NEW MEXICO BUREAU OF GEOLOGY AND MINERAL RESOURCES

WATER RESOURCES of the LOWER PECOS REGION, NEW MEXICO

Science, Policy, and a Look to the Future

Peggy S. Johnson, Lewis A. Land, L. Greer Price, and Frank Titus, Editors

DECISION-MAKERS FIELD CONFERENCE 2003

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New Mexico Bureau of Geology and Mineral Resources
A Division of New Mexico Institute of Mining and Technology
2003

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a division of

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Preface

This volume was compiled for the third Decision-Makers Field Conference, organized by the New Mexico Bureau of Geology and Mineral Resources, a research and service division of New Mexico Tech. For seventy-five years we have served as the geologic survey of New Mexico, tasked with providing information to scientists, decision makers, and the general public on the geologic framework of New Mexico.

These conferences are one important way in which we accomplish that mission. In three days of focused discussions in the field, we explore issues of importance to the people of New Mexico. This year's trip to the lower Pecos River region of New Mexico focuses on water resources, for it is here that the critical water issues of New Mexico (and the arid Southwest in general) are playing out in a very real and compelling way. What happens on the Pecos River in the next few years will provide a path for solving other water crises in New Mexico—either through our success or our failure.

The authors of these papers were chosen based on their current positions, background, areas of expertise, or long-standing experience in New Mexico. It was our intention that they speak from a position of authority to provide the necessary background for understanding these complex issues, an understanding that is important to the general public as well as to those in decision-making positions.

We tried to achieve a balance of topics, issues, and voices, providing historical background, a look at current issues, and some idea of the directions that future science and policy might take. We asked individual authors to provide facts rather than opinions, but such papers invariably reflect to some degree the views of their authors. Those views do not necessarily represent the voice of the New Mexico Bureau of Geology and Mineral Resources or our partner agencies.

Although it is not our intention to lobby for specific legislation or press for change in one direction or another, it is our belief that sound policy-making must be based on sound science. Problem-solving is facilitated through open discussion and, ultimately, a thorough understanding of the problem. Our hope is that these conferences—and this guidebook—represent a step in that direction.

-The Editors

Map of Field Trip Area

An Introduction from the State Geologist

Peter A. Scholle, *New Mexico Bureau of Geology and Mineral Resources*

This year's Decision-makers Field Conference is the third in our ongoing series of meetings that deal with geological and hydrological issues in New Mexico. These conferences are designed to provide New Mexico decision makers with the opportunity to see, first hand, the influences and impacts of natural phenomena and human actions on our resources and landscapes. The conferences also provide an opportunity for participants to hear, see, and interact with leading scientific and technical experts from a wide range of partner organizations, who present material essential for an understanding of the relevant issues and their potential solutions. They are the authors of most of the papers in this volume. We strive to present a balanced program and to educate rather than lobby for specific legislation. Having said that, however, we and our many partners hope that the information presented, contacts made, discussions engaged in, and continued interactions after the trip will lead to useful legislation for New Mexico.

This year's meeting, on water issues in the lower Pecos River region, highlights some of the most important and contentious issues in New Mexico's future. The Pecos has always been a "difficult" river—prone to extremes of flow, from mere trickles at some times to massive, dam-destroying floods at others. Yet the surface and subsurface waters of this basin were the essential resource that drew people to this region in the first place. These waters, along with petroleum and potash, have been the principal source of most of the wealth generated in southeastern New Mexico since those early days. Today a wide range of interests are competing for those limited water resources, including traditional farming and ranching, municipal needs, a growing dairy industry, the water demands of native and non-native vegetation in riparian and higher-elevation watershed areas, the need to protect endangered species, and, of course, the ever-popular Interstate Compact- and Supreme Court-mandated water deliveries to downstream users in Texas. The situation is further complicated by current drought conditions that, if they are indeed part of a predicted drought cycle, may extend into the next several decades. Finally, there are the difficulties inherent in administering water allocations under the "prior usage" water laws of the West. These laws make water conservation difficult and lock in place historical patterns of water usage that are sometimes quite inefficient.

Clearly, the future of the lower Pecos River basin depends on rational and effective use of the scarce water supplies available in this arid region, with an eye not just on current users, but also on the needs of future generations. The consensus agreement recently reached by most of the competing parties in the lower Pecos River basin is certainly laudable, and vastly preferable to drawn-out conflict, expensive legal action, and decisions made by river masters, federal agencies, or judicial courts. The consensus agreement on the Pecos has been widely praised; it has been held up as a model for dealing with water issues in other parts of the state and indeed throughout the arid Southwest. Yet, in some senses, the agreement is not a very satisfying solution. For one thing, it involves the State buying back (on a voluntary basis) senior surface water rights of farmers and ranchers—an expensive scheme that is paid for largely by taxpayers from other areas of the state. It's a plan that may have long-term negative impacts on the productivity and economic base of the lower Pecos region and on its pastoral agricultural and ranching character. Although the consensus plan correctly recognizes the fact that water is a finite resource and that surface and subsurface water supplies are inextricably linked, it does not really address the efficiency of water use or the possibilities of finding additional water. It is essentially a status quo agreement that brings supply and demand back into balance mainly by addressing demand, and then only overall demand, not the savings that could be realized within the demand sector.

Perhaps we can do better. I believe that we should also be taking at least a fraction of the kinds of dollars being put into water-rights buybacks and investing them in both applied research and the implementation of positive solutions developed through that research. Such an approach eventually may allow resumption of the economic growth of the lower Pecos region, mainly through more efficient use of known water supplies, but also through development of currently untapped water resources. That requires not just scientific study, but also legal clarification of water ownership issues (particularly in the area of deep, saline waters, in particular those waters co-produced during a variety of energy-related activities). It may also require legislative incentives for the adoption of desirable but expensive water conservation or desalinization practices. Here, in no particular order, are some possible areas for further research and implementation:

- Uplands watershed management practices, especially forest thinning programs and other management issues related to water yields from headwaters areas;
- Salt cedar control and other riparian habitat management technologies;
- Improved drip irrigation and sub-plow-level irrigation systems or other technologies to achieve current or improved crop yields with less water use;
- Modeling of the effects of more efficient agricultural irrigation practices (with less return flow to rivers) on future in-stream water quality;
- Evaporation reduction technologies applicable to surface reservoir storage in desert areas;
- Improved understanding of optimal areas for temporary underground storage and later recovery of water;
- More accurate and cost-effective methodologies for monitoring of ground and surface water use;
- Delineation of moderately saline and highly saline ground water supplies throughout the region, coupled with a better understanding of their hydrogeology (especially recharge rates and the potential effects of withdrawing water from those units);
- Research on cleanup and productive use of waters associated with petroleum production (co-produced waters), dewatering of coalbed methane areas, $CO2$ sequestration, and other subsurface energy-related programs;
- Clarification of water-rights issues associated with co-produced waters;
- Research on more effective techniques of desalinization coupled with clarification of water-rights issues in this area, and incentives for establishing desalinization facilities;
- Modeling of methodologies for (and effects of) the disposal of saline brine residues from future desalinization programs;
- Legislative research into programs that would allow real water banking and water conservation without jeopardizing water rights. The buying, selling, and leasing of water rights is only part of banking. Savings are the essential core of most banking systems, and in the case of water banking this should include allowing injection of water into aquifers for subsurface storage as a productive use or being able to save, as well as sell or lease, water conserved through efficiencies in agricultural or industrial practices.

Certainly some work (in some cases substantial work) has been and is being done in all these areas, but generally not at a scale or pace commensurate with their importance to the critical water needs of New Mexico. It is my personal hope that this trip will not only elucidate the water problems on the lower Pecos, but will show participants two additional things: there is much we still don't know in many areas critical to proper water management, and research investigations to date have shown at least some promise in many of the areas listed above. But it will take substantially more scientific and technical study in many fields, and by many organizations, to bring that promise to fruition. New Mexico has the research talents in its national labs, its research universities, and in its private industry to solve collaboratively many of these problems. As in all such ventures, however, such research takes time; we should embark on that journey as soon as possible. Science and technology will not supply all the answers, but legislative, judicial, or technical decision making in the absence of good scientific information rarely produces the best results—the kind of results New Mexico requires in this area of critical needs.

Although it is impossible to guarantee that money invested in scientific research will produce positive results, it does appear to me to be a prudent investment, which may yield a future of at least modest growth for the region. The alternative is to continue relying simply on buyouts and reduced economic expectations, first here on the Pecos, and later, along the rest of New Mexico's major rivers.

Lessons from the Pecos River

Frank Titus, *New Mexico Bureau of Geology and Mineral Resources*

The saga of water exploitation in the Pecos River Valley is a classic. The tensions, manipulations, grandiose planning, engineering failures, political domination, personal successes, failures, and management judgments and misjudgments occurred on a grand scale. It is a century-long water-development tale out of the old West. But New Mexicans might wish to view it as a water-management wake-up call. It would have been wise 15 years ago, when the U.S. Supreme Court issued its 1988 Amended Decree in *Texas v. New Mexico*, to see it as a harbinger of uncomfortable things to come. We weren't ready to limit ourselves then. Now a great Southwestern drought threatens to reach historic proportions. We may be late in starting, but if we fail to extract useful intelligence from Pecos River history, we will be short sighted indeed.

We twisted the tiger's tail on this river, and the beast bit us. It was a real bite. I'll guess that the cumulative out-of-pocket costs to the people of New Mexico will add up to more than one hundred million dollars. That's part of the down side. The up side includes the cumulative value of crops we've grown on thousands of acres for more than five decades, with water that many have argued God surely intended to be ours. One can't help noticing that the cumulative economic benefit is nearly all in the past, and flowed to the state through the people of the Pecos Valley; most of the cost will be paid in the future, and likely by all of the people of New Mexico. If so, this will be a precedent for addressing other regional water problems.

THE FRAMEWORK

The Pecos River, with its headwaters high in the Sangre de Cristo Mountains of northern New Mexico, provided surface water for irrigation and other development in the Carlsbad area as early as the late 1800s. Shortly thereafter, farmers near and west of Roswell discovered the prolific and highly pressured aquifer in what became known as the Roswell artesian basin. This aquifer, capable of artesian flows (no pumping required) of thousands of gallons a minute from well heads, became the source for great agricultural development upstream from Carlsbad. Later it would become clear that these awesome irrigation wells intercepted ground water that, under natural conditions, fed the flow of the Pecos River, lying miles to the east of the westernmost artesian wells.

In 1948 New Mexico and Texas signed an interstate compact, agreeing on the amount of water the river must be allowed to carry on into Texas. This annual obligation is based on the measured amount passing the Fort Sumner river gage, plus the "flood inflow" from tributaries between Sumner Dam and Red Bluff Reservoir, on the Texas state line. Accurate calculation proved elusive. Nevertheless, for 33 years New Mexico was judged to be short in its annual deliveries to Texas. A lawsuit filed by Texas was heard by the U.S. Supreme Court, which ruled in 1988 that (1) New Mexico owed 14 million dollars for water not delivered in the past; (2) New Mexico must never again be short in its deliveries under the compact; (3) Texas' interpretation of river flows would prevail; and (4) a River Master, appointed by the Supreme Court, would ensure that the terms of the decree are met.

The combined effects of the current drought, and the failure (until recently) of all parties to agree on how to share the burden of annually delivering sufficient water to Texas, has threatened New Mexico's ability to comply with the Supreme Court decree. Non-compliance being risky, even foolhardy, Tom Turney and Norman Gaume, then state engineer and interstate stream engineer respectively, threatened the painful consequence of a "priority call" on the Pecos River and the Roswell artesian basin to force negotiation of a "consensus plan." That exercise, forcefully driven by Mr. Gaume, was finally agreed to by the parties on March 25, 2003.

THE CONSENSUS PLAN OFFERS HOPE

The consensus plan is a tough agreement among New Mexicans that specifies how they will ensure that water owed every year of the future to Texas will be delivered to Red Bluff Reservoir. The plan, born under duress but accepted by negotiators and their constituents alike, seems at this late date to be the only way out of a water controversy long in building. That is, the only way out if we want to keep some semblance of water control in the hands of New Mexicans rather than ceding it to the river master, an outsider, then through him very likely to the U.S. Bureau of Reclamation. So, for this river at this time, with its people and its history, this appears to be the right solution.

Does this mean that it's over, that we've won, and can go on to other issues? Not by a long shot. It would be well for the people of New Mexico to join with the people of the Pecos River valley in following this story to its end. The decision makers and people of the Pecos Valley must now implement the plan to which they've agreed. Then likely it will be all New Mexicans who will pay for the settlement, or, if it fails, likely pay for whatever final arrangement prevails.

THE PLAN—AND SOME QUESTIONS ABOUT IT

To predict final success or failure of the consensus plan, some important questions need answers:

- Will willing sellers for 6,000 acres of Carlsbad Irrigation District land come forward, so their land can be bought by the state and dried up?
- Will willing sellers for 12,000 acres of water rights above Brantley Dam (mostly from the Pecos Valley Artesian Conservancy District) be there when we need them?

These are two features of the consensus plan. Two other key features are that wells in the artesian aquifer will be provided to yield up to 20,000 acre-feet of ground water a year into the Pecos River itself to ensure, right from the start, that the required Texas water deliveries can be made; and that the Carlsbad Irrigation District will comply with its agreement not to intercept this augmented river flow and divert it for irrigation. There are other important questions which are not in the Consensus Plan:

- Will the land offered by "willing sellers" be priced reasonably? If not, what do we do?
- Will the state legislature provide the funds necessary to carry out the plan? It will be very expensive.

WAS THERE A BETTER WAY?

The answer may depend on how far back in time you want to go. If it's only five or 10 years, the answer is probably no; if it's to the 1950s or '60s, it might be yes. That choice of time frame isn't random. By the 1960s irrigation development in the Roswell artesian basin was widespread and was served by a great number of artesian wells exploiting the prolific limestone aquifer. Equally important, there was ample technical evidence by then that the ground-water production was intercepting water that under natural conditions had contributed directly to the flow of the river. In fact, the Carlsbad Irrigation District had requested that a priority call be issued against the Pecos Valley Artesian Conservancy District for depleting the river upstream from Carlsbad Irrigation District. State Engineer Steve Reynolds would not agree to it.

Salt cedar eradication was one solution that Steve Reynolds and others hoped would result in more water for Texas. Tens of thousands of acres have been root-plowed, sprayed, and continue to be controlled in the Pecos Valley, but it has produced no discernable increase in river flow. While this has been an active research area, comprehensive answers to date are elusive. The general problem is that removal of salt cedars usually allows the water table to rise toward the land surface, and then direct evaporation, or whatever vegetation takes over, again removes large volumes of water.

Until recently we weren't ready to limit productive acreage. But would other technologies have solved the problem? The answer is not clear. New Mexicans have not to this day looked seriously at low-water-use crops. Neither farmers nor New Mexico State University (NMSU), the state's land grant college, and recipient of large grants from the federal government, have shown any enthusiasm for a search for high-value, low-water-use crops. With respect to the supply side of the water equation, some limited prospects for new water supplies are promising. Desalinating the brines that are produced with petroleum in many oil fields is currently being explored. Another saline water source on the Pecos is the natural spring discharge into the river in the vicinity of Malaga Bend. But while desalination may have prospects for the future, it probably will always be too costly for agriculture.

Desalination should not be mentioned without noting the highly concentrated brines that are an unavoidable byproduct. In inland states such as ours, arranging for environmentally acceptable brine disposal can add a significant cost to the process. For coastal cities in the U.S. and elsewhere that environmental problem can be managed; but New Mexico is a long way from a marine shoreline.

Other technologies that might partly mitigate our water problems are known, of course, and many should be seriously investigated scientifically. They tend to fall into categories of providing only long-term solutions, or needing a great deal of research, or producing water only for high-value uses.

THE BROADER ISSUES—THE STATE'S WATER AFFAIRS

Each of us is aware to some degree that New Mexico has water problems looming in other parts of the state. The problems on the Rio Grande are just as intense as those on the Pecos and carry the potential for a much greater economic hazard. Then there are other rivers: the San Juan, the Gila, the Canadian; and the ground water of the Hueco Bolson and other border regions.

We wasted decades on the Pecos while we hung tough, refusing to negotiate. Now, aren't we wasting equally critical time statewide as vested interests in basins under pressure fail to concede that the state's ability to manage its own water affairs is imperiled? Why can't we get started on their critical negotiation? If we are to live sustainably, within our water means, everyone will have to cooperate in belt-tightening. Isn't high-stress negotiation the best way to find fair and equitable solutions?

What can we do as a state to help ourselves out of this quagmire? What can we learn from the Pecos story? Up front we should recognize that although each river-aquifer system is different, we have principles spelled out in law, and basin-specific contractual agreements, to guide statewide water management. The Pecos conflict festered, it can be argued, because we were slow to follow those principles. At the most fundamental level, we didn't meet our contractual commitments (the Pecos River compact), nor did we apply and enforce our prior-rights water doctrine.

Is there anything in the body of state water law that says we don't have to honor our compacts? Of course not. Are there words that say we don't have to honor the principles of water-right priority? Well, not exactly, but interpretations of the law have allowed acquisition of ground water rights that intercept water headed for a hydraulically connected river, thereby shorting future wet-water delivery to owners of senior surface water rights. No priority system can function that way. My own opinion is that in today's world strict adherence to priority isn't hydrologically feasible, nor, in all likelihood, politically possible. Decisions on how to change this part of the law should be made in the political realm, and the problem ought to be faced head on. It's a tough one. Not facing it places the decision process in the courts—exactly the wrong place. Having the courts simply reinterpret existing law cannot produce a final solution.

Here are some of the other questions we need to face:

- Why doesn't New Mexico law give status of some kind to water in rivers and their riparian habitats, as does every other western state? If riparian needs aren't acknowledged, how can we be sure the state engineer will administer water rights in a way that will leave some in the rivers? Having to rely solely on the federal Endangered Species Act is a contorted, imprudent way to manage the state's environmental affairs.
- Why does the state engineer have no practical, effective enforcement authority, to be used when he finds water-rights violations; isn't this lack almost unique among state regulatory agencies? And, can the state's legal and/or political system help the state engineer devise a way to make, and enforce, critical water-management decisions even if court adjudication of rights in a basin is not near completion?

THE IMPORTANCE OF LEADERSHIP

Steve Reynolds, our state engineer for 35 years, was a brilliant, self-confident man and an effective state engineer, a giant among western water leaders. He led the exploitation of New Mexico's water for the benefit of its people. But being highly supportive of growth, he also allowed heavy exploitation of water resources in the Roswell artesian basin—knowingly, I am convinced—reducing the flow of the Pecos River and thereby cutting the amount of water going to the senior surface-right owners in the Carlsbad Irrigation District. He surely knew that the state would ultimately have to deliver water under its Texas compact. But he also could calculate the economic value to New Mexico of expanding irrigation to the maximum extent possible for as long as possible, until forced to stop. Although his legacy has been an expansionist philosophy of water-resource use, his policies, which were designed to maximize growth and economic productivity, intentionally used all of the water available to the state, well beyond the point of sustainability. It gave us wealth, of a sort, and growth. But the consequences of those decisions, particularly in the face of the drought that is upon us, have now caught up with us, and we can no longer ignore the reality that the resource is finite.

We now have a new state engineer, John D'Antonio, and a new interstate stream engineer, Estevan Lopez. They answer to governor Bill Richardson, who has indicated a commitment to intelligent management of our water resources and an awareness that we face problems long in the making. Steve Reynolds inherited from the state engineers who preceded him, and passed on to those who followed, a philosophy that the engineer's job was to administer water rights in the state, not to manage the state's waters. Although this may have been practical in earlier times, it is not possible today.

Tom Turney was the first state engineer in New Mexico (1995–2002) to recognize that water-rights administration must finally and forever give way to water-resource management. He had indispensable philosophical help from Norman Gaume, interstate stream engineer (1998–2002). They named the process "active stream management." A key element in the evolution of their perceptions surely had to be the intense processes required to cut the Gordian knot of the *Pecos Valley vs. Texas* water-resource problems. Another intense problem, addressed but not yet solved, was water delivery to Texas under the Rio Grande Compact.

Messrs. D'Antonio and Lopez, I know, recognize that they cannot back away from the transition to a new water-management philosophy for the state. We wish them well. More importantly, though, all of us should be prepared to aid, educate, and encourage them to our best ability. They have been handed jobs of critical importance to New Mexico. Their recent predecessors have plowed the fields well—done their very best to move their offices into the modern world of water affairs. In fact, in this one area, I think we've made a lot of progress in facing our problems and moving toward water solutions that are pragmatic, equitable, and can help preserve the environmental charm of New Mexico.

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.

Regional Geology of the Pecos Country, New Mexico

Lewis A. Land, *New Mexico Bureau of Geology and Mineral Resources*

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.

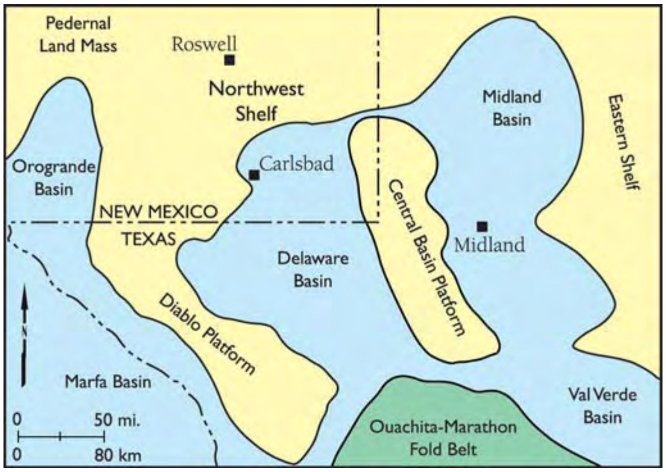
Most of the crest and eastern slope of the Sacramentos is capped by limestones of the San Andres Formation. San Andres limestones constitute most of the artesian aquifer that provides water for irrigation in the Roswell artesian basin of Chaves and northern Eddy Counties. Where it is exposed at the surface, 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



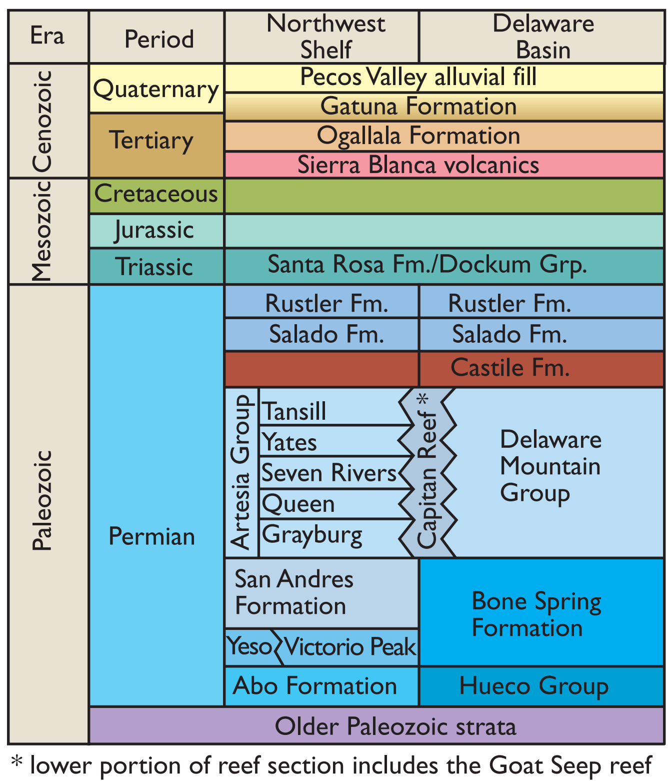
Paleogeographic map of southeastern New Mexico and west Texas in middle Permian time, about 250 million years ago. Areas occupied by ocean basins and relatively deep water are shown by blue shading. Tan shading indicates shelf and platform areas that were periodically flooded by shallow seas.

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.

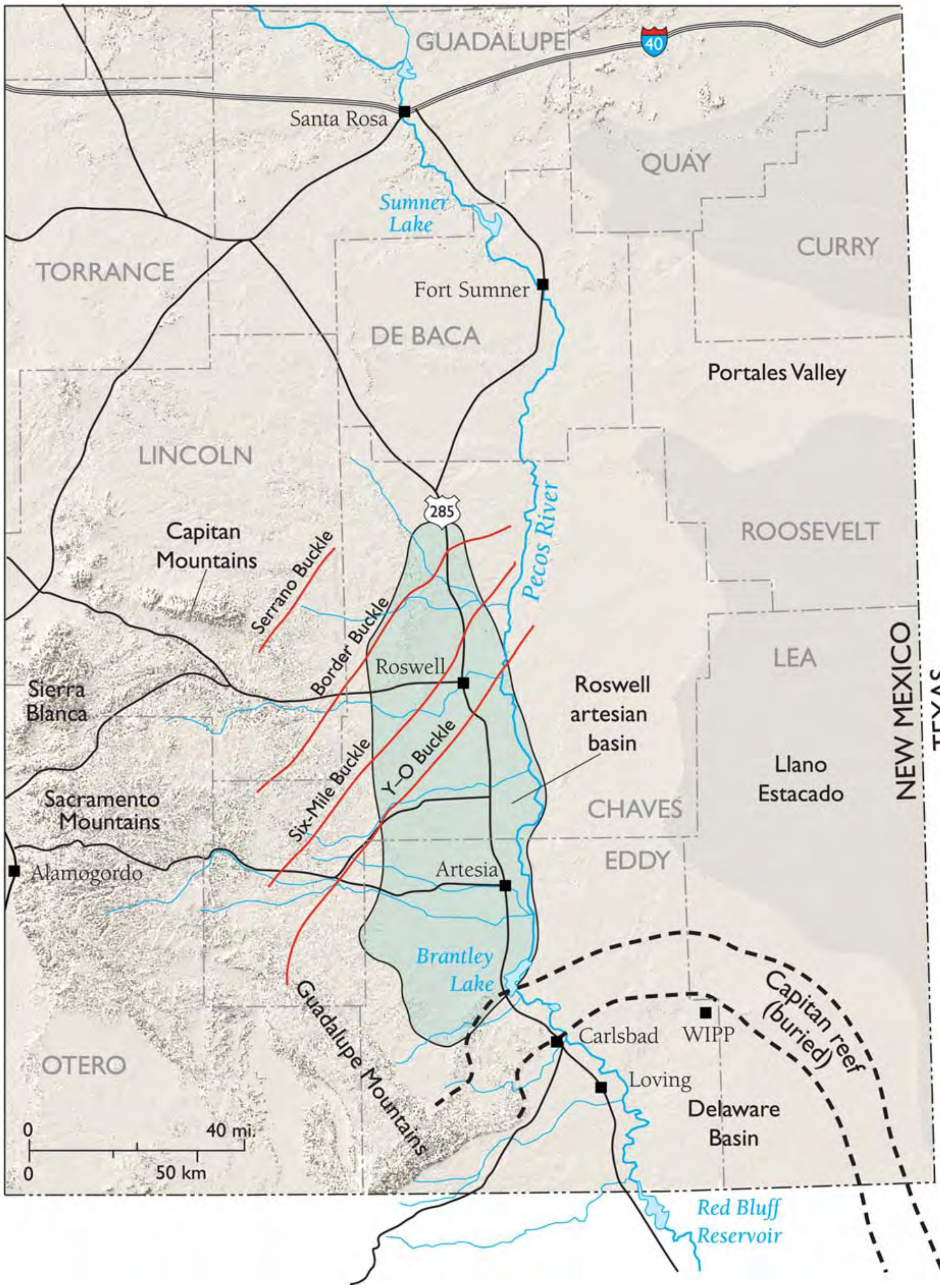
Later, a great reef grew around the upper rim of the Delaware Basin, almost completely encircling it with a limestone escarpment hundreds of feet thick. This enormous structure, the Capitan reef, was constructed in very shallow water by a multitude of reef-building marine organisms including sponges, 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.

