augmentation pumping, retirement of irrigated lands, and a variety of changes to reservoir operations. All parties associated with the ad-hoc committee and the settlement have reviewed the results of these analyses and are in general agreement that the results are reasonable and useful to those who must decide how a number of major problems on the Pecos can be and should be addressed. It is anticipated that the model suite will be used for EIS evaluations associated with endangered species actions and changes in river operations associated with the Lewis adjudication settlement.