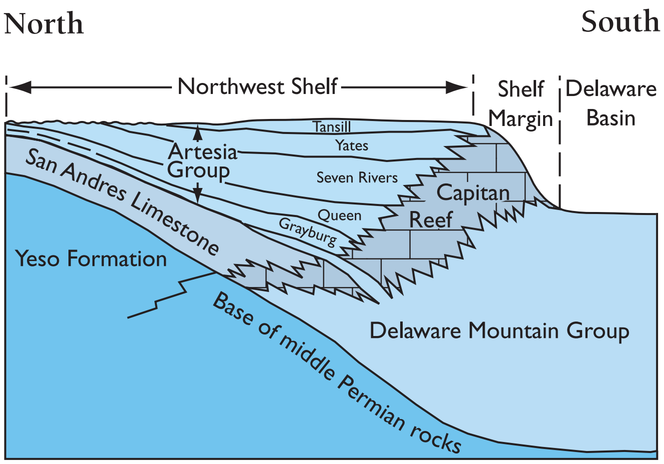
As we follow the strata of the Artesia Group farther north, the environment in which they formed changed from the shallow waters of an open marine lagoon to an arid coastal region characterized by ephemeral streams and salt flats. Because of this change in depositional environment across the Northwest 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



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.

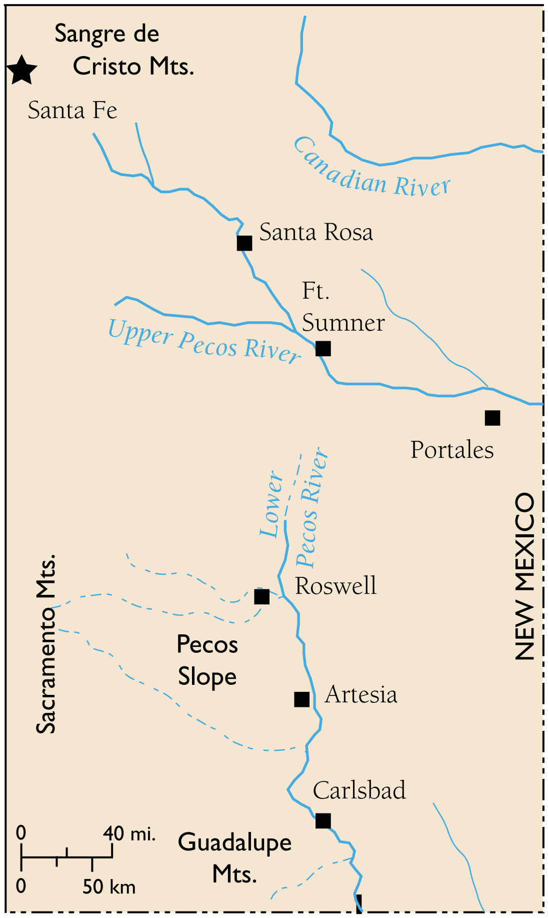
into red mudstone, gypsum, and salt. These are the rocks exposed in the Seven Rivers escarpment east of Roswell, where they host the striking gypsum sinkholes of Bottomless Lakes State Park. Because of their very low permeability, mudstones and gypsum of the Artesia Group also serve as the confining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

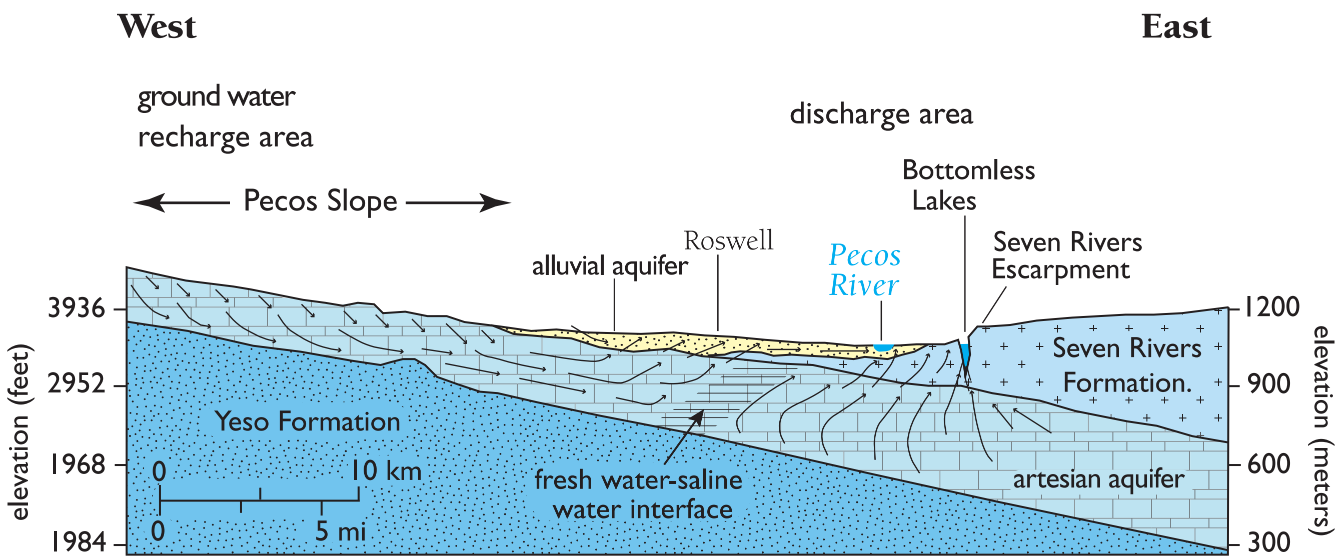
Backreef limestones of the Artesia Group in Slaughter Canyon, Guadalupe Mountains, New Mexico.

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.



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.

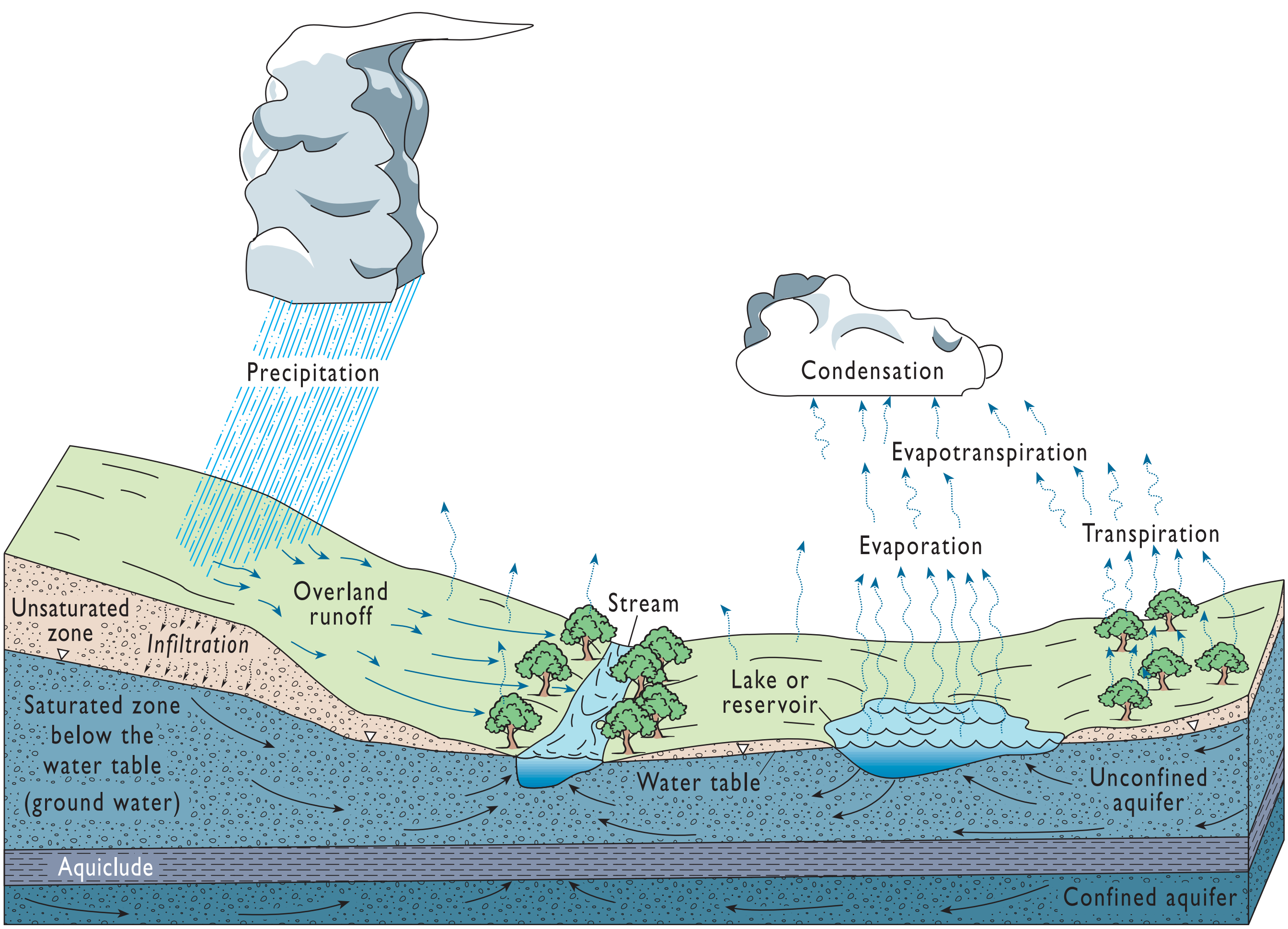
To a large extent, growth and economic development in the lower Pecos Valley have been determined by the geology and hydrology of southeastern New Mexico. The first European settlements in the area were established near surface water sources. The town of Eddy, now Carlsbad, was located near Carlsbad 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.

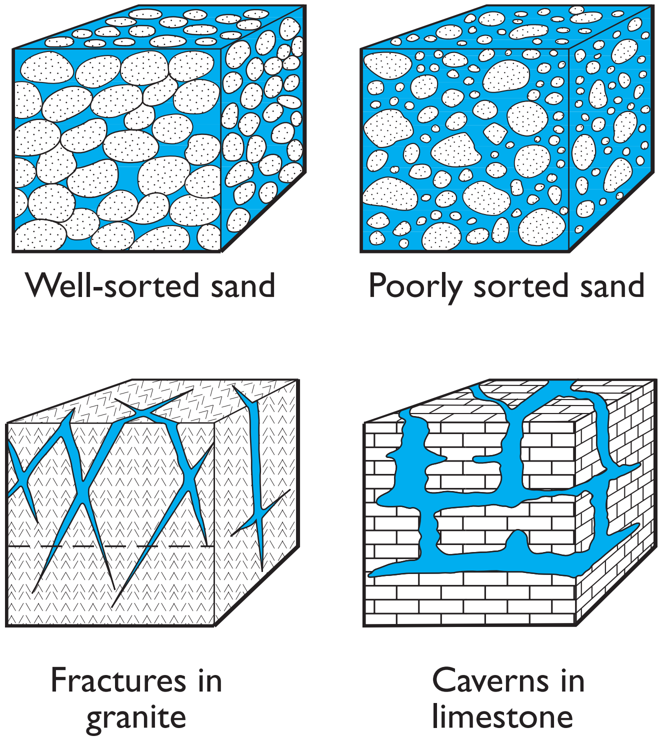
Most of New Mexico is a desert. A desert is defined as a region with a mean annual precipitation of 10 inches or less, and so devoid of vegetation as to be incapable of supporting any considerable population. Precipitation in New Mexico ranges from 6.7 inches at Shiprock to a maximum of 26.2 inches at 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.

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."

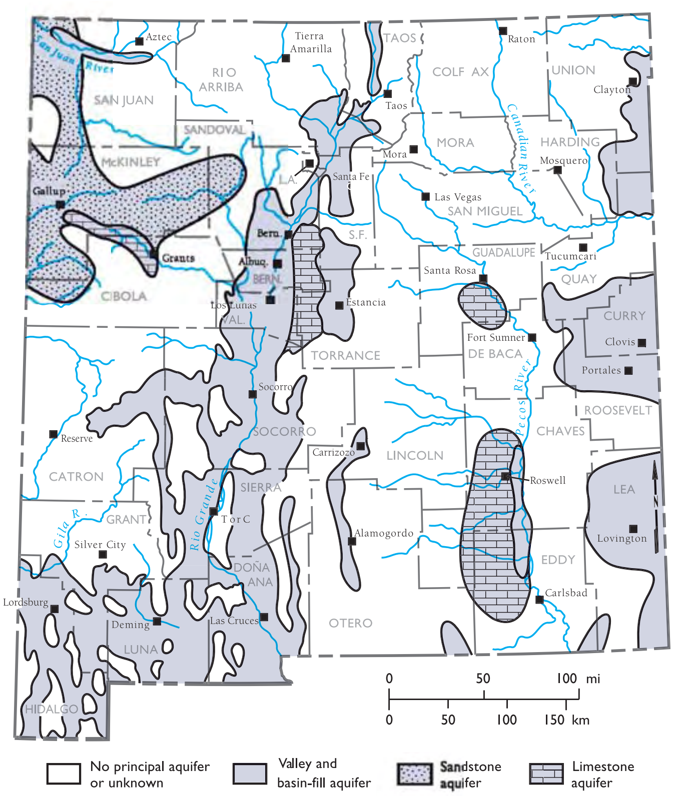


Pore space in sand, gravel, and other unconsolidated deposits, fractures in crystalline and consolidated sedimentry rocks, and dissolution cavities in limestone provide storage for ground water aquifers.

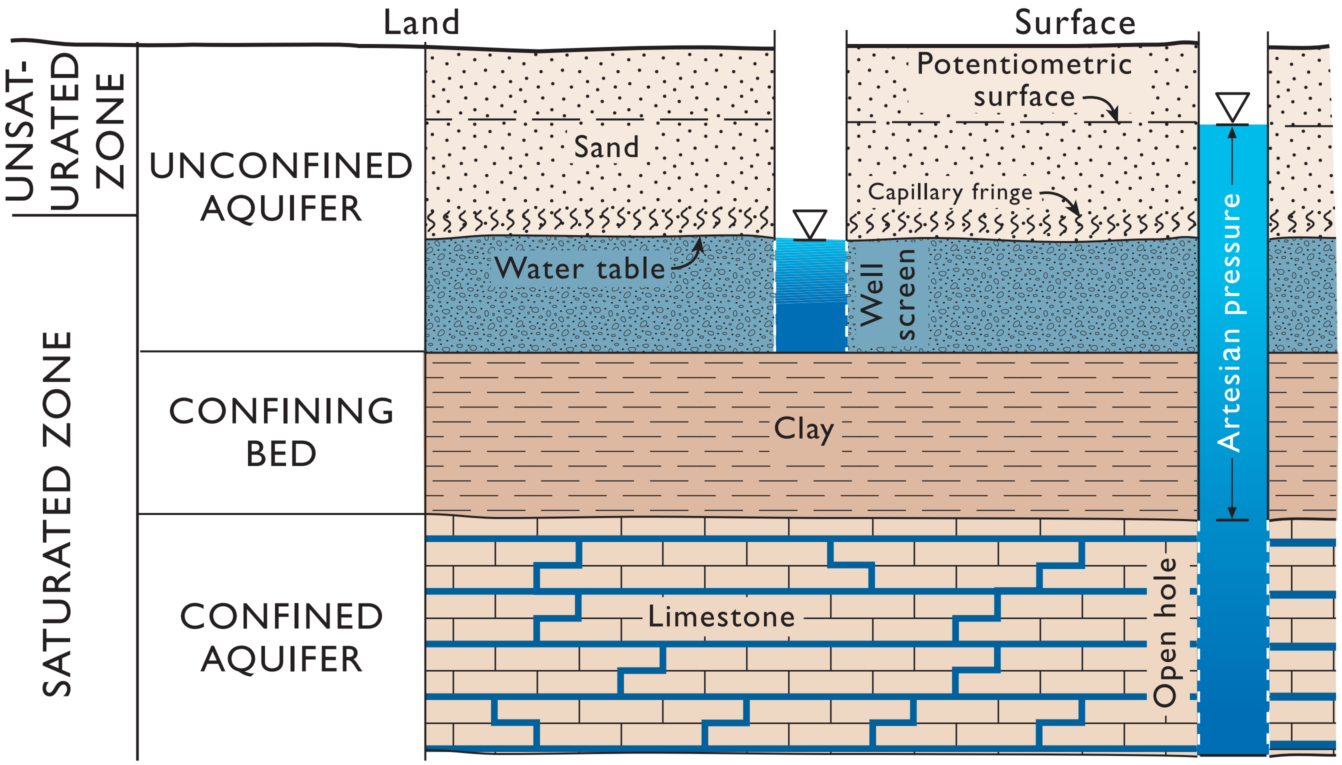
GROUND WATER

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.

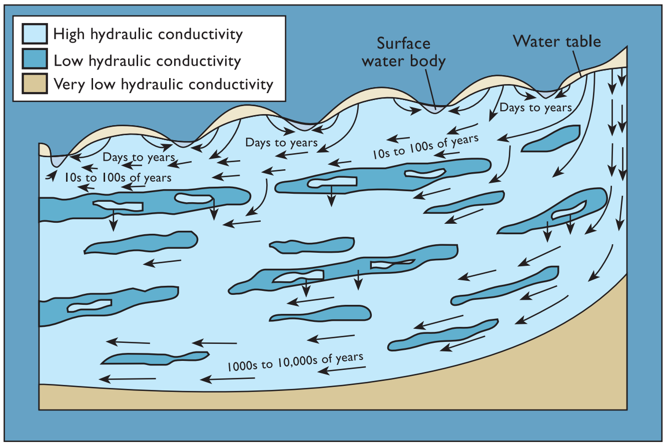


A typical relationship between an unconfined aquifer, confining bed, and confined aquifer, as occurs in the Roswell artesian basin, and the occurence of water-table and artesian wells. Note that the hydraulic head is higher in this instance in the artesian aquifer than the water-table aquifer; hence 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.

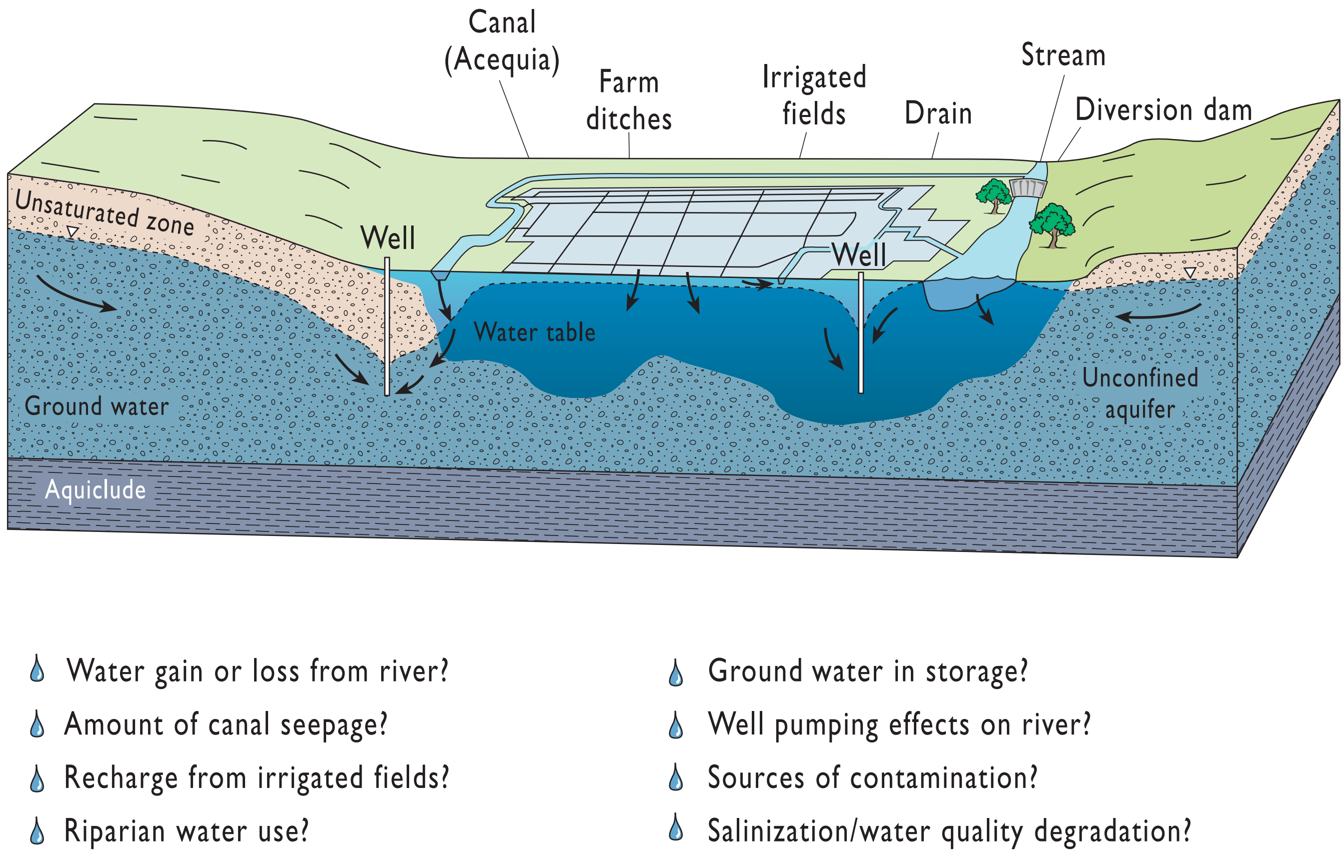
Aquifers are complex three-dimensional flow systems, with subsystems that occur at local, subregional, and regional scales. Faults, low permeability rocks, and differences in the thickness and character of water-bearing beds over short distances can form barriers to ground water flow and partition the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

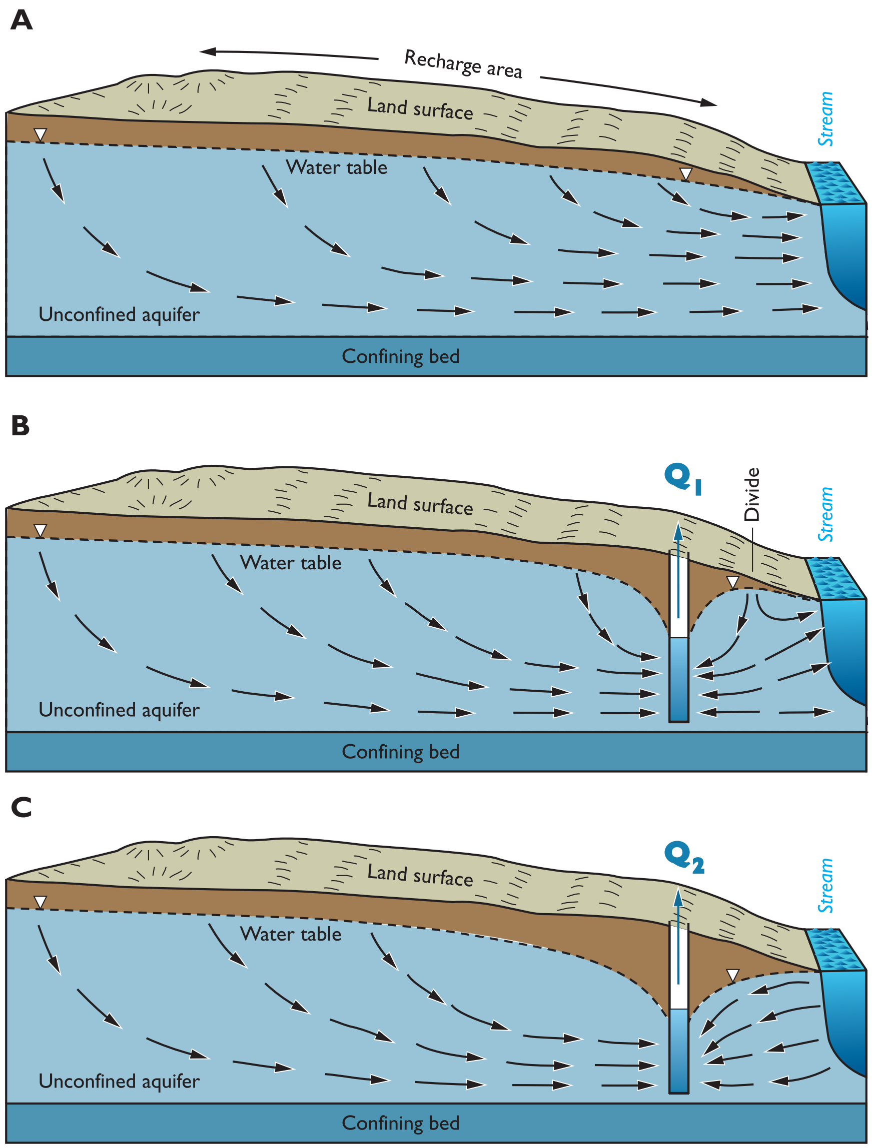


This cross section of a typical irrigated river valley where the stream and aquifer are connected illustrates some of New Mexico's prevalent hydrologic and water management issues.

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.

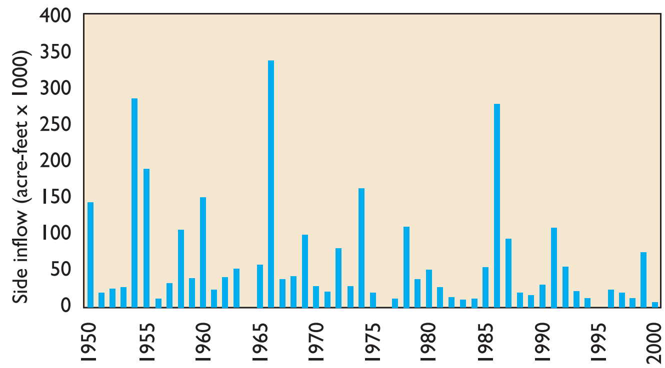
Winter, T. C., Harvey, J. W., Franke, O. L., and Alley, W. M., 1999, Ground water and surface water, a single resource: U.S. Geological Survey, Circular 1139, 79 pp.

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*

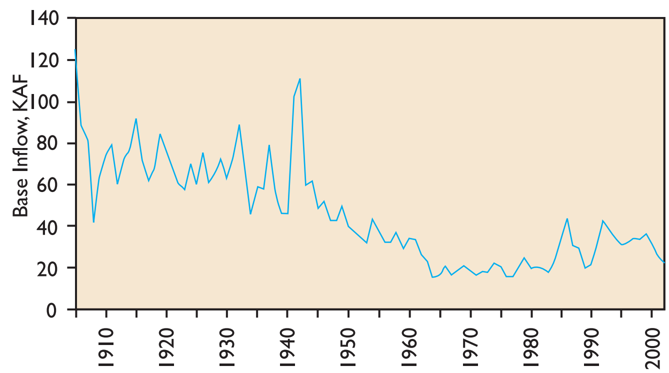
The Pecos River is typical of many western U.S. rivers, originating in high alpine mountains—in this case the Sangre de Cristo Mountains of northern New Mexico—whose snowmelt runoff is one source of the river's reliable water supply. The river then travels through desert or semi-desert regions where 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.

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.



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.

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.

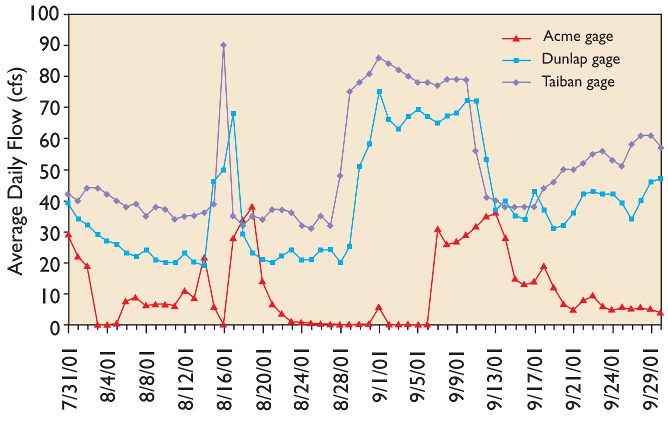
Farther south, significant ground water inflow occurs in the Roswell–Artesia area. Here base inflow originates from the artesian and shallow aquifers of the Roswell artesian basin. These aquifers are recharged from the mountains and tributaries west of the Pecos River. This base inflow has been as high 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.

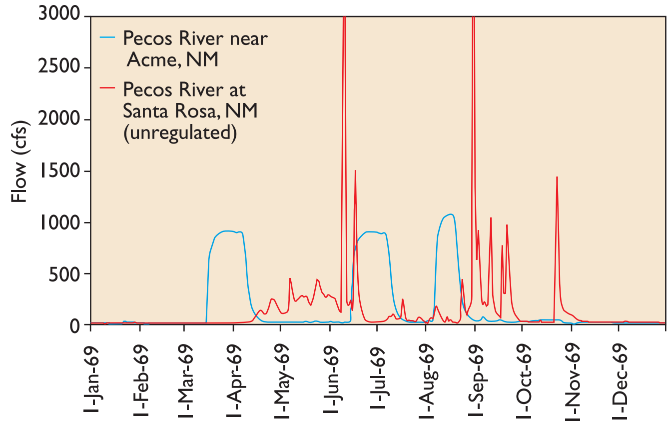
HYDROLOGY—LOSSES AND CONSUMPTIVE USES

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

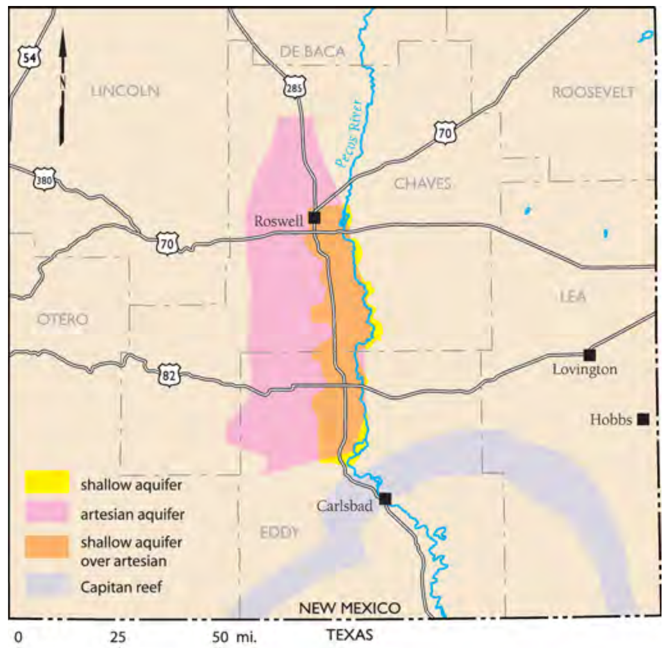
Brantley Dam.

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.

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.

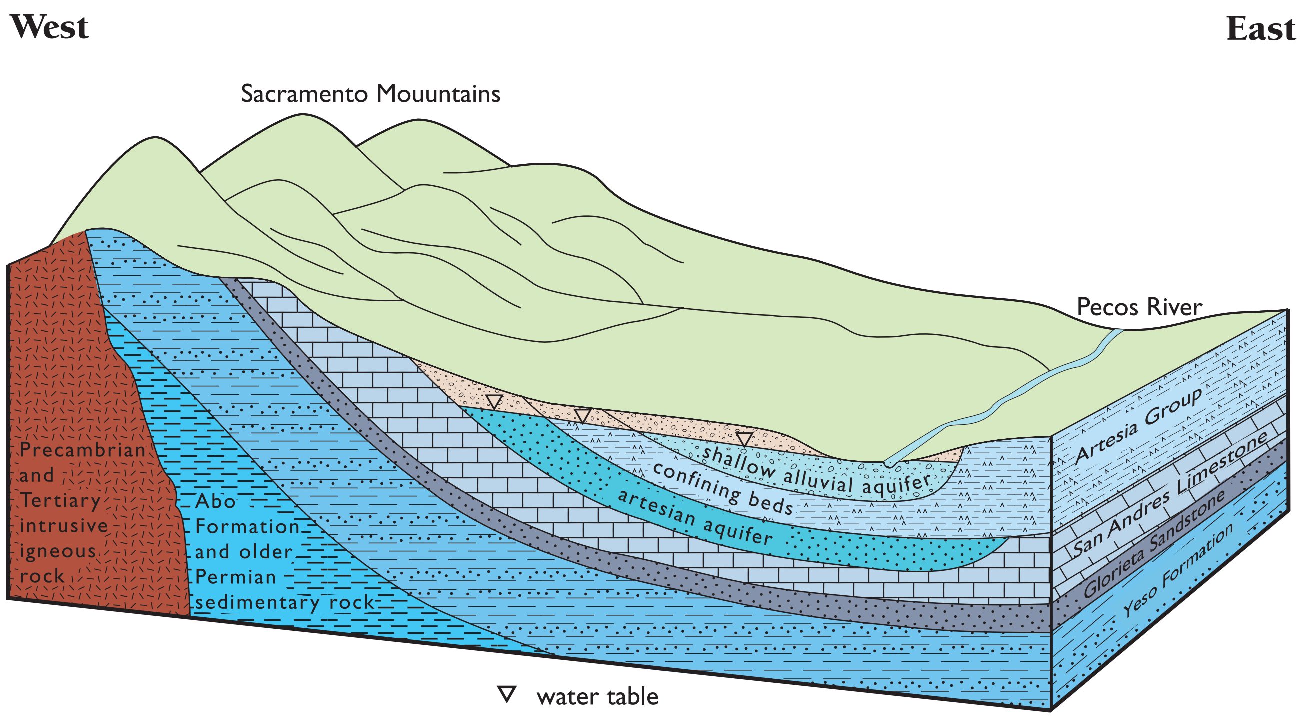
HYDROGEOLOGY

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

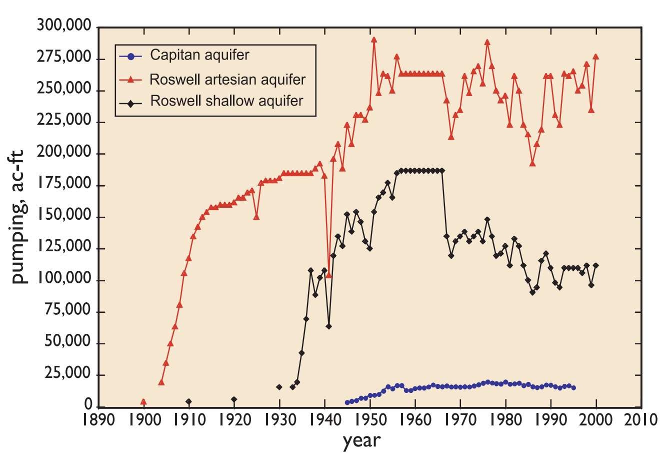


Schematic west-to-east cross section illustrating the relationships between the shallow aquifer, confining beds, and carbonate aquifer in the Roswell–Artesia area.

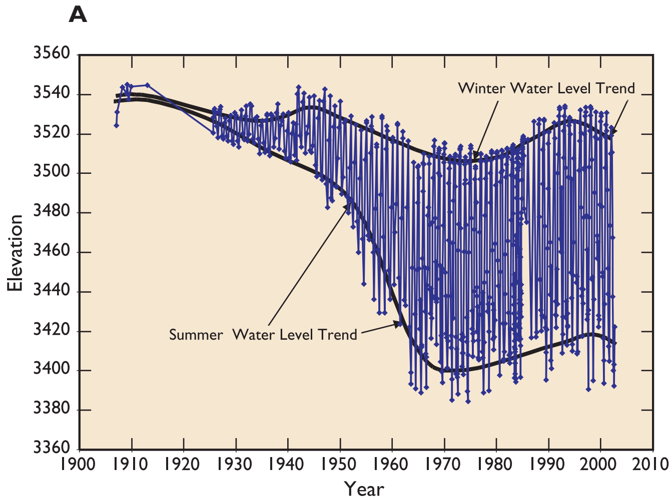
into the aquifer. The artesian aquifer is 300–500 feet thick. Near the Pecos River, the top of the aquifer lies at a depth of about 1,100 feet.

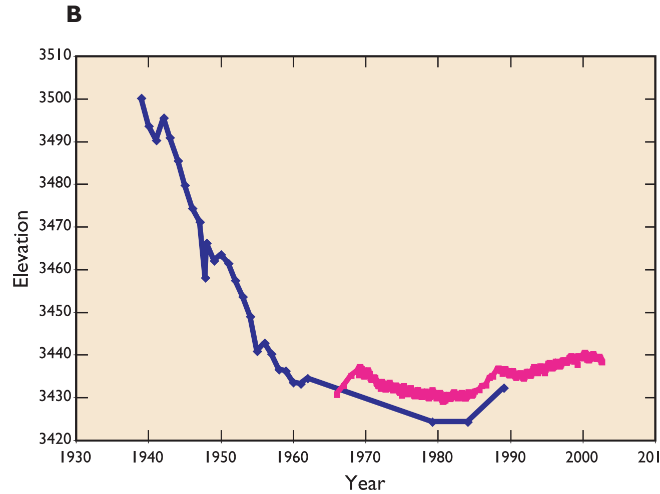
Although the carbonate rocks of the artesian aquifer are present farther east in the subsurface, they are much less permeable here because the pattern of ground water circulation ends with discharge to the Pecos River. Clay-rich rocks of the Permian-age Artesia Group (the confining beds) lie above the 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.

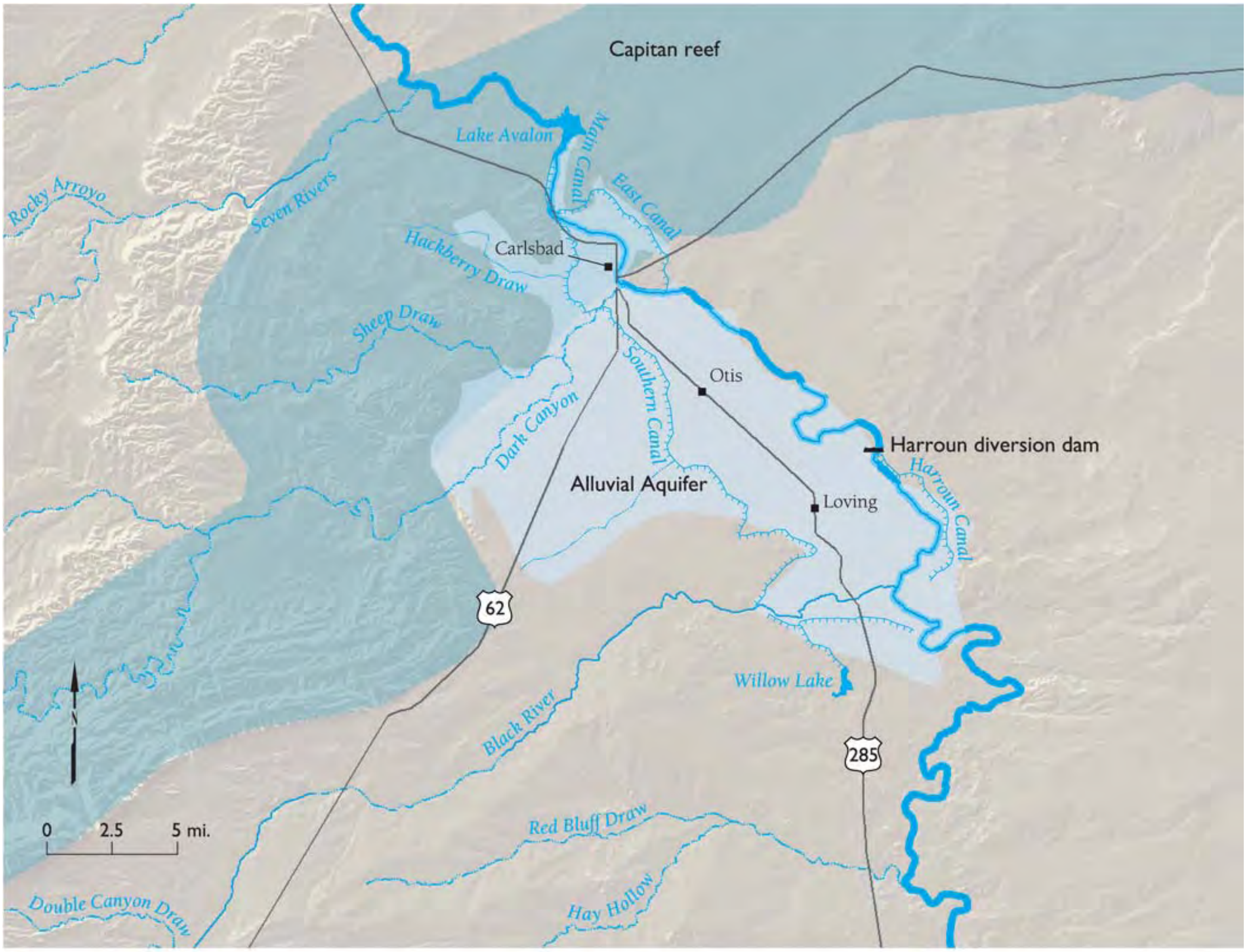
Water levels in the Roswell artesian basin show the effect of ground water development. In general, water levels declined rapidly from the mid-1930s to 1965, were roughly stable until about 1985, rose until the mid-1990s, and now appear to be declining again. Water levels in the artesian aquifer show 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.

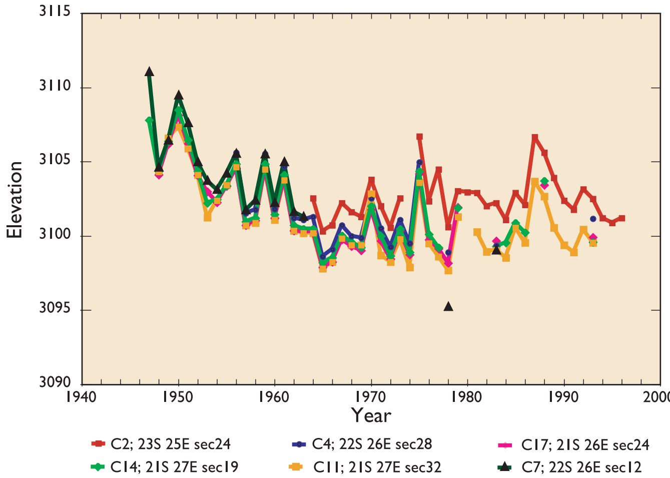
CAPITAN AQUIFER

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 ground-water 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.

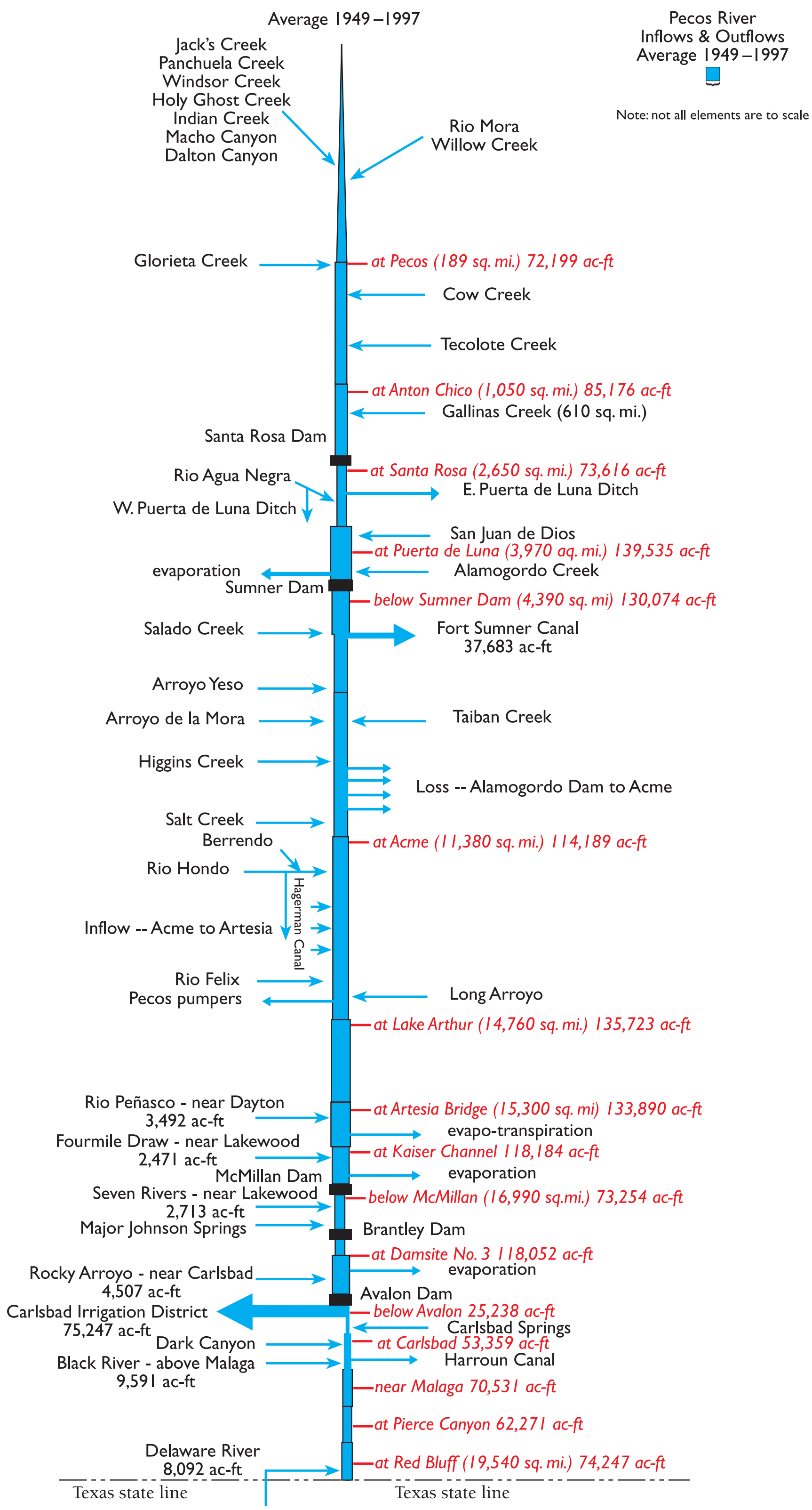
New Mexico's obligation is determined by a complex set of instructions called the River Master's Manual. The primary factor in determining New Mexico's obligation is flood inflow. Flood inflow is determined from an examination of river gage records combined with a series of hydrologic calculations. It 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.

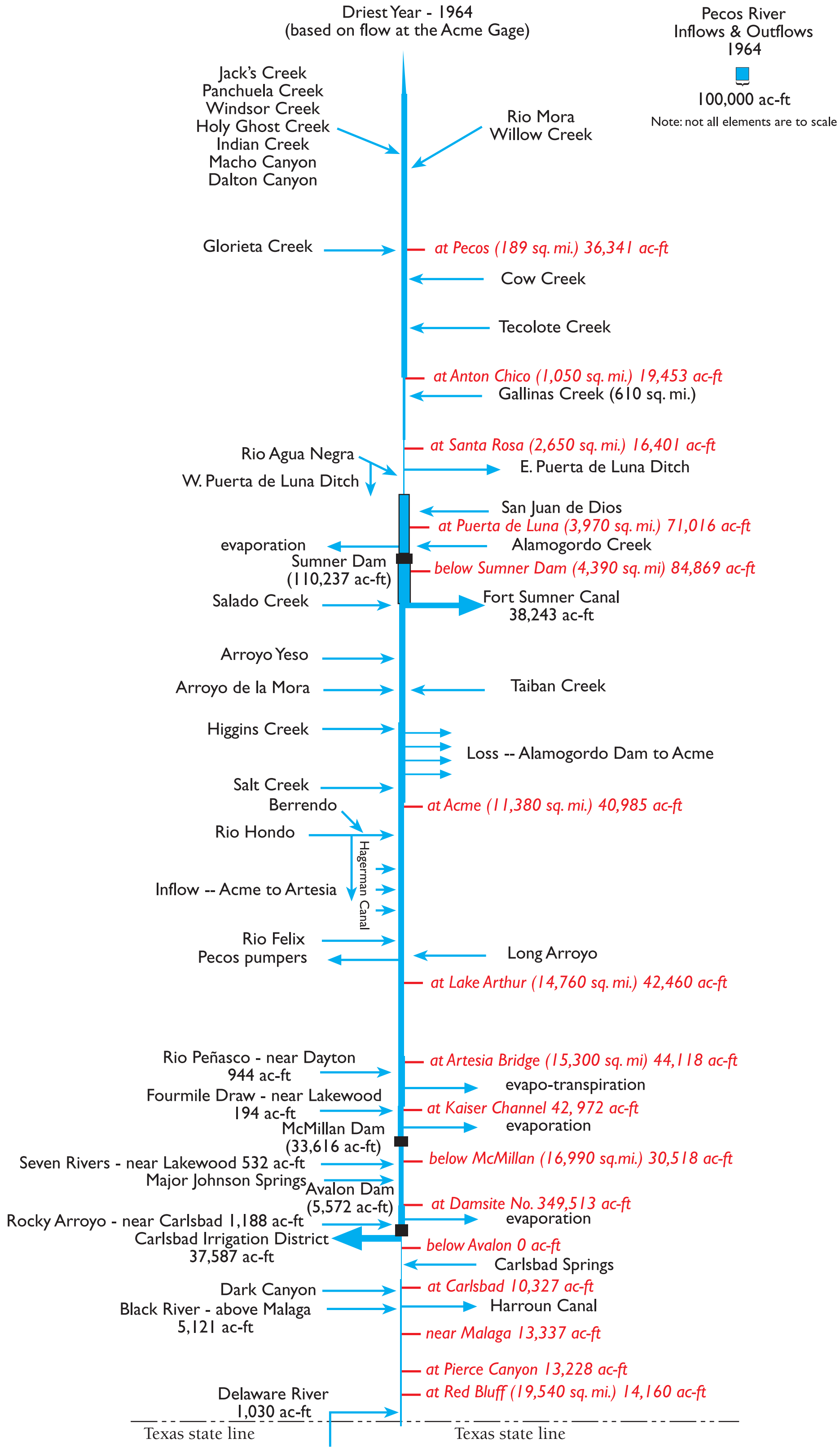
THE ENDANGERED SPECIES ACT

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.

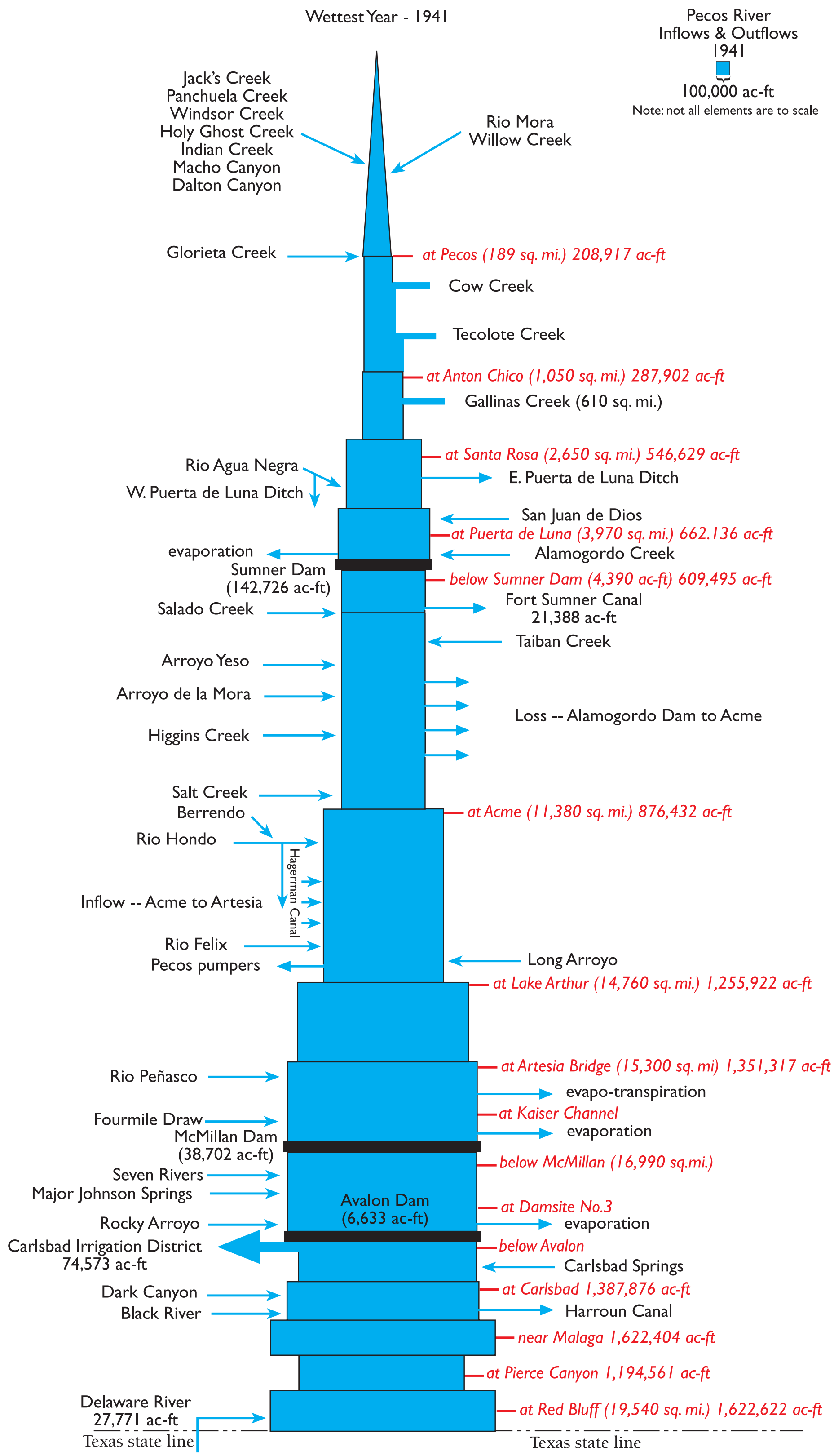
The most recent modifications that have been implemented by the Bureau of Reclamation to support the fish include changes to the block release operations, bypass of water through Sumner Dam, and retirement of irrigated agriculture to offset the effects of the changed operations. The modification of block 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)

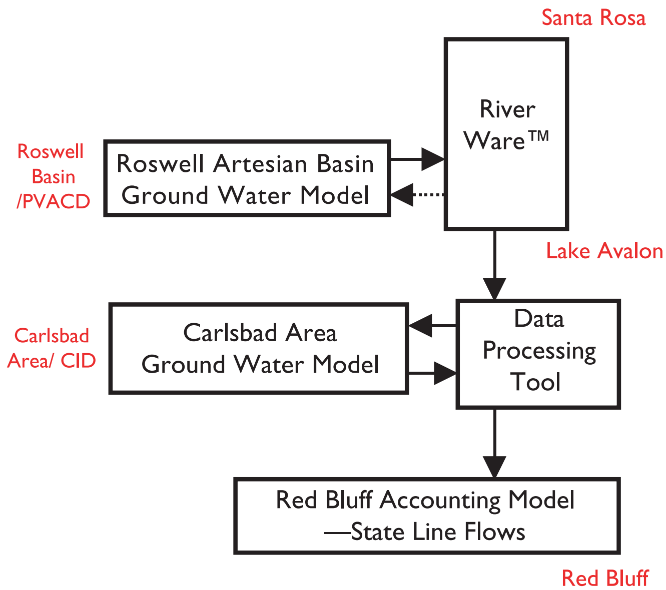


Diagram of model interaction.

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)

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.

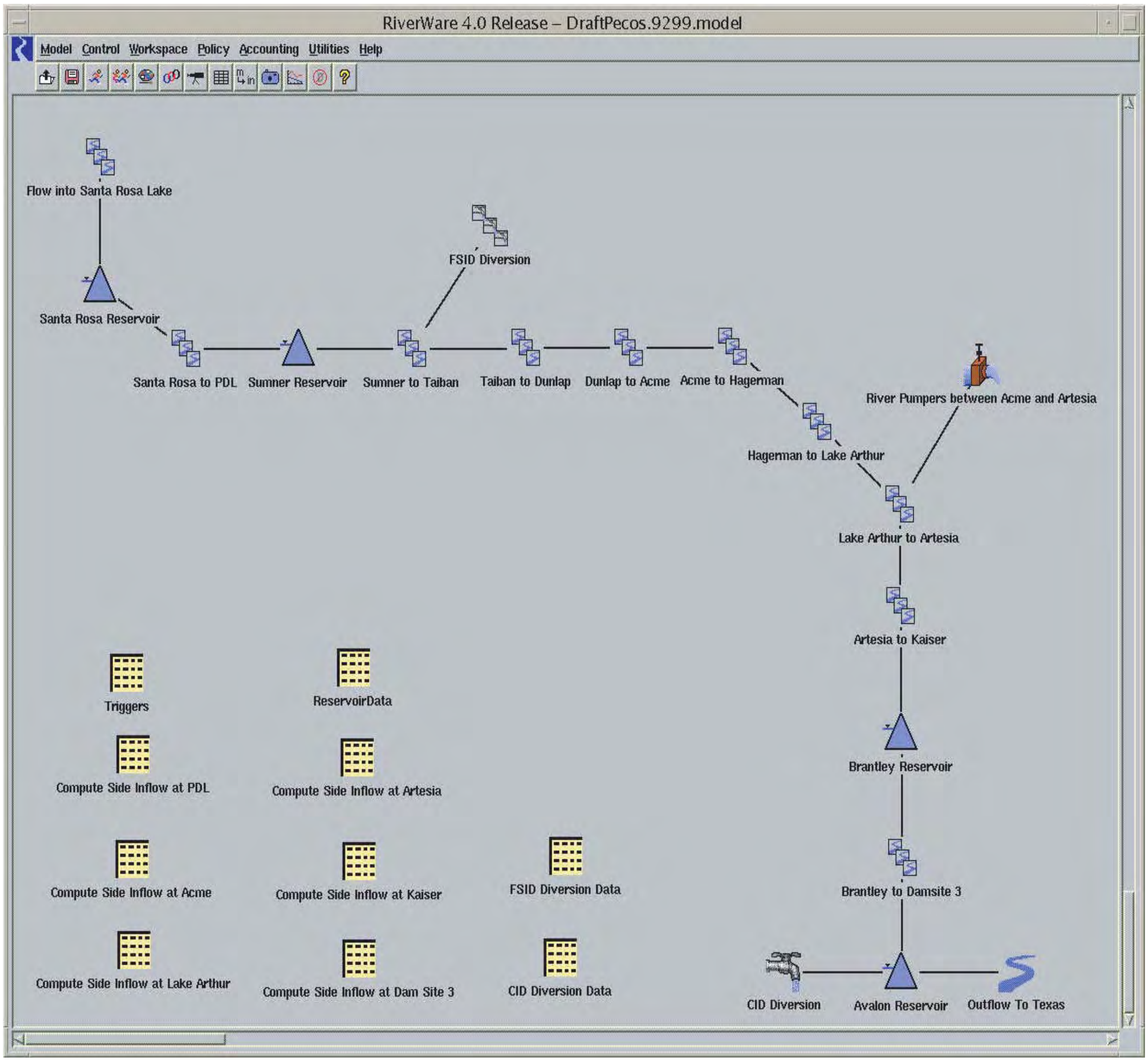
INTRODUCTION TO MODELING

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.

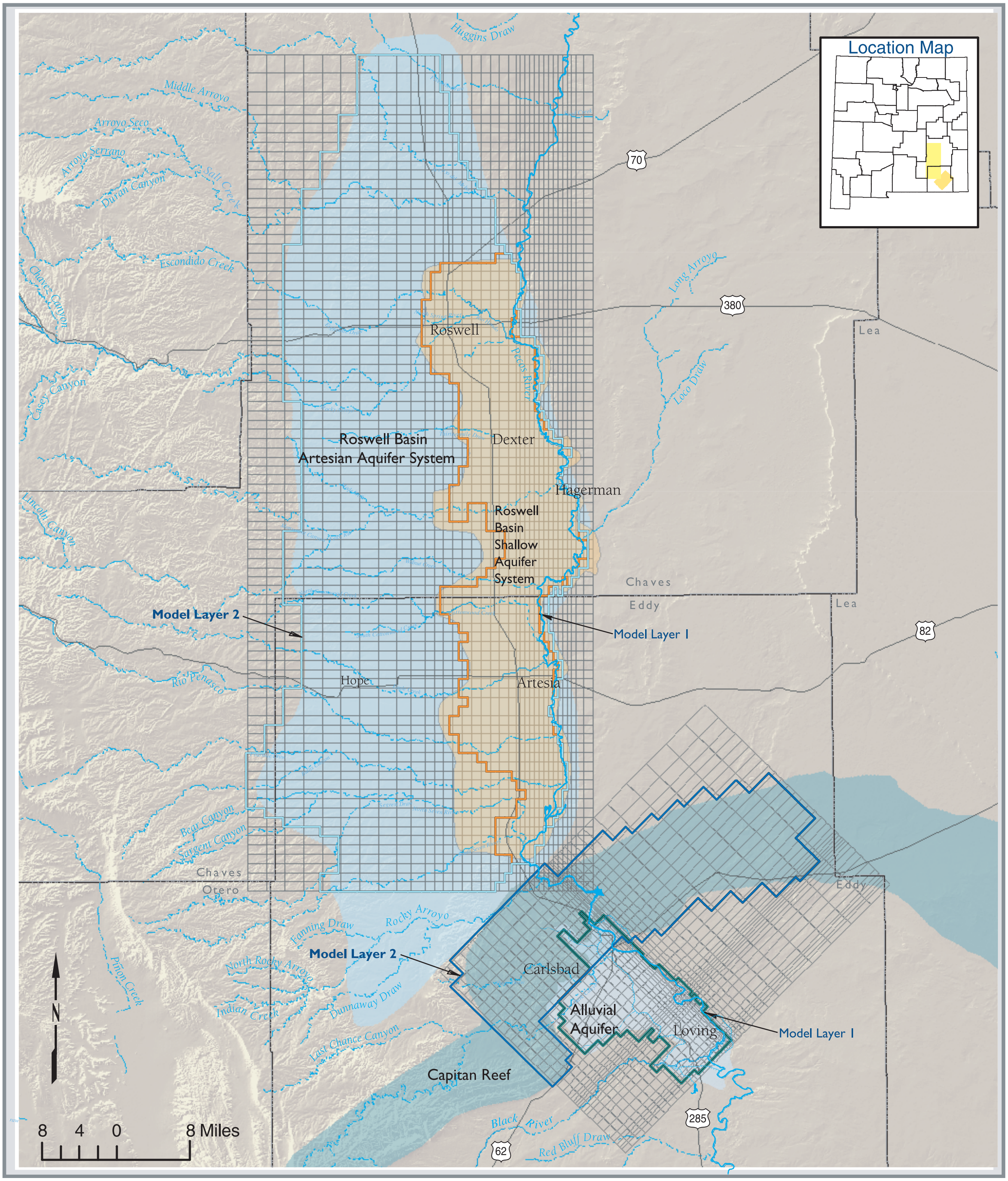
ROSWELL AND CARLSBAD GROUND WATER MODELS

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.

CHAPTER TWO

THE HISTORICAL AND LEGAL FRAMEWORK

DECISION-MAKERS
FIELD CONFERENCE 2003
The Lower Pecos Region

Raising the gates at Lake McMillan, ca. 1895.

The U.S. Supreme Court in an Original Jurisdiction Action *Texas v. New Mexico*, No. 65 Orig. (Pecos River)

John E. Thorson, *Attorney and Water Policy Consultant*

In 1948 New Mexico and Texas entered into the historic Pecos River Compact, and the negotiators were fully confident that the agreement would put conflicts between the states behind them. Only thirty years later, the states were before the U.S. Supreme Court to ascertain and enforce the meaning of the 1948 compact. Texas complained that New Mexico had failed to deliver all the water required by the compact. The Supreme Court eventually ruled in Texas's favor, requiring New Mexico to pay for past under-deliveries and issued a decree specifying New Mexico's obligations in the future.

THE PECOS RIVER COMPACT

After an unsuccessful attempt in 1925, New Mexico and Texas negotiated a compact in 1948 apportioning the Pecos River. The compact was approved by New Mexico and Texas in 1949 and ratified by Congress that same year. Although a water apportionment compact, the agreement is unusual in that it recognizes New Mexico's early uses but essentially guarantees Texas the same amount of water that it received in 1947 (the "1947 condition").

At least two major problems contributed to eventual litigation between the states over the compact. One problem is what has often been called the "failed critical assumption" underlying the compact. New Mexico was unduly optimistic about how much water could be salvaged by eliminating water-thirsty salt cedar from riparian areas. Between 1967 and 1975 the U.S. Bureau of Reclamation root-plowed 19,000 acres of salt cedar in the Acme-Artesia reach of the river, but there was no measurable increase in base flow attributable to the eradication program.

A second problem of the compact was its reliance on an "inflow-outflow" methodology that had been developed by an engineering committee at the time of the compact. In simplest terms, the methodology used water data records from 1919 forward to correlate river flows near Alamogordo Dam (now renamed Fort Sumner Dam) to river outflow at the New Mexico state line. This correlation became known as Plate No. 2, Senate Document 109, and was used by compact administrators (along with other provisions of an

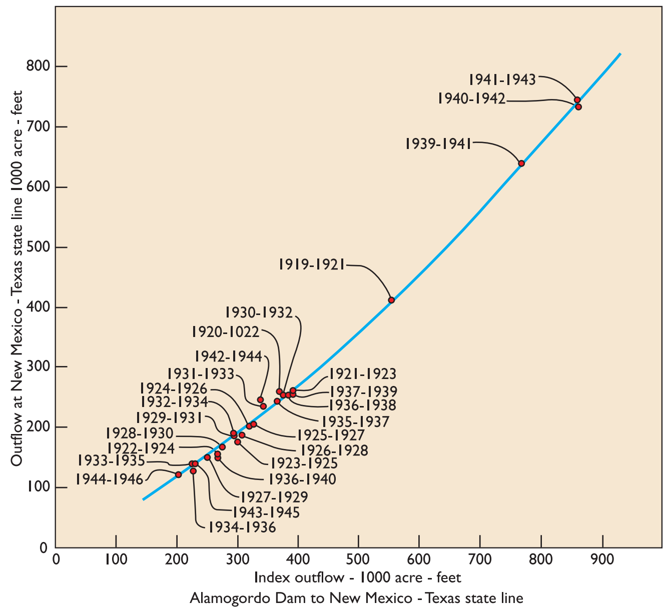


Plate No. 2 from the original Pecos River Compact, plotting inflow at Alamogordo Dam against mandatory outflow at the New Mexico–Texas state line.

inflow-outflow manual) to determine New Mexico's annual water delivery obligation under the compact.

Unfortunately, the inflow-outflow correlation was erroneous, "[f]or it became clear . . . ," in the words of the U.S. Supreme Court, that "state-line flows were significantly below the amount that one would have predicted on the basis of the inflow-outflow manual, with no obvious change in either natural conditions along the river or in man's activities."

MAJOR LITIGATION EVENTS IN *TEXAS V. NEW MEXICO*

New Mexico and Texas bickered for years over the meaning and implementation of the "1947 condition," as used in the compact. Finally, Texas sought the U.S. Supreme Court's permission to commence an "original jurisdiction action." In 1975 the Supreme Court allowed Texas to file its complaint against New Mexico and appointed a Special Master.

After initial proceedings before the Pecos Special Master, the Supreme Court in 1980 affirmed the

Special Master's interpretation of the "1947 condition" (Article III(a) of the compact) to mean depletions due to New Mexico water uses that were in place in 1947, along with certain projected uses.

In 1987 the U.S. Supreme Court adopted the Special Master's calculation of a 340,100 acre-feet shortfall (for years 1950–83) and suggested that New Mexico repay the deficit over ten years with "water interest" for any bad-faith failure to deliver these additional amounts. At the same time, the Court entered the original decree and made certain provisions for its enforcement. New Mexico was ordered to comply with Article III(a) of the compact and to deliver water each year in an amount calculated according to the Texas version of the "inflow-outflow" equation. The Court also suggested that its decree might be modified once the river is better understood.

The Supreme Court entered an Amended Decree in 1988, as recommended by the Special Master, appointing a River Master, adopting the Pecos River Master's Manual (originally Texas trial exhibit no. 108), and specifying a water accounting procedure for verifying state-line water deliveries. Neil S. Grigg, a West Point civil engineer serving on the faculty of Colorado State University, was appointed as River Master. He continues to serve in this position.

In 1989 the Special Master conducted hearings on Texas's remedy. Three potential remedies were available to Texas: (1) specific performance, that is, the repayment of actual water; (2) monetary damages based on New Mexico's economic gain as the result of the under-deliveries; or (3) monetary damages based on Texas's economic loss as the result of the under-deliveries. A recovery in water would have meant an additional delivery obligation of 38,500 acre-feet per year for ten years—on top of New Mexico's average delivery obligation of 80,000 to 90,000 acre-feet per year. Although Texas argued for water, its actual aim appeared to be the recovery of the $1 billion claimed to be New Mexico's illicit gain. Texas also offered evidence that its farmers had lost $51 million in profits because of under-deliveries.

New Mexico countered these arguments with expert testimony that a water remedy would be extremely wasteful since, over the ten-year period of deliveries, Texas farmers would gain by $2.5 million but New Mexico would lose $85 million. New Mexico argued that a monetary remedy calculated on its gain would be appropriate only if New Mexico had been guilty of bad faith in withholding water. New Mexico's experts also testified that Texas farmers would have made only $8 million in additional profits with the water under-delivered over thirty-five years.

The states eventually reached a settlement, approved by the Supreme Court in 1990. New Mexico agreed to pay $14 million for past compact violations. Although the Court retained jurisdiction, the case was essentially over. As one of New Mexico's attorneys remarked shortly thereafter, "I think we won." Since 1991 little has happened before the Supreme Court.

ENFORCEMENT OF *TEXAS V. NEW MEXICO* AMENDED DECREE

The Supreme Court's Amended Decree (1988) provides a detailed water-accounting procedure for monitoring and verifying whether New Mexico has satisfied its obligations under the compact and the decree. The River Master supervises the process. The basic verification of state-line water deliveries is a three-year process:

1 Calendar Year 1 (Water Year)—Water is delivered to Texas at the state line.
2 Calendar Year 2 (Accounting Year)—River Master determines whether deliveries during Calendar Year 1 satisfied New Mexico's Art. III(a) obligation. If New Mexico has satisfied its delivery obligation for Calendar Year 1, the monitoring process for that year is complete. If New Mexico has under-delivered, the process extends into a third year, pursuant to an approved plan adopted by the River Master.
3 Calendar Year 3 (Compliance Year)—Before March 31, New Mexico must have complied with an Approved Plan to remedy any shortfall.

Recent Deliveries The compact and the Amended Decree provide that New Mexico must deliver to Texas approximately 45 percent of the flows past Alamogordo Dam (now Fort Sumner Dam) plus flood inflows between Alamogordo Reservoir (Sumner Lake) and the state line. From 1987 through 2000, New Mexico had maintained a positive balance in deliveries to Texas and had a cushion of more than 10,000 acre-feet going into water year 2001. Unfortunately, New Mexico under-delivered for five of these fourteen years and had razor-thin positive margins for three other years. Much of the accumulated credit results from large net deliveries in 1988 and 1992. The river is highly variable, year to year, but the recent trend does not favor New Mexico.

Proceedings In the Event of a Shortfall If New Mexico delivers all the water that was due in Calendar Year 1 by March 31 of Calendar Year 3, then any issue concerning under-deliveries during Calendar Year 1 is put to rest. Of course, each calendar year commences a separate two- or three-year cycle of monitoring and compliance, and phases from separate years overlap.

New Mexico may not be able to deliver all the water that was due in the previous year. Under the Supreme Court's Amended Decree, New Mexico does not have to deliver sufficient water in all instances to meet the previous shortfall. Before March 31 of Calendar Year 3, New Mexico only must comply with the River Master's Approved Plan to remedy the shortfall—*whether or not sufficient water is actually delivered under the plan.*

Subsequent Proceedings It is uncertain how the Supreme Court will proceed if the River Master files a Compliance Report indicating New Mexico's noncompliance. Will the Court resolve any such motion based solely on the Compliance Report, and pleadings in response to the report, or appoint a new Special Master to conduct additional proceedings? Note that the Supreme Court has indicated it will give great deference to the River Master's determinations. The River Master's final determinations concerning the Final Report (accounting), Approved Plan, and Compliance Report will be subject to review by the Court only on a showing that the Master's determination was "clearly erroneous."

Decree Provisions of Texas v. New Mexico The Amended Decree in *Texas v. New Mexico* establishes the required state line deliveries as the senior right on the Pecos River system (with the possible exception of "federal regulatory water rights" under the Endangered Species Act). Additionally, the Pecos River Compact requires "in maintaining the flows at the New Mexico–Texas state line . . . New Mexico shall in all instances apply the principle of prior appropriation within New Mexico." This requirement for intrastate priority apportionment is New Mexico law by virtue of the State's ratification of the compact. This requirement is also federal law by virtue of the Law of the Union Doctrine—i.e., Congress's approval of the compact.

FUTILE CALL

In addition to the general reluctance of many states to strictly enforce priorities, there are exceptions to strict priority administration. For example, a priority call to curtail upstream junior uses is "futile" if water will not reach a senior's diversion because of channel losses or evaporation.

The leading futile call case is *State ex rel. Cary v. Cochran*, decided by the Nebraska Supreme Court in 1940. The court indicated that a senior call on the Platte River would be futile where upstream juniors would cease to divert 700 cubic feet per second (cfs) to deliver 162 cfs to a downstream senior. The court indicated, however, that priorities will be enforced so long as water can be delivered in "usable quantities" to the senior. "Usable quantities" is a complicated factual issue, and the determinations of water administrators will be upheld unless unreasonable or arbitrary.

A variation of the futile doctrine is sometimes applied to ground water use when junior pumpers reduce the water table out of reach of the senior appropriator's well. Must all junior pumping cease in deference to the senior who may have a shallow well? Some state courts have held that the senior with an unreasonably shallow well cannot prevent the utilization of an aquifer by others. In Colorado "[t]he appropriate remedy may not be curtailment of well withdrawals. Rather, it may involve other management tools; for example, adjustment between users of the cost of drilling deeper wells . . . or the [responsible agency] may fashion additional management criteria."

The U.S. Supreme Court has also recognized the futile call doctrine where the call on the river by a downstream state would be futile. In *Washington v. Oregon* (1936), concerning the Walla Walla River, an original action was dismissed upon the Special Master's finding that Oregon's upstream diversions did not materially reduce water available to the Washington user. Washington had also failed to demonstrate by clear and convincing evidence that the injury would be of a serious magnitude.

In *Texas v. New Mexico*, New Mexico could attempt to invoke the futile call doctrine in proceedings before the River Master preceding the Approved Plan and Compliance Report, or later before the U.S. Supreme Court. Futility may be difficult and expensive to prove. New Mexico's evidence developed in 1988–89 for the remedies phase before the Special Master may provide the basis for this interstate, futile call defense. As one of New Mexico's attorneys at the time summarized:

> *There are three fundamental problems with irrigation down in the Red Bluff District [of Texas]. . . . The first problem is carriage losses. If you start with 10,000 acre-feet at the state line, by the time you divert it into the Red Bluff irrigation canals you are left with about 6,000 acre-feet. By the time that water gets to the farmers' headgates, you are left with 3,000 acre-feet of water. Thus, you have a 70% carriage loss from the state line to the farms. . . .*
>
> *The second fundamental problem . . . is salinity. There is a place in the river south of Carlsbad called*

> *the Malaga Bend, where there is a lot of brine accretions. . . . The average salinity of the water that Texas could have expected to receive, even had New Mexico delivered the extra water, would have been around 7,000 ppm. During some of the years between 1950 and 1986, Red Bluff would have received water with a salinity of twenty tons per acre-foot.*
>
> *[T]he third problem the Red Bluff District faces is the extreme variability in flows of the Pecos River. . . . exacerbated . . . by the fact that the Red Bluff Dam . . . has never been used to even out the flows of the river in Texas. . . .*
>
> *The bottom line was, faced with these natural problems, the Texas farmer never could make much of a profit from Pecos water. . . .*

NEW MEXICO'S OPTIONS

If New Mexico under-delivers Pecos River water to Texas in 2003 or subsequent years, it has options for reducing water use in New Mexico and also options concerning its relationship with Texas. Some of these have been tried in the past, and others are currently being pursued by the state engineer and Interstate Stream Commission.

Intrastate Options Elsewhere in this guidebook are articles that address in some detail the "consensus plan" developed in tough, extended negotiations by an ad hoc committee of Pecos Valley stake holders, all of whom had a great deal to lose if they failed to devise a viable plan. If this plan can be fully implemented, it holds promise of assuring compact-mandated water deliveries in the future.

Alternatively, New Mexico might opt to employ strict priority administration to prevent or make up a shortfall under the compact, though this would be socially disruptive and politically unpopular. The New Mexico legislature may strengthen the State's ability to enforce priorities by adopting more detailed priority administration rules, similar to those in Colorado. Indeed, the state engineer may be able to promulgate such a set of rules under his existing authority:

> *The state engineer may adopt regulations and codes to implement and enforce any provision of any law administered by him and may issue orders necessary to implement his decisions and to aid him in the accomplishment of his duties. In order to accomplish its purposes, this provision is to be liberally construed.*

The acquisition of water rights by eminent domain is another possibility. The New Mexico Supreme Court has recognized that the Interstate Stream Commission can exercise eminent domain in order to satisfy interstate water obligations.

Interstate Options New Mexico has both legal and negotiating options for approaching Texas. The strongest legal defense, in submissions and argument both before the River Master and the Supreme Court, may well be the futile call doctrine, as previously discussed.

New Mexico may also attempt to negotiate "interest-based" solutions with Texas that might have less serious consequences for New Mexico. At a minimum, an early negotiated agreement might avoid legal expenses, delay, and the risk and uncertainties associated with a multi-year legal proceeding. For instance, if New Mexico anticipates a shortfall, it might negotiate in advance a liquidated damage amount (per acre-foot of water or per acre of irrigated land) for Texas users. The State might lease or buy-out Texas users with a corresponding adjustment to the compact and Amended Decree. New Mexico might acquire supplemental water in Texas for Texas users at less cost than would be required to augment flows in New Mexico. New Mexico might pay for improved means of diversion in Texas. New Mexico might negotiate other forms of consideration, such as increased deliveries on other interstate river systems or apply any credits on other river systems, although this would be complex and controversial.

CONCLUSIONS AND RECOMMENDATIONS

A period of more than fifteen years has passed since the U.S. Supreme Court ruled that New Mexico had under-delivered 340,100 acre-feet of water under the Pecos River Compact and adopted procedures to prevent shortfalls in the future. New Mexico has undertaken a continuous program to prevent such shortfalls, but recent conditions indicate that the margin between compliance and noncompliance with the Court's decree is very thin—especially in dry years.

In fashioning policies for water management in the Pecos River system, New Mexico decision makers should candidly recognize that:

- **The problem has not been solved—**Despite many efforts, recurring chronic Pecos River water shortages have bedeviled New Mexico since the 1948 compact. And, importantly, the consensus plan, although promising, is far from being implemented.

- **Delay and denial are not options—**River management is now more difficult because of the Endangered Species Act and other developments. New Mexico should proceed deliberately and expeditiously in an attempt to avoid a shortfall or to mitigate it if it occurs.
- **New Mexico should encourage cooperative measures with Texas—**Although the dispute has a long history, there are many newcomers to positions of responsibility in both states who may take a fresh view of these issues. The states might agree on a mediator to facilitate discussions concerning any shortfall and mitigation measures. New Mexico and Texas will be neighbors for a long time.

The Endangered Species Act

Gary L. Dean, *U.S. Bureau of Reclamation*

This year marks the thirtieth anniversary of the Endangered Species Act. Signed into law by President Richard M. Nixon on December 28, 1973, the act is the consequence of almost three-quarters of a century of federal legislation identifying, conserving, and protecting our nation's natural heritage. President Nixon said of the act when he signed it, "Nothing is more priceless and more worthy of preservation than the rich array of animal life with which our country has been blessed."

For more than a quarter of a century, it has been the sentinel for endangered species. More than 515 recovery plans presently exist, but only a dozen or so species have recovered sufficiently to be removed from the list of endangered species since the law was passed. However, success is not measured only in the full recovery of a listed species. The strength of the law lies in its ability to prevent an individual, group, corporation, or agency from jeopardizing the continued existence of a listed species, or from destroying or adversely modifying its designated critical habitat. The act promotes the conservation of threatened and endangered plants and animals and their habitats.

The Endangered Species Act has endured thirty years of criticisms and repeated attempts to repeal or amend it. Few other acts have elicited such a wide range of emotions, especially here in the West. The western United States has the greatest diversity of endangered species. Of the more than 1,200 nationally listed plant and animal species, 796 species are found in the western United States, including Hawaii and Alaska. Hawaii alone accounts for 36 percent of these species.

Species evolve over time and become adapted to their habitats. Each occupies a niche, reducing competition with other species by becoming specialized to a particular resource or by utilizing a specific space. This is known as resource partitioning. Those species threatened by changing conditions or displaced from their habitat by more generalized species risk extinction. By 2002, 639 species of plants, fish, and wildlife had been classified as extinct in the United States. Whereas more than half of this number have been recorded within the last 50 years, it is not clear whether this apparent escalation is a result of some environmental condition or are species only recently recognized as endangered in the species listing process. Humans factor prominently in the ever-changing conditions of those resources. We are one of only a handful of species that can modify the environment to suit our needs. Can conservation of resources vital to other species be achieved without putting our nation's population at social, cultural, or economic risk? And if we fail, don't we ultimately still run the same risk of extinction ourselves? These sorts of questions continue to be at the center of the Endangered Species Act and are debated on every front.

HISTORY

When settlers first occupied portions of the Southwest—and in particular, the arid plains of southeastern New Mexico in the 1870s—they felt that the area was more suitable for livestock grazing than for agriculture. Large ranches occupied thousands of acres. Stock water was among the first water rights appropriated in this area. Competition among claimants became fierce, and turf battles over range and water ensued. The most notable battle in this area was the Lincoln County Range War, which, in spite of its name, had less to do with the range than it did with the competition of business. The most prominent character of this period was Pat Garrett, the Lincoln County Sheriff who shot and killed Billy the Kid in 1881. Garrett retired to his 1,800 acre ranch near Roswell, where he promoted irrigation and farming in eastern New Mexico, a notion allegedly planted there years before by his one-time friend, Billy the Kid.

This was a time of discovery across the West. Trails and railways were established. Naturalists accompanied surveyors and geologists who were attached to parties searching for alternative railroad routes throughout the West or associated with boundary surveys. Army officers recorded and reported the details of naturalists' collections of new plant and animal species, but the concept of "endangered species" simply didn't exist.

In the 1880s conservation objectives began to align with the need of the people. The need for dams and larger irrigation ditches to hold and convey water was important for stock water and irrigation. The conservation movement grew out of the firsthand experience of political leaders with the problems of western eco-

The Pecos bluntnose shiner.

nomic growth, especially western water development. The federal government created agencies to aid and oversee water development projects in the interest of the public and its growing need to conserve vital resources in the West. Dams were built on many waterways to store and increase the precious supply of water for the benefit of agriculture.

The efficient development of water resources presented many opportunities, especially for wildlife. Habitat diversity for both aquatic and terrestrial species began to increase. Popular game species such as brown trout, yellow perch, and largemouth bass were introduced by the U.S. Fish Commission in New Mexico as early as 1883. The development and management of game and fisheries would be an added feature. Fish and wildlife were considered common property. The earliest known regulations were game laws created by states or territories. New Mexico created some of its own conservation regulations. For instance, it was illegal to take fish with poison, drugs, explosives, or by artificial obstructions; operators of mills or factories were forbidden to discharge sawdust or other wastes into open waters. Other laws would follow through the turn of the century. By the 1900s many of these regulations had passed into federal law.

The first federal act of its kind was the Lacy Act of 1900, which prohibited interstate commerce of animals killed in violation of state game laws. The Migratory Bird Treaty Act of 1918 and the Black Bass Act of 1926 prohibited persons from (among other actions) taking, capturing, killing, possessing, disturbing, and transporting across (into or out of) state or national borders any species protected by the one of these acts. Presently there are over 800 migratory species of birds listed under the Migratory Bird Treaty Act. Even the accidental killing of one of these birds can carry criminal penalties.

In 1966 the first of the true endangered species acts appeared. The Endangered Species Preservation Act of 1966 provided that the Secretary of the Interior could acquire land for habitat protection and identify species that were threatened with extinction. It required the secretary to create a list of species that were threatened with extinction. In 1969 the Endangered Species Conservation Act replaced the Endangered Species Preservation Act of 1966. This act directed the Secretary of the Interior to prohibit the importation of listed fish and wildlife species and subspecies that faced extinction. Many point to this as the beginning of the environmental movement, which emerged from a groundswell of popular demand for conservation from sovereign government practitioners. Other environmental legislation, including the Clean Air Act (1963), the Clean Water Act (1972), and the National Environmental Policy Act (NEPA, 1969), stressed only the quality of the human environment.

With the Endangered Species Act of 1973, Congress held that various species of fish, wildlife, and plants in the United States had been rendered extinct as a consequence of economic growth and development untempered by adequate concern and conservation. Listed species were considered of “aesthetic, ecological, educational, historical, recreational, and scientific value to the Nation and its people.” The act has undergone several amendments further defining its authorities and setting scientific policy guidelines. Indeed, the Endangered Species Act has become the most powerful tool of this nation's environmental and wildlife protection toolbox.

In the Southwest a great number of species are listed under the Endangered Species Act. In New Mexico alone there are 54 federally listed species and 118 state listed species. In 1989 a federally threatened subspecies, the Pecos bluntnose shiner (*Notropis simus pecosensis*), was brought to the forefront of endangered species issues in New Mexico, just two years after its listing. The U.S. Bureau of Reclamation had just constructed one of the last major dams of the late twentieth century: Brantley Dam, just north of Carlsbad. In order to test the safety of the dam, the Bureau of Reclamation moved water from two upstream reservoirs to fill Brantley Lake. Placing almost the entire year's storage of water in Brantley Lake early in the season left little water in the two upstream reservoirs to make further deliveries for the rest of the year. This action prompted the U.S. Fish and Wildlife Service to contact the Bureau of Reclamation regarding probable impacts to the Pecos bluntnose shiner. The Bureau of Reclamation consulted with the Fish and Wildlife Service, under Section 7 of the Endangered Species Act, over the effect of dam operations on the federally threatened shiner.

The consultation resulted in a Jeopardy Opinion, a decision by the Fish and Wildlife Service that concluded that the proposed action jeopardized the Pecos bluntnose shiner and modified its critical habitat. The Fish and Wildlife Service directed the Bureau of Reclamation to fund a five-year scientific study to determine the biologic and hydrologic needs of the Pecos bluntnose shiner. Studies by the Fish and Wildlife Service and the New Mexico Department of Game and Fish over a five-year period were completed in 1997. The results of these studies prompted a change in the way dam operations should be run in the future.

High-volume, extended releases (known as block releases) were a detriment to the Pecos bluntnose shiner. Eggs and larvae were being pushed farther downstream into unsuitable habitats, such as deep confined channels and the large impounded water of Brantley Lake. Low flows or no flows between block releases left fish with diminished habitats or in isolated pools, where they might be subject to predators or left to die as pools dried. Coarse-grained sediments were trapped behind the dams, whereas fine-grained sediments such as clays went downstream to armor the banks, thus reducing the wide, braided, and sandy channels that created much needed habitats for the shiner, and allowing highly invasive plant species such as the tamarisk (salt cedar) to further narrow and stabilize the banks.

IMPLICATIONS FOR PECOS RIVER OPERATIONS AND MANAGEMENT

The problems of the Pecos River are only a few of similar problems facing many native fish species of New Mexico. It is a challenge to all New Mexicans to think harder about the state's finite resources and how they should be managed. Can we live with the Endangered Species Act? Or, perhaps more importantly, how would we fare without the Endangered Species Act? Will the Pecos bluntnose shiner still be here in years to come? Will our farmers still be here? We now stand at a crossroads.

There is room for both the shiner and the farmers, but it will take reasoning, compromise, and understanding on the part of everyone involved. Albert Einstein gave us this basic premise over 60 years ago and it still holds true: "We live in a world of problems that can no longer be solved by the level of thinking that created them." At the time this was written, state and regional decision makers had agreed on plans regarding the future of the Pecos River, but plan implementation had yet to begin. However, managers, scientists, and farmers have invested great energy and a lot of time in their search for the best answers to the intense problems of the region. If our level of thinking has matured since the days of taming the West, then it will be time well invested.

SUGGESTED READING

Fugate, F. L. and Fugate, R. B., 1989, Roadside history of New Mexico. Fifth Printing, March 1997: Mountain Press Publishing Company, Missoula, 483 pp.

Hufstetler & Johnson, 1993. The Turbulent History of the CID, Watering the Land: National Park Service, Rocky Mountain Region, Division of National Preservation Programs, 180 pp.

Sublette, J. E., Hatch, M. D., and Sublette, M., 1990. The Fishes of New Mexico: University of New Mexico Press, Albuquerque, 408 pp..

Irrigation Districts in New Mexico: A Legal Overview of Their Role and Function

John W. Utton, *Sheehan, Sheehan & Stelzner, P.A.*

In New Mexico, as in other western states, irrigation districts were created to take advantage of federal reclamation law. Forces converged at the end of the nineteenth century to support the creation of a federal role in the development of western water. First, the public land laws of the nineteenth century did not work; land and water monopoly scandals abounded. Second, there was a decade of drought that began in 1886. The third factor was the political philosophies and common sense of John Wesley Powell. Powell was a political philosopher who proposed a whole new system of government for the arid region based upon the nature of the arid West rather than upon the standard preconceptions of distant legislators. To Powell, western water control was a national issue that required a federal presence. With Theodore Roosevelt's election, there was presidential support for a program of federal dam and reservoir building. The June 17, 1902, Reclamation Act was the result.

The Reclamation Act promised farmers water storage and distribution systems of a massive size at federally subsidized, interest-free rates. In order to take advantage of this federal program, local organizations had to be established. Irrigation districts were created with the sole purpose of delivering irrigation water to their members. Some irrigation districts have since evolved to also provide hydroelectric power generation, operation of recreational facilities, drainage, flood control, sanitation, and municipal and industrial water supply. All of the seventeen contiguous western states have adopted irrigation district laws, although some are called water conservation, water improvement, or reclamation districts.

On the Pecos River there are two irrigation districts: the Carlsbad Irrigation District (CID) and the Fort Sumner Irrigation District (FSID). CID operates the Carlsbad Project under contract with the U.S. Bureau of Reclamation. FSID is not a federal reclamation project, but obtained funds from the Bureau of Reclamation for reconstruction of its diversion dam. The other large irrigation entity is the Pecos Valley Artesian Conservancy District (PVACD), which is a ground water irrigation district that is also not part of a federal project. Under state law, all three districts are political subdivisions of the state.

Irrigation districts in southeast New Mexico.

LAW OF IRRIGATION DISTRICTS

The New Mexico statutes (NMSA 1978, chap. 73 arts. 9-11) provide for the creation and operation of irrigation districts. Article 9 applies to irrigation districts in general, whereas Articles 10 and 11 apply to irrigation districts cooperating with the United States under reclamation laws. Because both CID and FSID have entered into contracts with the Bureau of Reclamation, both are considered irrigation districts cooperating with the United States.

In general, irrigation districts are created by petition when a majority of resident landowners owning more than one-half of the lands within a proposed irrigation district sign a petition for the creation of an irrigation district and file the petition with the Board of County

Commissioners. After public notice, the Board of County Commissioners establishes the boundaries of the irrigation district and holds an election for the district's board of directors. After the initial election, one new board member is elected each year. After the initial three-year period, board members serve offset terms of three years.

The board of directors has the power and the duty to manage and conduct the affairs and business of the district; to enter into contracts; to employ agents, attorneys, and employees and prescribe their duties; and to establish rules and regulations for the distribution and use of water within the district. The board has the power to construct, acquire, or purchase canals, ditches, reservoirs, reservoir sites, water, water rights, rights-of-way, or other property necessary for the use of the district. The board has no authority to incur debt or liability beyond the express provisions of the act, and such debt or liability is absolutely void.

The board has the power to distribute and otherwise manage the district's water. It must distribute water on a *pro rata* basis to each landowner, based on the lands assessed under the act. The board may also lease or rent water to occupants of other lands within or outside the district for not less than one and one-half times the amount of the district's assessment tax. The board also has the power to initiate suits in order to protect or preserve its rights under the act.

Article 10 of New Mexico's irrigation district statutes provides a statutory scheme for irrigation districts to collaborate or "cooperate" with the federal government for funding, operation, and management of an irrigation project. Such collaboration is often necessary because the federal government provides long-term, low- or no-interest loans for the construction, maintenance, and operation of irrigation projects. Without this federal assistance, many large irrigation projects simply would not be possible; the capital needed cannot be raised at the local or state level. Pre-existing irrigation works can be included in a federal project upon signed consent of four-fifths of the owners of the existing works as filed with the Board of County Commissioners.

Regarding the applicability of federal law to federal reclamation projects, the statute reads: "[A]ll water, the right to use of which is acquired by the district under any contract with the United States, shall be distributed and apportioned by the district in accordance with the acts of congress and rules and regulations of the secretary of the interior, and the provisions of said contract in relation thereto." (chap. 73, arts. 10–16.) From this, it appears that water rights obtained independently from a federal contract would not have to be distributed and apportioned in accordance with federal law but, rather, in accordance with state law, which calls for distribution as the board judges to be in the best interest of all parties concerned. This statute also preserves prior water rights, prohibiting the diversion of water that would be detrimental to a prior right.

Concerning property ownership, Article 10 provides that all property acquired under this act shall immediately vest in the irrigation district. There is a proviso, however, that an irrigation district may convey property to the United States insofar as needed for the construction, operation, and maintenance of works by the United States pursuant to a contract with the United States.

With respect to land and water management, Article 13 provides authority for cooperating districts to acquire and deal in land and water rights in the name of the district and for the use of the district. It also allows the board of directors, upon application of a landowner or upon its own motion, to transfer water rights from lands within the district that are not suitable for irrigation to lands that may be profitably and advantageously irrigated. And it includes notice provisions for water transfers as well as an opportunity for protest and an opportunity for a hearing. The transfer of water is generally thought to be within the sole authority of the state engineer. Surprisingly, however, the state engineer's authority over transfers of water within a cooperating irrigation district is limited. The district, however, is required to notify the state engineer after such transfers.

LAW OF ARTESIAN CONSERVANCY DISTRICTS

Artesian waters are ground waters that are under pressure in an aquifer, typically under enough pressure to bring the water to the surface if the aquifer is penetrated by wells. New Mexico provides by statute for the formation of artesian conservancy districts for the purpose of conserving the waters of any artesian basin within the state whose boundaries have been scientifically determined and whose waters have been beneficially appropriated for private, public, domestic, commercial, irrigation, or other purposes. This law was enacted to authorize the formation of PVACD in the Roswell artesian basin.

An artesian conservancy district may be formed when one-third of the landowners of the lands to be embraced by the district petition the district court for formation, setting forth the proposed name of the district, the purpose or purposes of the district, the lands to be encompassed by the district, and the benefits that the lands of the district will receive as a result of its formation. After public notice, the opportunity to file objections, and a hearing, the district court will determine whether the district should be organized and, if so, will issue a declaration to that effect.

Upon declaration of the court that the district has been organized, the district becomes a political subdivision of the state and a body corporate with all the powers of a public or municipal corporation. The district's board of directors is vested with the power and authority to carry out the provisions and purposes of the Artesian Conservancy Act. This includes the authority to levy assessments against property, based on the net taxable value of the property, to generate revenue to pay for costs of improvements within the district.

Underground waters not under artesian pressure may also be included in artesian conservancy districts if the boundaries of the underground basins have been reasonably ascertained, the waters are being beneficially used, a substantial portion of the ground water is derived from the artesian basin, and the underground and artesian waters are so closely related that the artesian district can effectively conserve the ground water. The artesian conservancy district's board of directors must determine by resolution that it is desirable to include non-artesian ground water within the artesian conservancy district, and then petition the court to amend the decree to include such waters.

OWNERSHIP OF WATER RIGHTS WITHIN CID

The ownership of water and interests in water has become a significant debate, arising in the context of stream adjudications and federal reclamation projects. Analysis of the federal authority and responsibility over federal reclamation projects involves an analysis of the relationships in the project between the landowners who use the water, the irrigation districts that represent landowners in the management of the project, and the federal government that provides initial project funding and management. These relationships are established and influenced by a complex system of federal law, state law, interstate compacts, and contracts.

The Fifth Judicial District of New Mexico has recently addressed the water ownership question as a threshold issue in the ongoing *Lewis* adjudication. This adjudication involves a dispute over water rights within the Pecos River stream system. Water rights are claimed by landowners and by the United States. The United States claimed water rights ownership by conveyance from the Pecos Irrigation District and by appropriating rights under NMSA 1978 chap. 72, arts. 5–33. The threshold issue before the Fifth Judicial District was whether project water rights were rights of the United States or rights of the district members. Relying primarily on the Washington State case of *Dept. of Ecology v. Acquavella* and the New Mexico decision *Holguin v. Elephant Butte Irrigation District*, the Pecos court found that "the beneficial ownership of Project water rights is vested in landowners in the Project measured by the amount of water devoted to beneficial use. Ownership of water rights in the Project are appurtenant to land in the Project upon which they are devoted to beneficial use. Project water rights are not owned by the United States or the CID."

It is important to note that, although finding that the United States had no interest in "water rights," the court did find that the United States and the CID have certain ownership rights and interests in the physical works and in diverting and storing water. The court characterized these governmental rights and interests as the authority to divert and appropriate water for the use and benefit of landowners pursuant to the Reclamation Act, and the right and interest in storage and distribution of project water to accomplish project purposes. The court stated that the "rights, interests, duties and obligations of the parties in connection with dams, reservoirs, storage and distribution facilities, and of the landowners to receive water therefrom are set forth in the agreements among the respective parties and New Mexico statutes pertaining thereto." In its reconsideration of the issue, the court left open the determination of what the government's precise ownership rights and interests are; however, the court was clear in determining that the government's rights are not water rights. Thus, the court followed long-established New Mexico law that vests water rights in the landowners who apply water to beneficial use.

SUGGESTED READING

Beck, Robert E., 1991, Water and Water Rights, Michie, 7 vols.

Clark, Ira G., 1987, Water in New Mexico—a history of its management and use: University of New Mexico Press.

Priority on the Pecos

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No western interstate compact is as deeply and explicitly committed to the idea of priority enforcement as the 1948 Pecos River Compact. No other interstate compact thus far has so explicitly required priority enforcement to make up for compact under-deliveries. And no other interstate compact has seen such a complex response to the problem of under-deliveries at the state line as the decade-long New Mexico efforts between 1990 and 2000 to meet possible compact shortfalls and the very recent 2001–2003 legislative solutions. The fact that the ultimate compact solutions range so far afield from the traditional notions of priority enforcement is one measure of how far interstate water law in general (and the Pecos River Compact in particular) has strayed, for better or worse, from its prior appropriation roots.

As a means of apportioning a scant and variable water supply among claimants, the notion that the oldest users get first access to the available supply of water is deeply engrained in the prior appropriation doctrine. But the principle that priority in time of the establishment of a water right gives the better right to water from a common source was firmly and explicitly established in the water codes adopted across the West at the turn of the twentieth century. Then, in New Mexico, the priority principle was added to the 1912 state constitution's provisions on water. All state-based water rights were subject to priority principle.

In theory at least, the constitutional principle of priority allowed a senior water right holder to call priority against a junior holder of a water right from the common source. Once appropriately called, the junior user could take no water until the senior claimant had received 100 percent of his supply. In the parlance of western water law, there was no sharing of shortages.

Of course, such a priority system required an established hierarchy of priorities on a stream system, so that all claimants knew indisputably where they stood with respect to each other. Such a system required the establishment of quantities to which each right was entitled, so that the claimants knew when there was not sufficient water from the common source to fulfill their right. Such a system also required a central administrator committed to priority enforcement.

Each of these critical factors in priority enforcement has been difficult to establish in New Mexico in general, and on the Pecos River in particular. The formal establishment of priorities and quantities for all Pecos River water rights claimants has been, to say the least, time consuming and elusive. The underlying suit to adjudicate all Pecos River water rights was filed in 1956, and today, almost fifty years later, it is still not complete. As more and more rights are adjudicated, more and more rights are metered, but neither the rights nor the sources are yet sufficiently measured to allow for system-wide allocations based on priority enforcement. And New Mexico state engineers have hardly devoted themselves to the priority principle. Under these circumstances, priority enforcement is difficult at best.

It is even more difficult on the Pecos River, for another even more important reason. Senior water rights on the Pecos River, principally in the Carlsbad reach of the river, are diverted from surface water sources. Junior water rights, principally in the Roswell reach of the river, are diverted from ground water sources. New Mexico has recognized for longer than any other western state that ground water sources and surface water sources are commonly interrelated, and nowhere more so than in the Acme–Artesia reach of the Pecos River. In the days before significant ground water development in the Roswell area in the early twentieth century, the Roswell artesian and shallow aquifers, a magnificent natural reservoir that collected water easily and yielded it more easily to wells, contributed a large amount of water to the base flow of the Pecos River. Wells tapping those aquifers reduced that ground water contribution in half by the mid-1930s. Continued ground water withdrawals would further reduce that contribution until it approached zero. Less base flow in the river meant less surface flow for the downstream Carlsbad Irrigation District, which held senior rights on the river. From the distance of an abstract legal system, it looked like a perfect situation for the priority mechanisms of New Mexico's prior appropriation system.

The problem was that ground water typically doesn't behave in a way that allows for reasonable priority enforcement. Efficient use of priority enforcement requires that when a junior right shuts down, the senior right receives the foregone water promptly. But when the junior water right is a ground water right, especially a well located some distance from an interconnected stream, it may take a very long time, sometimes years, for the foregone ground water to reach the river and the downstream senior irrigator. By then circumstances may have changed, the senior right holder may have too much (rather than too little) water, and the priority rationale collapses.

The lawyers have a name for such priority calls that will do no good: “futile calls.” The doctrine is pretty well established in western water law and fairly well developed in states like Colorado with active surface water priority enforcement. The doctrine has never taken hold in New Mexico, because New Mexico has seen such little priority enforcement of any kind. Even if priorities were enforced in New Mexico, it’s clear that the “futile call” doctrine would impose a major obstacle to shutting down junior Roswell wells to make up an under-delivery in state-line, compact-mandated water.

In addition, the general law of interstate compacts does not require priority enforcement within a state to meet interstate compact obligations. In the path-breaking 1938 *Hinderlider* case, the United States Supreme Court specifically held that compacting prior appropriation states did not have to rely on priority enforcement within their borders to make compact-mandated deliveries. The compacting states could agree on alternative systems, including in the case of the La Plata River Compact, rotating all of the water in the stream between the two states.

Why then is priority enforcement such an important factor in the administration of the Pecos River Compact? For one, it is still the law in New Mexico and the one constitutionally mandated method for apportioning a short supply between claimants to a common source. More importantly, priority enforcement, as a centerpiece of the doctrine of prior appropriation, is an explicit requirement of the 1948 Pecos River Compact itself. Article IX of the compact, a seemingly obscure and innocuous paragraph, provides:

> *In maintaining the flows at the New Mexico–Texas state line required by this compact, New Mexico shall in all instances apply the principle of prior appropriation within New Mexico.*

With this provision, the compact drafters meant to avoid the problem associated with the *Hinderlider* case; now the compact itself required New Mexico to enforce priorities to make up for compact shortfalls. Representatives of the Carlsbad Irrigation District (CID) at the final compact negotiations at Austin, Texas, in 1948 insisted on inserting the provision to protect the downstream, senior district rights from compact calls before the upstream, junior Roswell rights had contributed 100 percent of their junior entitlement.

Despite the provision in the compact and in basic New Mexico law, the chronically water-short CID always had trouble securing a full Pecos River supply. In 1976, as a parting shot, the retiring long-time head of the CID formally asked the state engineer to enforce Pecos River priorities for the benefit of an under-supplied CID. State Engineer Reynolds responded first by proposing what would become, 25 years later, a ground water augmentation plan for the Pecos River. When opposition surfaced, he insisted that the water rights of the system were not firmly enough established by adjudication to allow for priority enforcement.

The shortage problem became more acute in the late 1980s with the addition of interstate compact shortfalls to intrastate CID ones. A Supreme Court decree mandated that New Mexico provide, on average, an additional 10,000 acre-feet per year at the New Mexico–Texas state line. A literal reading of the compact’s Article IX would have required priority enforcement to make up for the water. Once again, in early 1990, State Engineer Reynolds called for augmentation wells in the Acme–Artesia reach of the river. Once again, Pecos River water interests balked. For awhile, priority enforcement looked like the only alternative.

State engineer experts told the state legislature that priority enforcement wouldn’t work because of the delayed effect of junior ground water wells on surface water supplies, and, even if it would, it would be an economic disaster for southeastern New Mexico. Combining hydrology and economics, the state experts showed that a compact-inspired priority call on the Pecos River might require New Mexico to shut down all water rights established after 1926, with a cost to New Mexico of billions of dollars. As an alternative, the State proposed to buy and retire water rights in the basin in order to provide additional compact-required flows at the state line.

The proposal went very much against the fundamental prior appropriation grain of New Mexico state law and Article IX of the compact. After all, junior water rights were by their very nature subject to the first call of senior rights; you didn’t pay to curtail them. But the State’s purchase-and-retirement plan had the obvious virtue of offering compensation for loss and of buying only from willing sellers.

The problem was that, without basin-wide agreement, there was no guarantee that the additional water would reach the New Mexico–Texas state line where it would count for compact purposes. Once again, part of the problem was the senior, chronically under supplied 25,000 acres within the CID. Water added to the Pecos River in the Acme–Artesia reach would be taken by the CID to provide the full supply that its priority guaranteed it, but that upstream uses had denied it. Without CID's consent and agreement, the new compact water wouldn't reach the compact state line.

For the first couple of years of the twenty-first century, state officials struggled with the problem. The 2002 state legislature extended the period and increased the appropriation for the Pecos River purchase program, but now attached a new condition: No funds could be expended unless the principal Pecos River water users first agreed on a system that would get the additional compact water to the state line. The state money provided part of the carrot attached to this stick. But Interstate Stream Commission officials had an even more important tool for settlement: priority enforcement itself. If the entities did not agree, then the State would have to enforce formal priorities with the disastrous impacts predicted since the early 1990s. Priority enforcement had switched from a centerpiece of New Mexico state and federal Pecos River Compact law to a threat whose consequences should be avoided at any cost.

Dressed in these new clothes, priority enforcement finally worked. The Pecos River institutions that had fought over the river for the better part of the twentieth century finally agreed to a complex solution in early 2003. The agreement allocated land to be purchased by the State among the competing areas of the river. The agreement also allowed purchased water to reach the compact-critical state line. Most importantly, however, from the point of view of priority principles, the agreement provided for the augmentation wells in the Roswell–Artesia reach that had been suggested since 1976. Now, in 2003, all the parties agreed that the Interstate Stream Commission could divert from state-owned augmentation wells as much as 100,000 acre-feet in any five year period but no more than 35,000 acre-feet in any one year to make up for compact shortfalls. The parties agreed to let that water pass to the state line.

It remains to be seen whether this complex solution will work. Clearly, the 2003 agreements represent an engineering solution to the slow response time of ground water on the Pecos River. The augmentation wells may provide a new and effective model for priority enforcement where junior water rights are ground water rights, and the delay in response to curtailment always has plagued the prior appropriation doctrine. The augmentation wells do quickly add junior ground water to the senior surface water supplies and so promise to reinvigorate conjunctive ground and surface water management with the basic prior appropriation principles mandated by both state law and the Pecos River Compact.

How We Got Here: A Brief History of Water Development in the Pecos Basin

John W. Shomaker, *John Shomaker & Associates, Inc.*

Familiar themes in the exciting history of the West have been played out in the course of water development in the Pecos Basin, and, as any good western should, the story may have a happy ending. The account starts long before the first Europeans arrived in the sixteenth century, but that is the beginning of the written record.

THE UPPER PECOS: PUEBLO AND SPANISH ACEQUIAS

In 1540 Coronado visited Pecos Pueblo and described villages and the irrigation of small tracts as far down the river as Puerto de Luna. The first Spanish settlement in the region, near Pecos Pueblo, was established in 1794, and by 1805 some 200 families had arrived in the upper Pecos. The Indian population decreased because of disease, pressure from Plains tribes, and perhaps other causes, and by 1840 had all but disappeared. Irrigation expanded and good crops in the vicinity of Anton Chico were noted by Captain R. B. Marcy in 1849. Settlement south of Puerto de Luna seems to have been limited by fear of the Plains tribes.

FORT SUMNER AND THE FORT SUMNER IRRIGATION DISTRICT

Fort Sumner was established in 1862 on the east side of the river 5 miles below the present town as part of the government's Indian policy. Some 8,000 Navajo and 400 Mescalero Apache Indians were detained there (the Navajo coming from their homeland in the Four Corners region following the "Long Walk"). The U.S. Army built ditches and laid out some 6,000 acres to be farmed by the Navajo and Apache Indians. Agriculture there was not successful, although part of the land continued to be farmed after abandonment of the fort in 1868. Interest was revived in 1903, and two individuals filed to appropriate 550 cubic feet per second (cfs) of the natural flow of the Pecos.

The Fort Sumner Land and Canal Company took over the filing. In 1906 they began construction of a diversion dam 2 miles above the town and a canal to serve approximately 10,000 acres. Acreage served by the upper part of the canal grew from 590 acres in 1909 to 6,650 acres in 1937. In 1918 the system was sold out of receivership to the Fort Sumner Irrigation District, which built a new diversion dam 3 miles above the original one. The district's water right, adjudicated in 1933, is for 100 cfs of the natural flow of the river to be applied on 10,999 acres.

THE GREAT SPRINGS AT ROSWELL AND THE HAGERMAN CANAL

Settlement of the lower Pecos Valley began in the 1870s. By 1880 some small farms were being irrigated from the North and South Springs and the Berrendo Springs. In 1889 Ralph Tarr of the U.S. Geological Survey counted 14 irrigation ditches in the vicinity of Roswell; the ditches were gradually extended until most of the flow from the springs was being used. Irrigation of small farms also developed along the Rio Bonito and Rio Hondo, the Rio Felix, and the Rio Peñasco, beginning in or before 1880.

Construction of the Northern Canal began in 1883 to divert water from the Rio Hondo just east of Roswell. Its purpose was to collect spring waters and return flow from irrigation. Three artesian wells were drilled between 1900 and 1910 above the canal diversion on the Hondo to supplement the stream flow, and later, after the springs had almost ceased to flow in the 1930s, water was supplied from a number of flowing wells. Water was carried southward about 5 miles beyond the Rio Felix for irrigation of lands along the Felix. The original scheme, conceived by P. R. Boone, C. D. Bonney, Capt. J. C. Lea, and Pat Garrett (the Lincoln County sheriff who shot Billy the Kid in 1881), included a canal system extending to the Texas state line. The system was taken over by J. J. Hagerman in 1889 and completed by 1904. It was purchased in 1907 by local water users organized as the Hagerman Irrigation Company. By the late 1930s the Northern Canal had come to be known as the Hagerman Canal.

CARLSBAD: THE PECOS IRRIGATION AND IMPROVEMENT COMPANY AND ITS SUCCESSORS

Large-scale agriculture based on irrigation from the Pecos itself was first envisioned in the mid-1880s by

Map of the Pecos River watershed in New Mexico showing locations and features mentioned in text.

entrepreneurs who included Garrett, Joseph Stevens, and John A. and Charles B. Eddy. Large land holdings were acquired by the Pecos Irrigation and Improvement Company, generally by purchasing individuals' 640-acre claims (filed under the Desert Land Act of 1877).

In 1886 overgrazing, exacerbated by drought, led to the loss of over 35 percent of the valley's cattle (the "big die"). This may have been what motivated Charles B. Eddy to build a small canal the next year to irrigate a tract near La Huerta, north of Carlsbad. The initial success of that enterprise led Stevens and the Eddy brothers to incorporate the Pecos Valley Land and Ditch Company in 1887. By 1888 Garrett had merged his ideas with Eddy's, and they were joined by Robert W. Tansill, a successful Chicago cigar manufacturer in New Mexico for his health, and Charles W. Green, a newspaperman and promoter.

A new "Pecos Irrigation and Investment Company" was incorporated to develop the projects. A diversion dam at the site of the present Avalon Dam, the Main Canal, and a flume across the Pecos to serve the Southwestern Canal were under construction in 1889. The diversion dam, McMillan Dam, and the canal system were soon complete, but floods in the summer of 1893 washed out the diversion dam, damaged the canal system, and nearly destroyed McMillan Dam. The system was repaired, but financial stresses led to takeover by the Pecos Irrigation Company in 1900. Floods in 1904 again destroyed Avalon Dam, and heavy siltation and leakage had already diminished the usefulness of McMillan Reservoir.

The U.S. Reclamation Service, predecessor of today's Bureau of Reclamation, took the project over in 1906,

Carlsbad Flume 1890.

made repairs and enlarged McMillan Reservoir, then built Alamogordo (now Sumner) Dam in 1937. The Carlsbad Irrigation District (CID) developed rapidly; in 1926 members irrigated slightly more than their 25,055 water-right acres. Two more reservoirs, impounded by Santa Rosa Dam and Brantley Dam (which replaced the now-breached McMillan Dam), were completed by the Army Corps of Engineers in 1980 and the Bureau of Reclamation in 1988, respectively. The Carlsbad District is entitled to store a total of 176,500 acre-ft behind Avalon, Brantley, Sumner, and Santa Rosa Dams.

ARTESIAN WATER

The term artesian water refers to ground water that is under pressure. Artesian wells are those wells that breach the confining rock unit, allowing water to rise above the top of the aquifer and, in some case, to flow to the surface under its own pressure. A well drilled in 1891 by Nathan Jaffa in Roswell, although it flowed only about one gallon per minute (gpm), was the harbinger of an impressive new supply. By 1900 there were 153 flowing wells in use, largely to water lawns and gardens. A great deal of irrigable land still lay around Roswell, and the water supplies from the springs were being fully used. Beginning around 1903, wells were drilled for agricultural supplies between Roswell and Artesia. By 1905 there were 332 wells, and another 986 had been drilled by 1915 when drilling slowed dramatically. The wells typically flowed 500–1,000 gpm, and some reached 1,800 gpm. By 1937 approximately 57,000 acres were irrigated exclusively from artesian wells, and another 7,000 from a combination of artesian wells and other sources.

It was widely assumed (and hoped) that the supply was inexhaustible. The U.S. Geological Survey itself asserted in 1906 that "it is believed…there is no cause for fear that the water supply throughout the northern part of the Roswell basin will give out or become inadequate for all requirements under proper economy of practice." Even so, the area in which flowing wells could be found shrank from an original 663 square miles to 425 square miles by 1925; it was evident that the pressure in the aquifer was declining. At least as early as Cassius Fisher's 1906 report, it was recognized that discharge from the artesian aquifer, part of it through the North and South Springs and the Berrendo Springs, contributed flow to the Pecos.

Until the New Mexico State Engineer undertook administration of the Roswell Underground Water Basin in 1931 at the urging of local interests, ground water development had been unregulated. The Pecos Valley Artesian Conservancy District (PVACD) was formed in 1932 to "conserve the waters." It has plugged 1,518 wells since then, and has re-loaned some $20 million in state funds for ditch-lining and land-leveling projects, and more efficient irrigation systems, since 1958. PVACD also purchased and retired almost 7,000 acres of irrigation rights. Adjudication of water rights, begun in 1956, led to the retirement of about 12,000 "illegal" acres within 10 years.

THE SHALLOW AQUIFER

Alluvium in the Pecos Valley, which overlies the artesian aquifer and the confining beds above it, is in close communication with the river and is another important aquifer in the Roswell–Artesia area. Few wells tapped the alluvium until the late 1920s, but this new source became important very rapidly. By 1938 approximately 29,000 acres were being supplied entirely from shallow ground water, and another 10,000 acres were irrigated from a combination of sources that included the shallow aquifer. There is also a shallow aquifer in the Carlsbad area, which began to be developed in the 1940s to supplement the surface water supply.

The first artesian well ca. 1892, near Roswell.

TEXAS'S COMPLAINT AND THE PECOS RIVER COMPACT

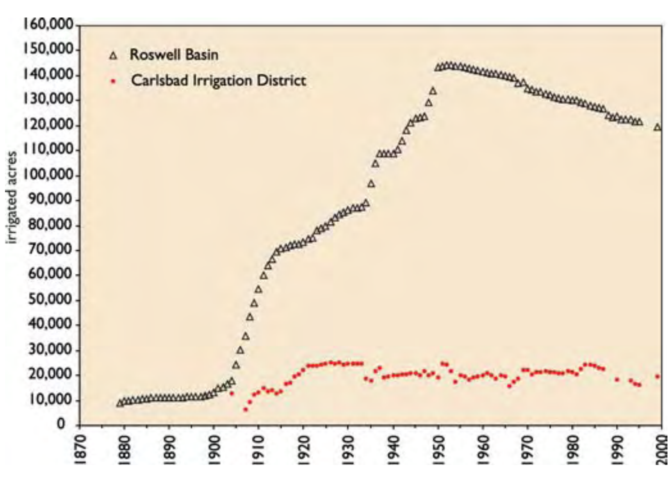
Irrigation from the Pecos had begun in Texas in 1877, and by 1914 work was under way or completed on ten projects totaling 173,000 acres. Water users in Texas were concerned about depletion of the supply from New Mexico. A compact to apportion water between the two states was negotiated in 1925 and ratified by both legislatures, but it was vetoed by the governor of New Mexico. The Alamogordo Agreement of 1935 set limits on New Mexico water use, in exchange for Texas's acquiescence in the construction of Alamogordo (now Sumner) Dam, and committed the two states to negotiate a new compact. The Pecos River Compact of 1948 has regulated delivery to Texas since, although with much controversy.

In 1971 Texas accused New Mexico of having failed to deliver 1.1 million acre-feet of water; in 1988 the U.S. Supreme Court found that New Mexico did indeed owe 314,000 acre-feet. New Mexico was required to pay $14 million in compensation, and to meet the delivery obligation every year.

ADJUDICATION

The process of legal confirmation of water rights began in the 1920s. The "Hope Decree" of 1933 defined the rights to use surface waters of the Pecos from the headwaters to Avalon Dam, but (with one exception) it excluded the related ground water. In 1956 the "Lewis" suit was initiated by the state engineer and the PVACD to adjudicate Roswell–Artesia basin ground water rights. The suit was enlarged to include the rights of the Hagerman Canal, then the Rio Hondo system, and ultimately (in 1978) all surface and ground water rights in the entire Pecos Basin.

The Carlsbad Irrigation District's Pecos River water rights are generally senior to the Roswell area's ground water rights but are subject to the flow of the river, which has often been insufficient. The CID asked the state engineer to enforce priority in 1976, claiming that water use in the Roswell basin had impaired its rights. Litigation of a number of issues, including ownership of rights, acreage, priority dates, and limits on diversion and consumptive use, continued in the Lewis case until a settlement was signed by PVACD, the Carlsbad Irrigation District, the United States, and the State of New Mexico on March 25, 2003.



Irrigated acres in the Roswell basin and Carlsbad Irrigation District.

THE SYSTEM IN BALANCE: THE SETTLEMENT OF 2003

The settlement, presumably impelled by the prospect of draconian action by the State of New Mexico as a shortfall in state-line delivery loomed, confirms the acreage in the Carlsbad Irrigation District; provides for purchase of irrigated lands by the State to reduce the depletion of water in the basin (as many as 6,000 acres in the CID, 11,000 acres in the Roswell basin, and 1,000 acres in the Fort Sumner District); and establishes a program for pumping of an average of (not to exceed) 20,000 acre-feet per year from the Roswell artesian aquifer to augment the natural flow of the Pecos for the benefit of the CID, and to meet the delivery requirement at the state line. It has taken more than a century for large-scale water use in the Pecos Basin to mature, so that it is more or less in equilibrium with the supply and with obligations to Texas. That we have reached this point is grounds for optimism.

SUGGESTED READING

Clark, I. G., 1987, Water in New Mexico—a history of its management and use: Albuquerque, University of New Mexico Press, 839 pp.

Fiedler, A. G., and Nye, S. S., 1933, Geology and ground-water resources of the Roswell Artesian Basin, New Mexico: U.S. Geological Survey, Water-Supply Paper 639, 372 pp.

Hall, G. E., 2002, High and Dry—the Texas-New Mexico struggle for the Pecos River: Albuquerque, University of New Mexico Press, 291 pp.

Kraai, P. T., 1993, Conflict resolution on the Pecos—the Pecos River Compact: New Mexico Water Resources Research Institute, 38th Annual NM Water Conference Proceedings, WRRI Report 284, pp. 87-95.

National Park Service, 1993, Watering the land—the turbulent history of the Carlsbad Irrigation District: National Park Service and Bureau of Reclamation, 179 pp.

CURRENT ISSUES

Assessment Of New Mexico's Stream Gaging Program

Tom Morrison and Jack Frost, *Office of the State Engineer*

Many of the activities of the New Mexico Office of the State Engineer and Interstate Stream Commission (OSE/ISC) require high quality data regarding surface water flows, diversions, return flows, and stream effects of ground water pumping. The U.S. Geological Survey (USGS) and the OSE/ISC jointly fund stream gaging at approximately 100 sites in New Mexico. In 2002 the agencies assessed the gages and the statewide network for the ability to meet OSE/ISC goals for the Active River Management (ARM) program. ARM requires accurate stream flow estimates at key sites and river reaches, followed by the capability to process these data quickly and make them available for water managers. Improvement in the measurement of low and high flows is a priority, as these levels are critical to ARM's goals.

The USGS operates our program as part of its national gaging network. Overall, the program has not kept pace with current surface water information needs. These needs include monitoring very low flows in response to drought, the Endangered Species Act, increased competition for water, and the state's interstate compact delivery obligations. The Pecos River, the Rio Grande, and the San Juan River each have been confronted with shortages and new endangered species issues during the recent drought.

Not included in this review are many gages, dam releases, and diversions managed by the Bureau of Reclamation, the Corp of Engineers, and many irrigation and conservation districts. In fact, federal and local entities such as irrigation districts control most of the water works throughout the state. In the past the OSE/ISC has relied on the USGS and these entities for data and procedures in our accounting of surface water movement in New Mexico.

NATURE'S CHALLENGE

Estimating stream flow is difficult at the precision sometimes needed. To estimate flow, stream gages relate stream height to measured discharge. Occasionally, manual flow measurements calibrate (rate) the gage. Most gages are situated on favorable, yet natural stream reaches. Fewer gages have constructed control structures to enhance precision.

The Dunken gage on the Rio Peñasco.

Gaging problems are obvious: The variability in stream flow affects accuracy; data are most abundant for average flow conditions, and poorest during infrequent high and low flows. Many sites have broad sand channels that constantly shift. Tamarisk and other water loving plants choke channels and gages. Low flows meander away from the gage. Although sites are carefully selected, at some locations even the best estimates contain uncertainties unacceptable for monitoring—very low maintenance flows for endangered species, for example. Yet gages are being used for this purpose.

The statewide network straddles water projects including dams, diversions, return flows, and ungaged tributaries. New, constructed stream alterations may facilitate better gaging, but they may not be feasible at many sites. For the foreseeable future labor-intensive, frequent manual measurements are the best solution at some gages.

FINDINGS OF THE ASSESSMENT

By several criteria, the USGS national gaging program has declined, and ours has followed this trend. Declines are attributed primarily to diminished funding. The number of active gages in New Mexico has decreased to about the same number that were active preceding the 1950s drought. Some neighbors, like

Colorado, now do more measurements themselves (as part of their ARM program).

Of the 84 gages inspected in 2002, 19 need to be replaced and 25 require improvements in order to maintain (but not necessarily enhance) data quality. ARM will also require additional, high quality measurement locations, including diversions and returns. However, in planning new gages, it is important to recognize that rivers adapt to constructed structures in such a way that their effectiveness is uncertain until they are installed and calibrated at varying flows.

On a positive note, technology has led to real-time gaging and reporting. Most gage data are now telemetered to the USGS, processed, and posted on the Internet. However, processing time lags (called "finalizing the data") have caused problems in instances where information is needed for endangered species and compact compliance. Although provisional, real time data are relied on by many water managers.

BASIN CONDITIONS

For compact accounting and other purposes, the agencies identified 14 gages as most important in the cooperative program. The distribution of key gages by basin is as follows:

Pecos River	5
Middle Rio Grande	4
San Juan River	3
Upper Rio Grande	2

In the Pecos River basin, sandy channels and very low flows result in poor discharge estimation. Although important for compact administration, several sites are very problematic. Although average flows are much higher in the Rio Grande basin, several sites are problematic because of shifting and infilling channels. For example, San Marcial is critical for the silvery minnow, yet the channel has built up 15 feet, and low flows elude measurement.

PECOS AT ACME GAGE

Measurements of the Pecos River at Acme gage are essential for compact accounting and are also relied upon for maintaining minimum flows for the Pecos bluntnose shiner. Two gages monitor this site, one on each side of the channel, which is subject to very low flows. The gages switch back and forth depending on which side of the channel is occupied by the flow. The wide channel means small stream-height changes are associated with large changes in flow. Block releases at Sumner Dam also affect the channel and gages when higher flows leave the channel and move into the salt cedars lining the bank. Consequently, the gage rating is unstable, and the daily discharge estimates are poor (estimates may err more than 15 percent), whereas the annual records are rated "good" (within 10 percent). Because of the site conditions, no gage enhancement by itself will improve the flow estimates. The USGS has suggested a Web camera to observe flow conditions in real time, a control structure to guide low water toward a gage, and removal of salt cedars for about a mile above and below the gage.

According to the USGS, an "excellent" record (meaning 95 percent of the daily discharge data are within 5 percent of actual flow) is not achievable at this gage. The USGS states, "Good to fair is the best accuracy level that can be achieved over a long period." This translates into estimation accuracy where 95 percent of the daily records are within 15 percent of the actual flow.

NEW GAGES

Further study is needed to identify additional gaging sites. Future gaging requirements will be influenced by new stresses like municipal direct surface water diversion projects. Measurement needs associated with irrigation districts and acequias also require consideration. For example, the Middle Rio Grande Conservation District, one of the state's largest water users, only recently began measuring its diversions and returns. We need an integrated gaging plan that includes stakeholder participation.

FUNDING CONSIDERATIONS

In addition to challenging field conditions, funding availability has influenced the surface water program. Due to the constant threat of federal funding reductions, the agencies' ability to maintain the program is at risk. For the 2002 fiscal year both the State and USGS each provided $442,000 to fund the program. In a change to long-standing practice, in the 2003 fiscal year the USGS was no longer able to maintain an even match.

The New Mexico base cost is $11,900 per gage, similar to surrounding states. Of 84 gages, the USGS identified 17 substantial control-structure improvements totaling $300,000. Additional capital improvements were identified, but the effectiveness of different options requires further evaluation. A final determination of total funding needs to implement ARM goals must await detailed scoping.

IN CONCLUSION

Accurate flow estimates are fundamental for proper management of surface water resources. OSE/ISC, like agencies in most western states, still relies on the USGS for stream gaging. The stream-gaging expertise of the USGS is well established, and they are widely recognized for their independence and reliability, which confers a level of legitimacy in litigation and interstate compact interactions. Overall the cooperative program has served New Mexico reasonably well. Unfortunately, the existing gaging program has not kept pace with today's information demands. To adopt a more proactive stance in river management, New Mexico should begin conducting its own measurements to augment the USGS gaging program. Although the USGS has maintained a viable program, there are obstacles to addressing today's challenges. Water accounting has a long way to go in New Mexico, and it is important to recognize that there are limitations to accurate measurement caused by nature.

Although this gage assessment outlines many local improvements, it does not fully address the actions needed to improve the statewide network. Where gaging is inadequate, further study must determine whether more frequent measurement, improved controls or gages, or replacement or relocation, is the best approach. The future responsibilities and gaging plans of federal agencies and entities like tribes, municipalities, irrigation districts, and acequias have yet to be considered. An integrated gaging network must include stakeholder participation and funding, and it will require coordination between the various parties.

Ground Water Is Renewable Only If Managed That Way

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About half of the water used in New Mexico comes from aquifers—those underground geological strata that will yield water readily to wells. Annual ground water depletions have increased from less than a half million acre-feet in 1940 to one million acre-feet in 1965 and about 1.4 million acre-feet in 1990. More significantly, 90 percent of New Mexico's population uses ground water for its drinking water. This is the highest percentage anywhere in the western United States and the fourth highest in the United States. Although there is a huge amount of ground water in the state (thought to be around 20 billion acre-feet), only one-fourth of that is relatively fresh water.

Of course 5 billion acre-feet of fresh water is still a huge amount. So why are we worried? Because that water is spread so unevenly over the state. Some ground water, as in parts of the Rio Grande valley, the Roswell artesian basin, and parts of New Mexico's High Plains, is in great aquifers. But that is precisely the ground water already being heavily exploited or over-exploited, which is central to our concerns here. The rest, although cumulatively still a huge amount, is spread widely in small volumes in limited aquifers, remote locales, fluctuating (therefore unreliable) volumes, at great (therefore uneconomic) depths, of marginal quality, or is present in other situations that make it unavailable for other than local or small-scale use.

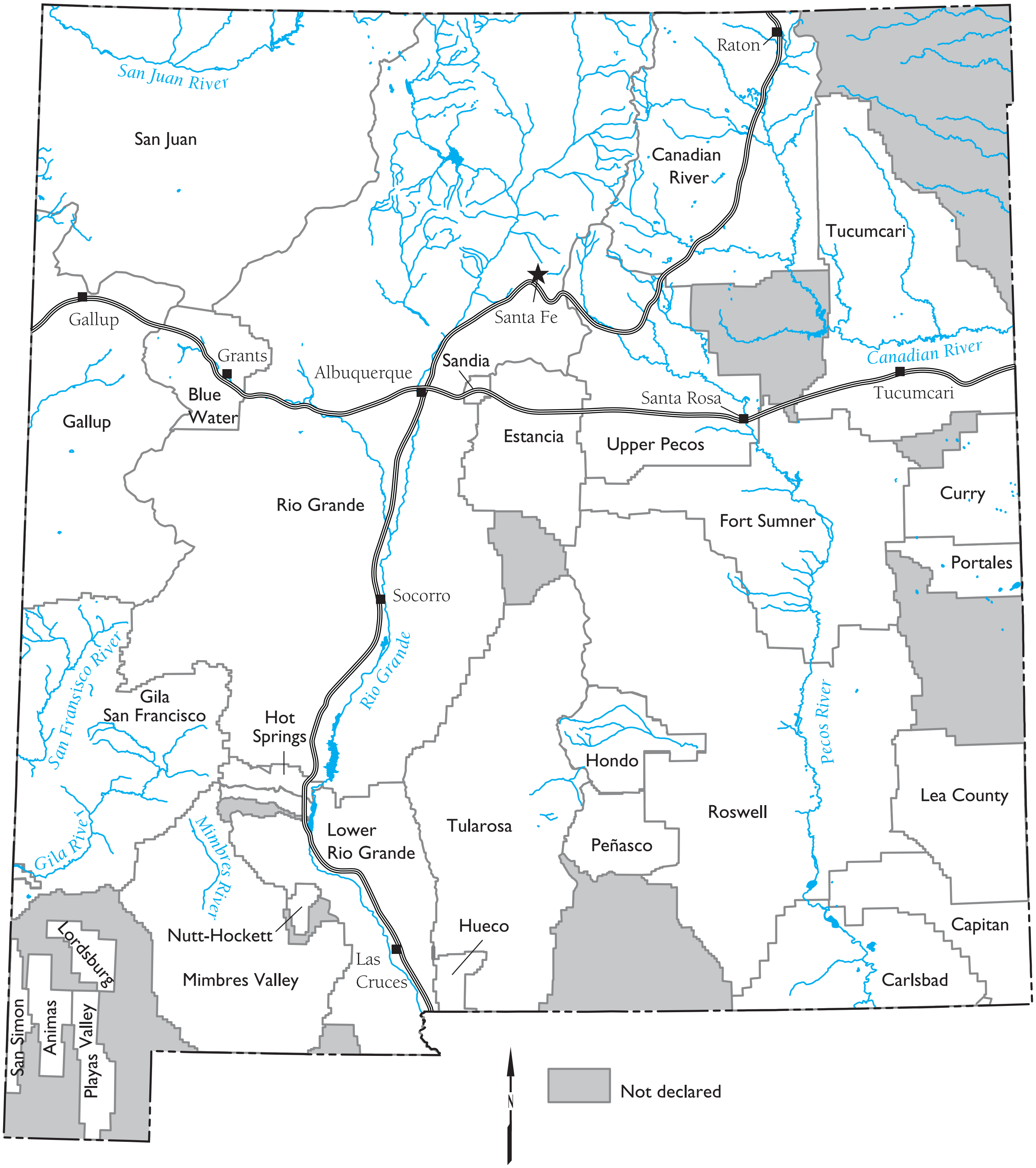
Unfortunately, because in the past we have elected to "administer water rights" rather than manage our water resources, we find ourselves relying more and more on ground water resources that are being used up. In areas where there is no recharge from surface water, the state engineer usually assigns ground water basins a forty-year life and assumes that new appropriations will not impair existing users, so long as the water in the aquifer will last each permittee (including the last to get a permit) at least 40 years. In stream-connected aquifers, the state engineer allows mining of ground water at rates that exceed the rate of aquifer recharge. When these policies were developed, the hope was that additional water could be obtained when needed from new water projects. The consensus now is that no new, large-scale water projects will be built and that water importation from outside the state is not likely in the foreseeable future. After all, other states are finding their populations increasing and their water reserves diminishing, just like New Mexico.

In some areas of the state, aquifers are declining at an alarming rate. This is true for parts of the Ogallala aquifer, a giant aquifer that stretches through eight states, including much of the eastern part of New Mexico. As the state engineer's office stated in a 1999 report, "…concentrated pumping in Curry and Roosevelt Counties in New Mexico as well as Bailey County in Texas will de-water large portions of the most productive areas of the basin as early as the year 2010." The Albuquerque aquifer is also suffering major declines. Locally, around some city wells, the water table has been lowered more than 150 feet. The rate of ground water mining in the middle Rio Grande is estimated at approximately 60,000 acre-feet per year.

We cannot continue to mine our ground water at current rates. Not only will we run out of water—in some places quite soon—but using more water will reduce river flows, dry up many springs, and potentially lead to land-surface subsidence, as occurred recently near the Buckman well field west of Santa Fe. Finally, holders of senior surface water rights suffer impairment from excessive ground water pumping.

THE WAY THE GROUND WATER RIGHTS SYSTEM WORKS

Until the state engineer "declares" a ground water basin, people may drill new wells without needing any approval whatsoever from the state engineer. New wells in undeclared ground water basins, or outside the declared boundaries of other basins, have been at the heart of serious water resource problems in our most important water basins. In the Pecos River valley, this process—unbridled ground water exploitation to the detriment of river flow—was well advanced



Declared ground water basins. Figure is from the Office of the State Engineer.

Declared Ground Water Basins	
Year	**Square miles**
1970	40,067
1980	71,706
1990	86,073
1997	102,598
1998	107,925
2000	110,345

Declared ground water basins in New Mexico.

decades before the functional interdependence between ground water and river flow was appreciated.

Once a ground water basin has been declared by the state engineer, new wells require a permit. Even so, water rights for wells in place when the basin was declared unfortunately are not compiled or separately evaluated when the basin is declared; that occurs only if the basin is adjudicated. By statute, the state engineer can approve applications for new water uses only if there is unappropriated water, and if the new use of water will not impair existing water rights. As noted above, however, in basins isolated from stream systems, well interference is allowed so long as the basin will provide water for the 40-year period designated by the state engineer as the "life of the basin."

In stream-connected aquifers, the state engineer now makes an effort to protect senior surface water rights and to keep the river "whole" for purposes of delivering water to downstream users and as required by interstate stream compacts and treaties with Mexico. The state engineer considers the timing and extent of anticipated pumping impacts on existing surface water rights in the streams. In theory, he allows new appropriations of ground water that will impact surface water only if there is no impairment to senior water rights owners and if the applicant buys and retires existing surface water rights to protect the river from further flow reductions.

Even so, the safeguards against ever-increasing interference with surface water rights through ground water exploitation are sometimes inadequate. State engineer models often have overestimated return flows, thus underestimating surface water depletions from pumping. And surface water rights provided by applicants to offset depletion often have been rights never exercised regularly or fully, which is exactly why they were for sale, whereas the new ground water permits tend to be fully exercised. In addition, prebasin water rights—those that come from pumping before a ground water basin is declared—carry with them the right to deplete surface water up to the full amount of the right. Not only are these rights not listed separately in compilations of surface water rights, but they have the disconcerting impact of causing surface water depletions that are delayed, and that increase year after year over a long period of time. All in all, cumulative impacts of pumping on surface water flows are inexorably increasing in many places in the state.

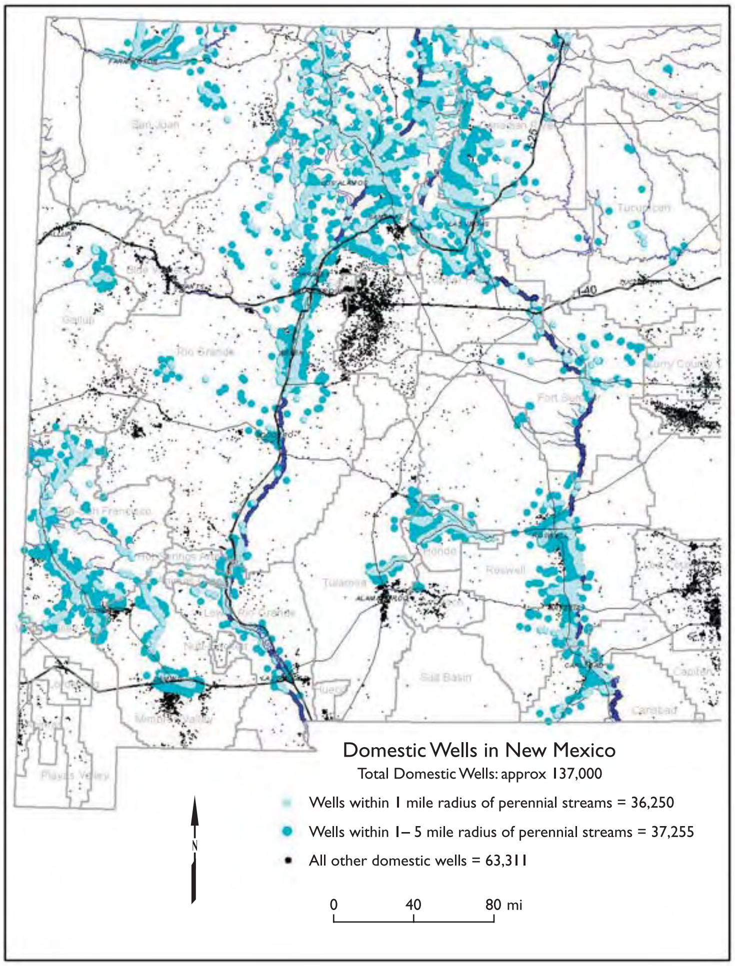
Interestingly, in a few places, the opposite is occurring. Some cities are pumping ground water, running sewage through water treatment plants, and discharging the treated effluent into a river at a greater rate than the accumulating negative effects on surface flow from the ground water pumping. Albuquerque's water treatment plant, for example, has a sign at the canal where its treated discharge flows into the Rio Grande announcing that this is the river's fifth largest tributary. Meanwhile, the city's ground water mining in the past 40 years has lowered the water table more than 100 feet under much of the city.

LACK OF METERING

The state requires well-discharge metering only in parts of some of its ground water regions, and there, only of large-yield wells. Domestic wells in most basins are not required to be metered unless they serve more than one household. We can estimate only roughly how much ground water domestic wells are withdrawing. And we don't know how much of the withdrawals are depleted, how much is returned to ground water as recharge, or what the effects are on surface water. Without this information, we cannot hope to develop an accurate and detailed water budget for the state's ground water use.

THE DOMESTIC WELL EXEMPTION

There is a significant exception to the prohibition against any new water uses that will interfere with existing users. It is the so-called "domestic well statute." This law provides that anyone may obtain a state permit for a domestic supply well—no matter what the consequences for anyone else's water rights. (A few municipalities have placed limitations on this.) Regulations have (until recently) allowed a standard three acre-feet per year (2,680 gallons per day) to be pumped, even though the state engineer estimates gross withdrawals per residence to average 0.35 acre-feet per year (313 gallons per day). The state engineer's office now estimates that about nine percent of New Mexico's residents rely on domestic wells.



Domestic wells from W.A.T.E.R.S. database, Office of the State Engineer, August 2000.

When the domestic well statute was enacted in 1953, people believed that domestic wells would not have much impact on aquifers. The state engineer's office has issued approximately 140,000 domestic well permits since then, however, and it continues to issue thousands of new permits each year. In 1999 nearly 6,000 domestic well permit applications were received and approved.

A recent report from the Office of the State Engineer on the domestic wells estimates that the potential annual domestic use ground water withdrawals range between 48,000 and 137,000 acre-feet per year (assuming the average amount withdrawn ranges between 0.35 and 1.0), roughly 45 percent of which is estimated to be net depletions. Yet with 140,000 domestic wells permitted at three acre-feet each, the actual withdrawals and depletions legally could be as high as ten times these amounts. We simply don't know.

The state engineer has concluded that the current domestic well statute gives him no discretion to deny an application and no grounds for investigating whether a domestic well would potentially impair senior water rights. Thus, although many of the tens of thousands of domestic wells in the state (when considered cumulatively) are interfering with senior water rights, new wells continue to be approved automatically. Whether or not the state engineer can constitutionally grant domestic well permits for wells that will impair existing water rights, it is plainly bad policy to ignore the impacts of those wells in areas where ground water aquifers are already overtaxed and where ground water demands are depleting water from fully appropriated stream systems.

For nearly 10 years the state legislature has tussled with the idea of changing domestic well policy. Policies from the Office of the State Engineer for most of this period have been nebulous and therefore have offered scant guidance to legislators. Recently, though, the state engineer's policies have become more focused. In recent annual legislative sessions, bills have been introduced that would mandate change, but they have died in committee.

Even though the state engineer believes that domestic wells cumulatively are impairing surface water rights in some areas, as well as the state's ability to meet its compact obligations, he has yet to amend the general regulations specifying a production limit. However, he has agreed that domestic well production may have more stringent restrictions imposed by local governments. Santa Fe County, for example, limits domestic wells in certain areas to 0.25 acre-feet per residence (223 gallons per day).

In a few adjudications, including in the *Aamodt* water rights adjudication in the Pojoaque valley, the court limited domestic wells to providing indoor water only (although a subsequent agreement in *Aamodt* has been reached that allows use of as much as 0.7 acre-foot per residence per year, or 625 gallons per day). Pursuant to a court order in *Arizona v. California*, on the Gila River the state engineer grants new domestic wells permits only for indoor use. Finally, in new guidelines for the Estancia Valley, the state engineer allows new domestic wells 0.5 acre-feet per year (447 gallons per day). If the well supplements an existing, permitted well, or if it also provides livestock water, it gets three acre-feet, but it must be metered.

SOME SOLUTIONS

Given the increasing population and corresponding increasing water demands in New Mexico, we do not think that the state realistically can reduce its ground water use to a truly sustainable level any time soon. We simply have grown too dependent on mining ground water (that is, exceeding the replenishment rates of an aquifer). To date, we've shown no willingness to limit water use to the amount annually available or to take the steps necessary to link growth to water availability.

Putting aside questions of whether sustainable ground water use is possible, or even desirable, we believe there are many steps that can and should be taken to improve the state's management of its ground water and begin to approach a more sustainable level of use. At minimum, these steps will help to reduce water waste, reduce impairment of senior water rights, and ensure that we use our ground water in the manner that most benefits the people of the state.

METERING AND REPORTING

Metering and measuring water is a cornerstone upon which effective and equitable water management depends. Whether the tiered ground water regulatory system described below is adopted or not, we must require metering on most, if not all, wells and return flows, and require reporting the results to the state engineer. Metering not only provides crucial data on water use, it is clear that it also can reduce water use. Presumably this is because the metering data give immediate and accurate feedback to water users. Without metering, it is difficult to develop and apply a water budget.

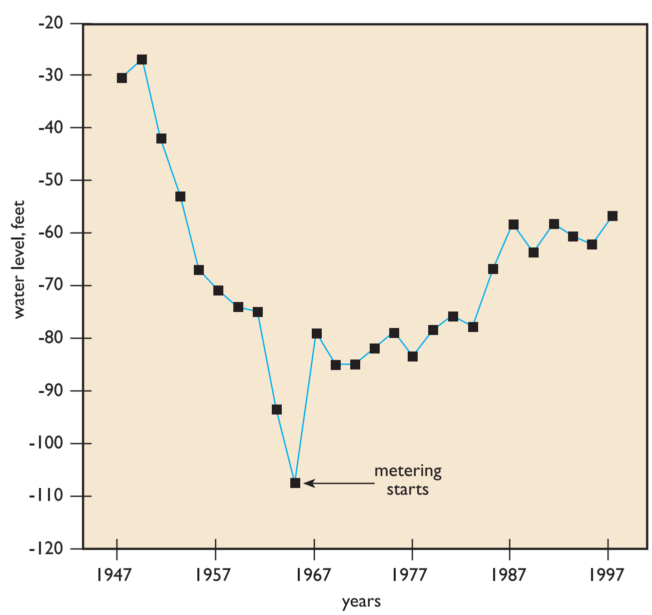
The degree to which metering and reporting to the state engineer are required could vary according to the degree of ground water problems in different areas, if a tiered system were to be adopted. Issues that need to be considered include whether the requirements would affect existing wells or only new wells, whether meters should be required on wells with very limited output, and how reporting to the state engineer would be implemented.

TIERED WATER MANAGEMENT AREAS

Some areas of the state are experiencing severe ground water declines and shortages. In other areas, demand is not yet outstripping supply, and there is no immediate need to alter the current regulatory system. This variation in impacts on available ground water calls for a layered or tiered regulatory system, with greater controls where the impacts are more severe and where communities' water supplies are most threatened.

We support a three-tiered ground water management system for the state. The most aggressive management would be in "critical management areas" (CMAs), those areas with excessive ground water level declines or where existing water rights are being impaired. The second tier would be an intermediate set of regulations for "Stressed Water Management Areas," where population density is sufficient to have a significant impact on water supply and the area is at risk of becoming a CMA but the problems are still less severe than those in a CMA. Measures could be taken in stressed water management areas that would be designed to prevent the need to elevate them to CMAs, or at least to delay elevation for some time. The third tier would be for areas that are sparsely populated, and where wells are dispersed and have a minimal impact on water supply and on other users (i.e., "minimal impact areas"); changes in these areas would be minimal or non-existent.

Recently, the state engineer has developed basin-specific ground water management guidelines for three areas with serious aquifer overuse problems: New Mexico's lower Rio Grande (below Elephant



Pecos aquifer well levels in the Roswell artesian basin. Vertical scale represents average water levels below land surface in 10 wells, measured 3 times per month. Figure from New Mexico State University, Agricultural Service Center.

Butte Reservoir), the middle Rio Grande valley, and the Estancia Basin. CMAs are established where ground water levels are declining rapidly and where the saturated thickness of an aquifer is expected to go below specified minimum levels within the 40-year planning period. The guidelines, among other things, attempt to protect CMAs by imposing extra limitations on pumping in and adjacent to those areas. The guidelines' restrictions on CMAs include some limits on domestic wells (required metering, prohibition on outdoor watering) and a prohibition on new appropriations. We applaud these new guidelines, but suggest there is a need for a more systematic process to establish and manage stressed and critical management areas throughout the state.

DOMESTIC WELLS

Domestic wells should be regulated. New local guidelines by the previous state engineer, Tom Turney, were encouraging. We trust that the new state engineer, John D'Antonio, will continue and expand these policy revisions. It is foolish for the state engineer to continue the inflexible pattern of past decades when wise water management statewide is so clearly needed.

In critical management areas, where an aquifer is in dire straits, new domestic wells should either be prohibited (unless existing water rights are acquired to offset the impacts), limited to 0.25 acre-feet per year, or limited to indoor use. Where a public water supply is available, domestic wells could easily be prohibited. (They are prohibited by municipalities in some limited areas.) Except in minimal impact areas, the developer or homeowners for all new developments should have to acquire sufficient water rights to supply the development rather than relying on domestic wells.

Metering of all new domestic wells should be required, and retrofitting meters on existing wells should be considered. Existing wells could be restricted to their historical use amounts—consistent with existing law that requires that a water right exists only for that water that has been beneficially used. In almost all cases this will be significantly less than three acre-feet per year. Residents would still be free to acquire additional water rights and transfer them to their residence if they wanted to have supplemental water. Acceptance of mandatory metering of domestic wells for existing wells could be greatly enhanced if the state provided at least partial funding. Meters can cost from about $85 to $250.

For effective regulation of domestic wells, the domestic well statute under NMSA 1978 chap 72, arts. 12-1 will have to be amended. A first step was taken in 2001 when the legislature enabled municipalities with water systems to prohibit new domestic wells near existing water lines. We trust that the legislature will ultimately accept this responsibility. The state engineer should have additional discretion to condition or deny new domestic well permits in areas where new wells would impair the right of existing users or hinder the state's ability to make interstate compact deliveries.

RECOMMENDATIONS:

- Create a tiered ground water management system with appropriate safeguards to protect areas where ground water supplies are threatened.
- Increase measuring, metering, and reporting of water diversions and consumption.
- Amend domestic well regulations and statutes to reduce the amount of pumping allowed and to remove the statutory requirement that every domestic well application must be approved; thereby limiting domestic-well impairment of prior rights and negative impacts on interstate compact deliveries.

This paper is a slightly modified version of a paper that first appeared as chapter 5 in *Taking Charge of Our Water Destiny* by Belin, Bokum & Titus (2002).

SUGGESTED READING

William M. Alley, Thomas E. Reilly, O. Lehn Franke, 1999, "Sustainability of Ground-Water Resources," USGS Circular 1186.

Belin, Alletta, Bokum, Consuelo, and Titus, Frank, 2002, Taking charge of our water destiny: A water management policy guide for New Mexico in the 21st century: 1000 Friends of New Mexico, 82 pp.

Office of the State Engineer, December 2000, "Domestic Wells in New Mexico: The impact of, and problems associated with domestic water wells in New Mexico." Available from the Office of the State Engineer or at www.ose.state.nm.us.

Environmental Regulation of New Mexico's Dairy Industry

Dale M. Doremus, *Ground Water Quality Bureau, New Mexico Environment Department*

Dairy farming in New Mexico has a long history dating back to Spanish colonization. According to the New Mexico Department of Agriculture, herd sizes statewide were as large as 40,000 in 1912, growing to 83,000 by the 1940s. During the middle part of the century herd sizes fluctuated as the dairy industry made the nationwide transition from small independent dairy farms to larger operations, marketing through nationwide cooperatives. The late 1990s were a period of rapid growth for New Mexico's dairy industry. The New Mexico State University Cooperative Extension Service reports that the industry grew from 105 producers and 80,000 cows statewide in 1990 to 175 producers and 310,000 cows in 2003. The industry had a 375 percent increase in overall milk production statewide during the same period. New Mexico now ranks seventh in the nation in milk production, eighth in the nation for cheese production, and has the largest number of cows per herd in the nation. New Mexico State University estimated the economic impact of New Mexico's dairy industry as approximately 1.5 billion dollars in the year 2000.

The large influx of dairies relocating to New Mexico from California, Texas, and Arizona in the early 1990s is attributed to a combination of several factors, including an ideal climate for herd health, availability of ready-made feed supplies, improved methods of transporting milk, and affordable farm land. The largest milk-producing counties in New Mexico are Chaves, Doña Ana, Roosevelt, Curry, Lea, and Eddy.

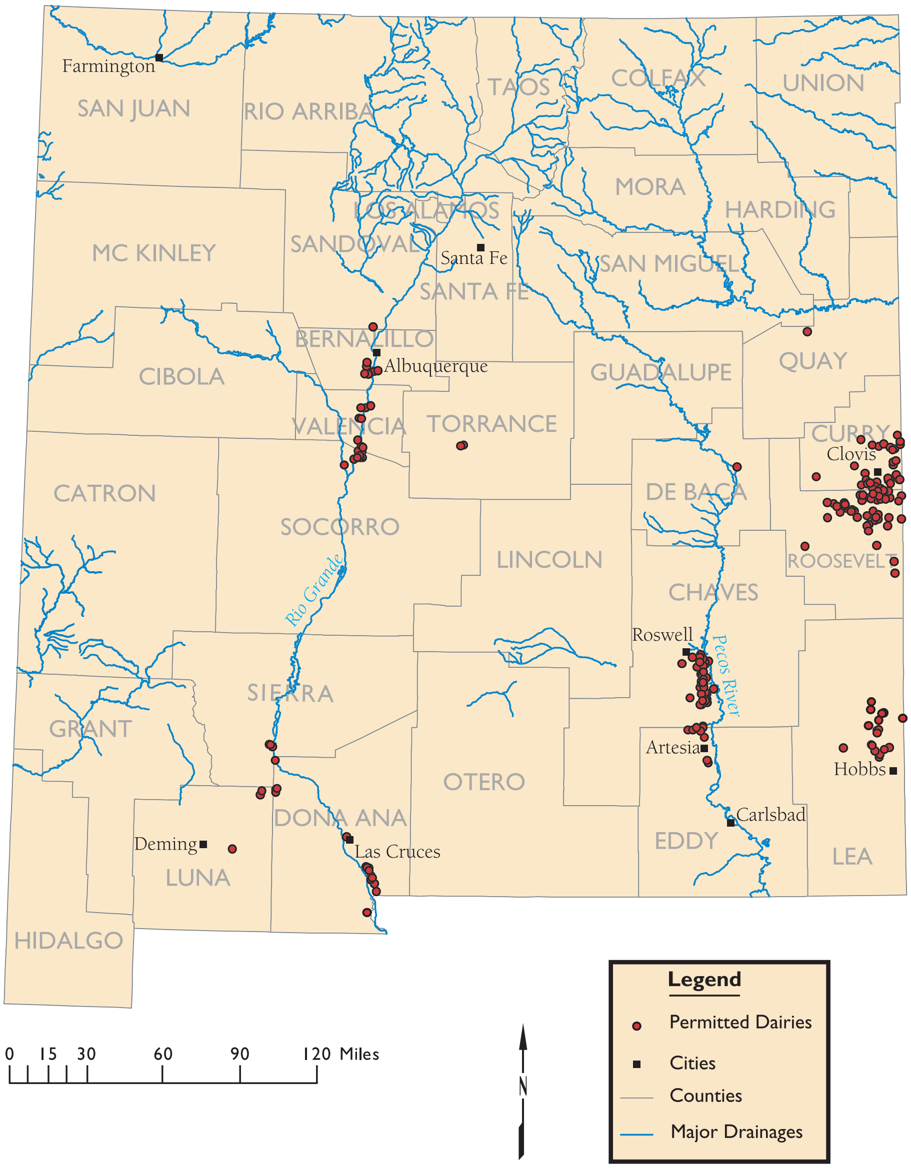
A routine part of business start-up operations for a dairy facility is obtaining required permits. Dairies are regulated by multiple state and federal agencies including the U.S. Food and Drug Administration, U.S. Department of Agriculture (USDA), U.S. Environmental Protection Agency (EPA), New Mexico Department of Agriculture (NMDA), New Mexico Office of the State Engineer (OSE) and the New Mexico Environment Department (NMED).

This paper will serve as an introduction to environmental regulation of the dairy industry in New Mexico, with a focus on water-quality regulation under the jurisdiction of the New Mexico Environment Department.

LAWS AND REGULATIONS GOVERNING WATER QUALITY AT DAIRY FACILITIES

Both state and federal agencies play a significant role in water-quality protection in New Mexico. New Mexico's ground water protection program was well established before most federal legislation and regulations addressing ground water quality were adopted. In 1967 the state's first water-quality protection law, the Water Quality Act, was adopted by the New Mexico legislature. This law was amended in 1973 to allow the State of New Mexico to adopt regulations requiring permits for water-quality protection.

By 1977 the State of New Mexico had adopted a comprehensive ground water-quality program applicable to most types of discharges through regulations promulgated by the New Mexico Water Quality Control Commission (WQCC). The WQCC regulations are the basic framework for New Mexico's water-quality management and protection programs. Key features of the WQCC regulations include numerical ground water quality standards, ground water discharge permit and pollution prevention requirements, and abatement requirements. The regulations and standards are designed to protect all ground water in New Mexico with a total dissolved solids concentration of 10,000 milligrams per liter (mg/l) or less.



Permitted dairies in New Mexico.

The foundation of the state's ground water pollution prevention program is the ground water discharge permit regulations. These regulations require that a person discharging onto or below the surface of the ground demonstrate that the discharge will not cause ground water standards to be exceeded at any place of withdrawal for present or foreseeable future use, and will not cause any stream standard to be violated. NMED's Ground Water Quality Bureau (GWQB) is responsible for administration of the WQCC ground water regulations as they apply to mining, industrial, domestic, and agricultural discharges. Ground water discharge permits include industry-specific and site-specific requirements.

The State also coordinates with the EPA in implementing the federal Clean Water Act, Safe Drinking Water Act, and other federal laws that contain water-quality protection provisions. The EPA administers permits that are applicable to Concentrated Animal Feeding Operations (CAFOs) pursuant to the federal Clean Water Act. These permits are federal permits intended primarily to protect surface water quality. The NMED Surface Water Quality Bureau (SWQB) coordinates with EPA in administering the CAFO program by certifying permits, conducting inspections, and providing program information to the public and permittees.

SOURCES OF GROUND WATER CONTAMINATION AT DAIRIES

New Mexico's dairies are concentrated in four areas. Three of these areas are located over alluvial aquifers along the middle Rio Grande, lower Rio Grande, and the Pecos River near Roswell. The fourth area is clustered in the east-central and southeastern side of the state on the Llano Estacado, which overlies the Ogallala aquifer. Shallow ground water and highly permeable coarse-grained sediments in alluvial environments along the Pecos River and Rio Grande are highly vulnerable to migration of contaminants to ground water. The permeable sediments overlying the Ogallala aquifer and its equivalent are also vulnerable to contaminant migration, although ground water occurs at greater depths in this area.

The primary ground water contaminant at dairies is nitrate, which is present in the form of organic nitrogen in dairy wastewater. Wastewater that moves downward through the vadose (unsaturated) zone usually encounters conditions that allow the conversion of organic nitrogen to nitrate, a common contaminant in ground water. Total nitrogen concentrations in dairy wastewater typically range from 200 to 500 mg/l as compared with domestic wastewater, which averages 60 mg/l. Nitrate is the contaminant of primary concern at dairies because the ground water standard of 10 mg/l for nitrate is based on human health impacts. Chloride and total dissolved solids present in the wastewater may also threaten ground water quality. NMED has identified ground water contamination at approximately 30 percent of permitted dairies, contamination that is primarily associated with past waste disposal practices. At several of these sites, nitrate concentrations in ground water have exceeded 150 mg/l.

Wastewater at dairies is typically disposed of by evaporation in lagoons and/or by land application to crops. Potential wastewater discharge sites at a dairy may include: the collection sump, wastewater delivery pipelines, irrigation ditches, storage lagoons, stormwater lagoons, manure solids storage, and land application areas. Unlined or improperly lined storage lagoons present the greatest risk of subsurface wastewater migration due to the constant hydraulic head that is produced from standing water in the lagoon.

Areas in which wastewater is applied to a crop can also be a significant source of ground water contamination when wastewater containing high concentrations of nitrogen is applied unevenly or at a rate that exceeds the nitrogen utilization capacity of the crops being grown. Facilities may apply chemical fertilizer and manure solids in addition to wastewater and therefore exceed the nitrogen uptake capacity of the crop. The vulnerability of certain soils to rapid infiltration is an important consideration in the design of land application programs.

As the dairy industry has grown in New Mexico, so has the understanding of management practices best suited for ground water protection at dairy operations. Initially, permits for dairies focused primarily on wastewater lagoons, the need for liners, and ground water monitoring. As the understanding of contaminant sources has progressed and data from ground water monitoring has become available, a more integrated approach to ground water protection based on site-specific dairy operations has been developed. For example, permits now require crop and nutrient management plans and include soil sampling to provide

Protection of New Mexico's Ground Water Resources

Programs to prevent ground water pollution have proven to be much more effective than cleanup programs in sustaining usable ground water supplies. Prevention of ground water pollution is much more cost effective than trying to clean up an aquifer after it has become contaminated. Cleanup is always expensive, often costing hundreds of thousands or even millions of dollars, and taking many years. In fact, cleanup is sometimes impossible at any price. Therefore, it is much less expensive in the long run to be sure that adequate resources are devoted to prevention of ground water pollution.

The ground water pollution prevention provisions of the WQCC regulations are designed to ensure the long-term protection of New Mexico's ground water resources. These ground water resources are essential to sustaining the state's populace, business, and agriculture. Approximately 90 percent of the total population of the state depends on ground water for drinking water. Nearly 80 percent of the population is served by public systems with water derived from ground water sources. Approximately 10 percent of the state population depends on private wells for drinking water. Nearly half of the total water annually withdrawn for all uses in New Mexico, including agriculture and industry, is ground water, the only practical source of water in many areas of the state.

In recent drought years, the state has depended even more heavily on ground water to sustain the state's residential population and business community. New Mexico encompasses some of the fastest growing areas in the United States. According to the U.S. Census Bureau, the population of New Mexico increased by more than 20 percent from 1990 to 2000. In November 1998, U.S. News and Water Online reported that population growth in parts of New Mexico is expected to outpace the water supply by 2025, despite conservation and reclamation projects. If these growth trends hold true for the future, New Mexico's need for clean water supplies will increase each decade. The scarcity of fresh water is and will continue to be one of the biggest issues facing New Mexico.

for early detection of potential ground water contamination. All dairies with lagoon systems now are required to have properly constructed liners with engineering oversight. Site-specific conditions dictate whether the liner is clay or synthetic. Written policies and guidelines have improved consistency in the requirements imposed on different facilities, and in communicating to the regulated community minimum standards for permit approval. The program has also been working with older permitted facilities to bring them into compliance with current standards, policies, and guidelines. As a result of these types of improvements, ground water permits are more protective of ground water quality today than in the past.

COOPERATIVE APPROACH TO WATER-QUALITY PROTECTION

During the past several years the Ground Water Quality Bureau has established a proactive and cooperative working relationship with dairy producers as well as other agencies that regulate and assist dairies. The New Mexico Environment Department understands that input from dairy producers provides important insight into dairy operations that is essential for developing practical management practices that are protective of ground water quality.

In light of the potential contamination sources associated with dairy operations, NMED and the dairy producers worked together in 1996 to develop a policy that set forth best management practices for storage and disposal of dairy wastes. The policy was designed to provide flexibility as well as consistency in the application of the regulations to the dairy facilities. The GWQB has also developed guidelines for liner material and construction of clay and synthetic lined lagoons as well as other guidelines that are applicable to dairy facilities. In 1997 the GWQB established a technical working group to provide a forum for open exchange of technical information related to ground water quality protection issues involving dairy operations. The dairy technical working group includes representatives from agriculture and dairy organizations, academia, state, federal and local agencies, and individual dairy farmers.

The federal CAFO regulations and permit requirements have significant overlap with ground water discharge permit requirements. Dairy operators are concerned about duplication of state and federal requirements. NMED has undertaken a collaborative effort to develop a unified regulatory approach for dairies that would satisfy requirements of both the federal Clean Water Act and the state Water Quality Act, within the limitations of each statute and respective regulations. Toward this goal the GWQB and SWQB are working with EPA and the Natural Resources Conservation Service to increase permit consistency and to reduce regulatory duplication and confusion.

Collaboration on water-quality protection between agencies and the regulated community has resulted in a better understanding of issues and a more comprehensive approach to regulation of dairies, which improves NMED's ability to protect water quality.

SUGGESTED READING

New Mexico Department of Agriculture, January 1993, Special Report: The New Mexico Dairy Industry, 1992.
New Mexico Department of Agriculture, January 2001, 2000 New Mexico Dairy Facts.
Sullivan, Hilary, January 2003, New Mexico Dairy Industry: New Mexico State University, Cooperative Extension Service.
New Mexico Water Quality Act (WQA), NMSA Sections 74-6-1 through 74-6-17.

Post-Wildfire Hydrology: Effects of Wildfire in New Mexico Ecosystems and Hydrological Response of Burned Watersheds

Deborah A. Martin, *U.S. Geological Survey*

New Mexico is dominated by fire-adapted ecosystems that have experienced frequent wildfires. On the basis of charcoal in bog sediments from the Jemez Mountains, scientists have determined that wildfires periodically burned these ecosystems throughout the last 9,000 years. However, since 1880 charcoal is noticeably absent from bog sediment cores, and the number of fire scars preserved on trees is significantly less. Both types of evidence indicate that the frequency of wildfires had diminished during the past century, probably as a result of overgrazing and active fire suppression.

In recent decades, however, there has been a dramatic increase in the frequency and size of wildfires in New Mexico. In the ten years between 1992 and 2002, an average of 1,986 fires per year burned an average of over 250,000 acres per year. More significant is the change in fire type, from low-intensity ground fires to stand-replacing fires in ponderosa pine ecosystems, which may then experience substantial flooding and erosion. This paper evaluates the hydrological and erosional consequences of wildfire by asking the question, "How are burned watersheds fundamentally different than unburned watersheds?" The main focus is the consequences of fire in steep, mountainous terrain dominated by ponderosa pine (*Pinus ponderosa*), because that is where most of the post-fire hydrological research has been conducted.

The hydrology of an unburned watershed can be depicted in terms of storage reservoirs and the transfer of water between those reservoirs. The main storage reservoirs are the vegetation canopy, the dead organic layer on the soil termed the "litter and duff," and the soil itself. The canopy includes the structure of needles, twigs, branches, and trunks that captures rainfall or snow. This precipitation is either evaporated to the atmosphere or delivered to the soil surface once the storage capacity of the canopy is exceeded. Excess water from the canopy storage, along with water falling directly on the soil surface, fills up the storage capacity of the litter and duff. Excess water is then delivered to the underlying soil surface, and it infiltrates the pore spaces of the soil. Two processes, saturation excess and infiltration excess, generate surface flow from hillslopes. If the storage capacity of the soil is exceeded (saturation excess), surface flow can occur. Saturation excess is rare in mountainous terrain, where it is more likely that surface flow will be generated by infiltration excess. That is, when the storage capacity of the litter and duff is exceeded and the excess water cannot infiltrate (infiltration excess), the water will run off over the surface of the soil. Infiltration excess also occurs when the rainfall rate exceeds the infiltration rate. Surface flow is the primary mechanism by which water is delivered to channels.

What has changed in a burned watershed? The most obvious change in a severely burned watershed is the loss of canopy by the combustion of needles and even tree branches. After a burn, the forest often looks like a moonscape with standing, blackened trees. Most of the structure of the trees will remain, though some trees will have fallen during the fire. Although diminished, the burned canopy still stores water. Measurements of the canopy storage capacity of three different sizes of ponderosa pine trees (small, medium and large) were made in both burned and unburned areas of Colorado, which are similar to burned and unburned areas in New Mexico. For a variety of storms having a range of intensities, durations, and total rainfall amounts, on average, unburned trees stored 61 percent of the incident rainfall, whereas burned trees stored 20 percent. Additional data need to be collected to strengthen these results, but this preliminary work may argue against cutting burned trees that continue to serve as storage reservoirs in a burned watershed, at least for a couple of years after a fire.

During a wildfire, the dead organic layer on the soil surface is completely or partially burned, leaving behind an ash layer and partially burned litter and duff. Both ash and the partially burned litter and duff retain some storage capacity and protect the soil surface from rain splash impact. But both are easily eroded from the soil surface by water and wind. Once the ash layer and litter and duff are removed from the soil surface, raindrops dislodge particles and pulverize soil aggregates to smaller sizes. These particles can clog the soil pores and reduce infiltration rates by sealing the soil surface. Decreases in infiltration rates after a wildfire are also attributed to a fire-induced reduction in soil wettability (hydrophobicity). Gasses that are produced by the burning of organic matter condense onto soil particles, making them water repellent or hydrophobic. In addition, the intense drying of the soil by wildfire can make it very difficult to wet the soil surface. The consequence of reduced infiltration rates and the difficulty in wetting the soil surface is that more water runs off a burned watershed than from an unburned watershed.

If rain falls on recently burned hillslopes at intensities greater than 0.4 inch per hour, surface flow increases rapidly and leads to flooding in stream channels. Often the flooding widens the channels, and the eroded sediment is transported downstream in the watershed, perhaps ending up in water-supply reservoirs. Very few burned areas have pre-fire hydrological data, including peak stream flow, which can be compared to post-fire data. Peak stream flow is the maximum amount of stream flow recorded, or known to have occurred, at a location. One area in New Mexico that has both pre-fire and post-fire data is Capulin Canyon. After the 1996 Dome fire in Bandelier National Monument and the surrounding Dome Wilderness, peak stream flows were 160 times the previously recorded peak stream flows. Even 22 years after the 1977 La Mesa fire, which also burned parts of Bandelier National Monument and adjacent Santa Fe National Forest, peak stream flows continue to exceed pre-fire magnitudes.

Evidence of the height of peak flows in Rendija Canyon after the 2000 Cerro Grande Fire. View is looking downstream. The bark on the upstream side of the burned trees has been abraded away by floodwaters carrying ash and sediment. Sand grains are imbedded in the tree trunks attesting to the force of the flowing water. Notice the sediment deposited in the channel and the 3-foot backpack leaning against a tree. Photograph by John Moody, U.S. Geological Survey, October 2001.

Downstream view of a flooding in Rendija Canyon burned by the 2000 Cerro Grande fire near Los Alamos. Water laden with ash and sediment is flowing in a channel that was completely dry before the fire. Because residents of Los Alamos use these channels as hiking trails, notification of the public of post-fire flooding hazards is extremely important. Photo by Thomas Trujillo, July 2001.

The severity of a wildfire has a substantial effect on a watershed's post-fire hydrological behavior. Severe wildfire will completely burn the litter and duff layer and the tree trunks on the ground, both of which impede surface flow off hillslopes. This occurred in parts of the Cerro Grande fire near Los Alamos. Also, in a high-severity wildfire all the needles on the trees are burned. By contrast, in a moderate-severity wildfire brown needles are left on burned trees. Those needles subsequently fall to the ground surface, protecting the soil against rain splash impact and acting as another storage reservoir. Moderate- or low-severity wildfires will leave partially burned litter and duff on the soil surface that are carried by surface flow to form small dams that impede flow. Interestingly, even the species of tree may make a difference in surface flow from hillslopes. Researchers have documented that ponderosa pine needles are more effective than Douglas-fir (*Pseudotsuga menziesii*) needles in forming the small dams. In short, there are several factors that will alter the surface flow from burned hillslopes, subsequently affecting the amount of water delivered to channels. Scientists are trying to quantify the relative importance of changes in storage reservoirs, surface flow, and infiltration rates in determining the hydrological behavior of burned watersheds.

Post-wildfire flooding and the subsequent erosion and deposition of sediment are major consequences of wildfire. These consequences may affect water users and aquatic organisms many miles downstream from the location of a wildfire. Most water-quality effects of wildfire are substantial, but ephemeral. In contrast, sediment and stream channel alteration are a persistent legacy of wildfire. With a shift toward an increasing number of stand-replacing wildfires in New Mexico ecosystems and other ecosystems in the western United States, a better understanding of the hydrological response of burned watersheds is needed. This is especially important in a scenario of climate change where extreme meteorological events may occur with greater frequency.

SUGGESTED READING

Allen, C. D., Savage, M., Falk, D. A., Suckling, K. F., Swetnam, T. W., Schulke, T., Stacey, P. B., Morgan, P., Hoffman, M., and Klingel, J. T., 2002, Ecological restoration of southwestern ponderosa pine ecosystems: A broad perspective: Ecological Applications, v. 12, pp. 1418-1433. Accessed April 2003 at http://www.swfa.org/doc%20files/Allen_SWRestoration.pdf

New Mexico Environment Department, 2001, Special water quality survey of the Pecos and Gallinas Rivers below the Viveash and Manuelitas Fires, 2000. Accessed April 2003 at http://www.nmenv.state.nm.us/swqb/Viveash_Fire_Report_02-2001.html

Veenhuis, J. E., 2002. Effects of wildfire on the hydrology of Capulin and Rito de Los Frijoles Canyons, Bandelier National Monument, New Mexico. U.S. Geological Survey, Water-resources Investigations 02-4152, 39 pp.

Effects of Forest Harvest on Water Yields

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The effects of forest management on the quantity, quality, and timing of runoff have long been of interest to land managers and water users. The ancient Greeks noted that clearing the forests could cause springs to dry up, although a large number of recent studies generally show that forest harvest increases annual water yields. The large variation in the hydrologic effects of forest management means that one or more studies can be found to support nearly any point of view. The resolution of these apparently disparate results requires a basic understanding of the underlying processes, including infiltration, interception, soil moisture storage, and evapotranspiration. Forest management, or the lack of management, can affect each of these processes in different ways, depending on the site conditions, how an action is carried out, and the hydrologic event of concern (e.g., annual water yields, summer low flows, spring snowmelt, or extreme rain events). Managers and decision makers commonly want a simple answer, but generalizations and predictions can be incorrect unless there is a clear link to the underlying causes.

The purpose of this paper is to summarize how changes in forest cover affect the amount and timing of runoff in forested areas in New Mexico, including the lower-elevation ponderosa pine zone, the middle-elevation mixed conifer zone, and the upper-elevation forests that grade from fir to spruce. The latter are the most important in terms of water yield because these high-elevation forests receive more annual precipitation, have lower evapotranspiration losses, and thereby produce most of the runoff. As discussed below, there is relatively little potential to affect annual water yields through forest management in the lower- and middle-elevation forests in New Mexico.

EFFECTS OF FOREST HARVEST ON ANNUAL WATER YIELDS

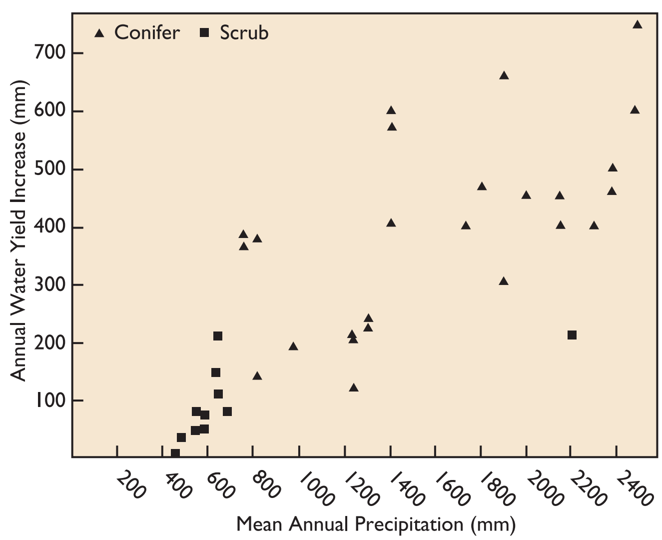
A useful starting point for understanding the effects of forest management on runoff is the simple water balance equation:

Runoff = Precipitation - Evaporation - Transpiration + Change in Storage

Evaporation also includes the loss of water by interception, which is the evaporation of water captured on plant surfaces during or immediately after a rain or snow event. Transpiration is the water lost through plants as a result of photosynthesis and respiration. In practice the evaporation and transpiration terms often are combined into a single evapotranspiration (ET) term, as it is difficult to distinguish the water lost to the atmosphere by evaporation from the water lost to the atmosphere through plants by transpiration.

In most cases the Change in Storage term in this equation can be ignored at the yearly time scale. In areas such as New Mexico, summer ET demand is much greater than the amount of summer precipitation. Hence the amount of water stored in the soil of an undisturbed forest at the end of the dry season is very low, resulting in minimal differences in soil moisture storage between years. Changes in the amount of stored water can be significant over shorter time scales (e.g., seasonally, monthly), but the annual change in storage for undisturbed forests will be very small relative to the errors in the other terms in the equation. Hence, the annual water balance equation can be reduced to the following, simpler relationship:

Runoff = Precipitation – Evapotranspiration



First-year increases in annual water yield after clearcutting as a function of mean annual precipitation. Each point represents a separate paired-watershed experiment. 100 mm is about 4.0 inches.

If the amount of annual precipitation is assumed to be constant, this equation indicates that the amount of runoff is controlled by the amount of evapotranspiration. It follows that a reduction in vegetation cover can reduce the amount of ET. However, in relatively dry areas or in dry years reducing the amount of vegetation may have little or no effect on runoff because increased evaporation from the soil compensates for the reduction in interception and transpiration.

A 1982 review of paired watershed experiments showed that removing much of the vegetative cover has no effect on annual water yields until annual precipitation is at least 18–20 inches. As annual precipitation increases beyond 18–20 inches, vegetation density increases and the water lost by ET shifts from soil evaporation to interception and transpiration. For the higher elevation forests in Colorado, all of the precipitation is used for evaporation and transpiration, regardless of the amount of vegetative cover, until annual precipitation exceeds 18 inches. In undisturbed forests approximately 72 percent of any additional precipitation beyond 18 inches becomes runoff, and the other 28 percent is lost to interception.

Because ET increases with increasing annual precipitation, removing the vegetative cover will result in progressively larger increases in annual runoff as precipitation increases. Studies in Colorado and elsewhere have shown that increases in water yield after forest harvest increase until annual precipitation reaches approximately 60 inches. For example, clearcutting a watershed in south-central Colorado with 21 inches of annual precipitation increased annual water yields by an average of 1.0 inch. At a site in central Colorado with approximately 26 inches of annual precipitation, cutting 50 percent of the vegetation (40 percent of the watershed) increased the average annual water yield by 3.1 inches. Forest harvests in ponderosa pine forests in Arizona typically have produced first-year water-yield increases of approximately 0.5–2.0 inches in areas that receive from 23 to 29 inches of annual precipitation.

This means that higher-elevation forests have the greatest potential for increasing water yields. However, the structure and density of these forests generally have been less affected by human activities and fire suppression. The lower- and middle-elevation forests have been more severely altered by human actions and generally pose a greater wildfire risk. Treatments to reduce the risk of wildfires in the lower- and middle-elevation forests have very limited potential to increase water yields.

TIMING AND VARIABILITY OF WATER-YIELD INCREASES

A reduction in forest cover increases water yields by reducing interception and transpiration losses. However, these water-yield increases vary considerably in timing, magnitude, and duration depending on the specific climatic, topographic, and geographic conditions in the watershed, and the pattern of forest harvest. In most forested areas in New Mexico the reduction in summer ET after forest harvest will be the main cause of any increase in runoff. General principles dictate that in drier years and in drier sites, as are common in New Mexico, the residual vegetation and soil evaporation use most of the available water, so summer ET savings due to forest harvest are minimized. In wetter years, and in areas where snow interception is less important, the reduction in summer ET contributes proportionally more of the increase in water yield. Similarly, summer ET will contribute more of the increase in water yield in areas with more summer precipitation, such as some of the ponderosa pine forests in Arizona and New Mexico. In areas with shallow soils there is much less potential to increase water yields because these soils will dry out regardless of vegetative cover.

In areas where most of the annual runoff comes from snowmelt, winter interception can be a much larger component of the annual water balance. In areas with a cold, dry snowpack, such as in much of the Rocky Mountains, forest harvest significantly increases the snowpack by reducing the amount of winter interception. Studies in high-elevation forests in Colorado have shown that the complete removal of the tree canopy can increase the total water content of the snowpack by approximately 20–45 percent, depending on aspect (the direction toward which a slope faces with respect to the rays of the sun). The reduction in winter interception is directly proportional to the amount of the canopy that is removed. In these snow-dominated areas, nearly all of the water-yield increase occurs in early spring when less water is taken up by soil moisture recharge and more of the early snowmelt is converted into runoff. Some of the water-yield increase in these snowmelt-dominated areas is also due to the reduction in summer ET, and this component is progressively more important in wetter areas and in wetter years.

The pattern of harvest can affect the magnitude of the resulting water-yield increase, particularly in areas with a transient winter snowpack and where reduced summer ET is the primary source of increased water yields. In the latter areas, any “excess” water may be scavenged by the adjacent trees before it is able to reach the stream channel. Hence the pattern and location of forest harvest relative to the stream channel can substantially affect the magnitude of a water-yield increase in lower elevation areas, and in the snow zone in drier years. In the higher-elevation and wetter subalpine zone, studies have shown that most of the winter interception savings following forest harvest will be transformed into runoff, regardless of the pattern of harvest or proximity to a stream channel.

Aspect can also affect the magnitude and timing of potential water-yield increases in higher-elevation forests by affecting both the amount of interception and the rate of snowmelt. In the subalpine zone, north-facing slopes typically have denser vegetation than south-facing slopes. The denser vegetation on north-facing slopes has higher interception rates, and this results in a greater potential for increasing water yields than on south-facing slopes. South-facing slopes also have a smaller potential for water-yield increases because they have more incoming radiation and higher temperatures, and this increases the potential losses due to soil evaporation.

There is considerable variability in the observed increases in water yields after forest harvest, and these can be explained by the interplay between evaporation, interception, and transpiration. In dry years a greater proportion of the precipitation is needed to recharge soil moisture and satisfy ET demands. In wet years less of the snowmelt or winter precipitation will be needed for soil moisture recharge, and there can be more soil moisture carryover. The net result is that the increase in runoff from forest harvest is substantially greater in wet years than in dry years. In the Fool Creek experiment in Central Colorado, the annual water yield increase ranged from 1.6 inches in the very dry year of 1963 to 6.4 inches in the exceptionally wet year of 1957. Similarly, the water-yield increase in a study in south central Colorado was twice as large in a wet year than in an average year, and no increase was recorded in years with below-normal precipitation. Studies in the ponderosa pine zone in Arizona also have shown that forest harvest may have little or no effect on annual water yields in dry years, but forest harvest can generate relatively large water-yield increases in wet years.

REDUCTION IN WATER-YIELD INCREASES OVER TIME

The discussion to this point has focused on water-yield increases that might be expected after removing some or all the forest canopy. In the absence of any other management activities, these increases in runoff will decline over time with forest re-growth. The snowmelt-dominated forests have the greatest potential for increasing water yields, as these areas produce most of the runoff and forest re-growth is slow due to the relatively cold, dry climate. This results in relatively slow rates of hydrologic recovery to pre-treatment runoff amounts. The longest-running study in the Rocky Mountains is the Fool Creek experiment on the Fraser Experimental Forest in central Colorado. Results from this study show an approximately linear decline in water yields after forest harvest from 1958 through 2000. The trend line from these data suggests that annual water yields will return to their pre-treatment values in approximately 65–70 years.

A faster rate of hydrologic recovery can be expected for faster-growing forest types, for species that re-sprout, and in drier areas. In Oregon and the southeastern U.S., annual water yields usually decline to pre-cut conditions within 10–25 years. Hydrologic recovery has been estimated to be 15–45 years for aspen. Recovery in drier sites, such as ponderosa pine forests, should be faster because relatively less re-growth is needed to return summer water losses to pre-harvest levels. Several studies in Arizona have shown that forest harvest can increase annual water yields from ponderosa pine forests, but vegetative re-growth eliminates these increases within 10 years. The increases were shorter-lived on drier sites and in watersheds where less harvest had taken place, and more persistent on wetter sites and where a higher percentage of the forest canopy had been removed.

EFFECTS OF FOREST HARVEST ON PEAK FLOWS

The effect of forest management on the size of peak flows is an important concern for resource managers and the public. An increase in the size or duration of high flows can increase sediment transport capacity, alter channel geometry by scour or bank erosion, and raise water levels in the affected streams. In general, forest harvest in snowmelt-dominated areas in the Rocky Mountains will increase the size and frequency of the larger flows. In the Fool Creek catchment, the annual daily maximum peak flow increased by 23 percent as a result of removing 50 percent of the forest cover. The average number of days with flow at or above bankfull increased from 3.5 to 7 days per year. Data from other studies in the central and northern Rocky Mountains have consistently shown that the annual maximum daily flow (i.e., the day in each year with the highest total runoff) increases by 40–50 percent as a result of completely removing the forest canopy. If only part of the forest canopy is removed, the increase in the size of the annual maximum daily flow is directly proportional to the amount of cover removed.

There is little evidence for an increase in the very largest instantaneous peak flows that have a recurrence interval greater than 2 years. In general, changing the amount of forest cover has a progressively smaller effect on the size of a peak flow as the magnitude of the peak flow increases. The underlying logic is that during the largest rain or snowmelt events the soils and vegetative canopy will have little additional storage capacity. Under these conditions much of the rainfall or snowmelt will be converted to runoff regardless of the amount or type of vegetative cover. There is little evidence to suggest that forest harvest can consistently and significantly change the timing of peak flows in snowmelt-dominated areas in the Rocky Mountains.

EFFECTS OF FOREST HARVEST ON LOW FLOWS

In snowmelt-dominated watersheds, summer rainstorms have little effect on summer stream flows, as the amount of rain is usually small relative to the available soil moisture storage. Summer low flows depend more on stored moisture than summer precipitation, and two recent studies have shown no statistically significant increase in low flows as a result of harvesting from 25 to 40 percent of the watershed. However, summer minimum daily flows did increase by approximately 10 percent for the harvested watershed in the Wagon Wheel Gap experiment in south central Colorado. This increase was attributed to the reduction in summer ET and resulting higher soil moisture on the treated watershed. However, this increase in summer low flows persisted only for the first five years after harvest.

Hydrologic theory and studies from other areas indicate that any increase in low flows is relatively short-lived compared to increases in peak flows and annual water yields. This can be attributed to the more rapid recovery of summer evapotranspiration rates after forest harvest than winter interception rates. Because water-yield increases are smaller in dry years and summer ET recovers more rapidly in drier areas, forest management generally will have little effect on summer low flows in the central and southern Rocky Mountains. Because most of the increase in water yields will come in the fall and winter in rain-dominated areas and in spring in snowmelt-dominated areas, water storage facilities are needed if an increase in runoff due to forest management is to be captured and used during the summer growing season.

SUMMARY

Reducing forest density has the potential to increase water yields, but the average long-term increase in water yield depends on the annual precipitation, the species being treated, the proportion of the canopy that is removed, the re-growth rate, and the length of time between treatments. Some of the key limitations on the potential to increase annual water yields include:

- Little or no water-yield increases can be expected in areas where annual precipitation is less than 18 inches.
- The greatest potential for increasing water yields is in the higher-elevation fir and spruce forests, with more limited potential in aspen and mixed conifer forests, and the smallest potential is in the ponderosa pine forests.
- At least 15 to 20 percent of the forest within a watershed must be removed in order to detect a statistically significant change in runoff.
- Most of the increase in runoff will come during the winter or spring, and there is little potential for forest harvest to increase baseflows.
- Forest re-growth means that hydrologic recovery occurs over a period ranging from approximately 10 to 70 years, so the long-term sustainable increase in water yield from forest harvest is much less than the potential water-yield increase in the first few years after forest harvest.
- The timing of the increase in runoff after forest harvest may limit the usefulness of an increase in water yield. The timing of an increase in runoff may not match up with the timing of peak demand.
- Water-yield increases from forest harvest also are smallest in dry years, when they are most needed, and larger in wet years, when they may be less useful. The seasonal and interannual timing of potential water-yield increases means that reservoirs may be needed to capture any increase in water yields resulting from forest harvest.

SUGGESTED READING

Baker, M. B., 1986, Effects of ponderosa pine treatments on water yield in Arizona: Water Resources Research, v. 22, no. 1, pp. 67–73.

Bosch, J. M., and Hewlett, J. D., 1982, A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration: Journal of Hydrology, v. 55, pp. 3–23.

Troendle, C. A., and King, R. M., 1985, The effects of timber harvest on the Fool Creek watershed, 30 years later: Water Resources Research, v. 21, no. 12, pp. 1915–1922.

Waters of the Sacramento Mountains Forest

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The Sacramento Mountains are located in south central New Mexico. They rise gently in elevation from the east and south to the escarpment along the western side and end at Sierra Blanca to the north. Their influence extends as far as they can be seen across the surrounding lowlands. Streams and aquifers charged by the mountain watersheds include the Tularosa Basin to the west, the Salt Basin to the south, and the Pecos River valley to the east. Today, the economy of the area is recreation and agriculture, with some logging.

The Sacramento Mountains have undergone many changes since European settlers arrived in the last half of the nineteenth century. At that time, large majestic trees dotted the landscape. Mountainsides were covered with lush grass, and springs or wet areas were prevalent. Ponderosa pine was the dominant tree at middle elevations, with fir and spruce dominating many of the higher slopes. Stands of aspen trees were common, mostly on old burns. Lower slopes were populated with ponderosa pine, piñon pine, one-seeded juniper, and alligator juniper. At all elevations, trees were much larger than they are today. Early records depict a landscape with large grassy parks interspersed with stands of timber in what is known as an open savannah. Low-intensity ground fires maintained this landscape of large trees with a lush carpet of grass underneath.

In 1883 a firewood inventory was commissioned for the territory of New Mexico. The inventory for the Sacramento Mountains indicated that 2–5 cords per acre of firewood were available throughout the higher elevations. This correlates to approximately 4–10 fairly large juniper or piñon pine trees per acre. The piñon-juniper foothills had 1–2 cords of firewood per acre, or 2–4 trees per acre.

Other territorial and early twentieth century surveys describe a similar savannah setting. General Land Office Survey notes from 1885 describing the Sacramento River area state that the "entire township is covered with a luxuriant growth of grass. Almost the entire township is covered with heavy timber of pine and fir of very good quality." In 1908 surveys along the southern boundary of the Lincoln National Forest noted scattered pine, piñon, juniper, and cedar.

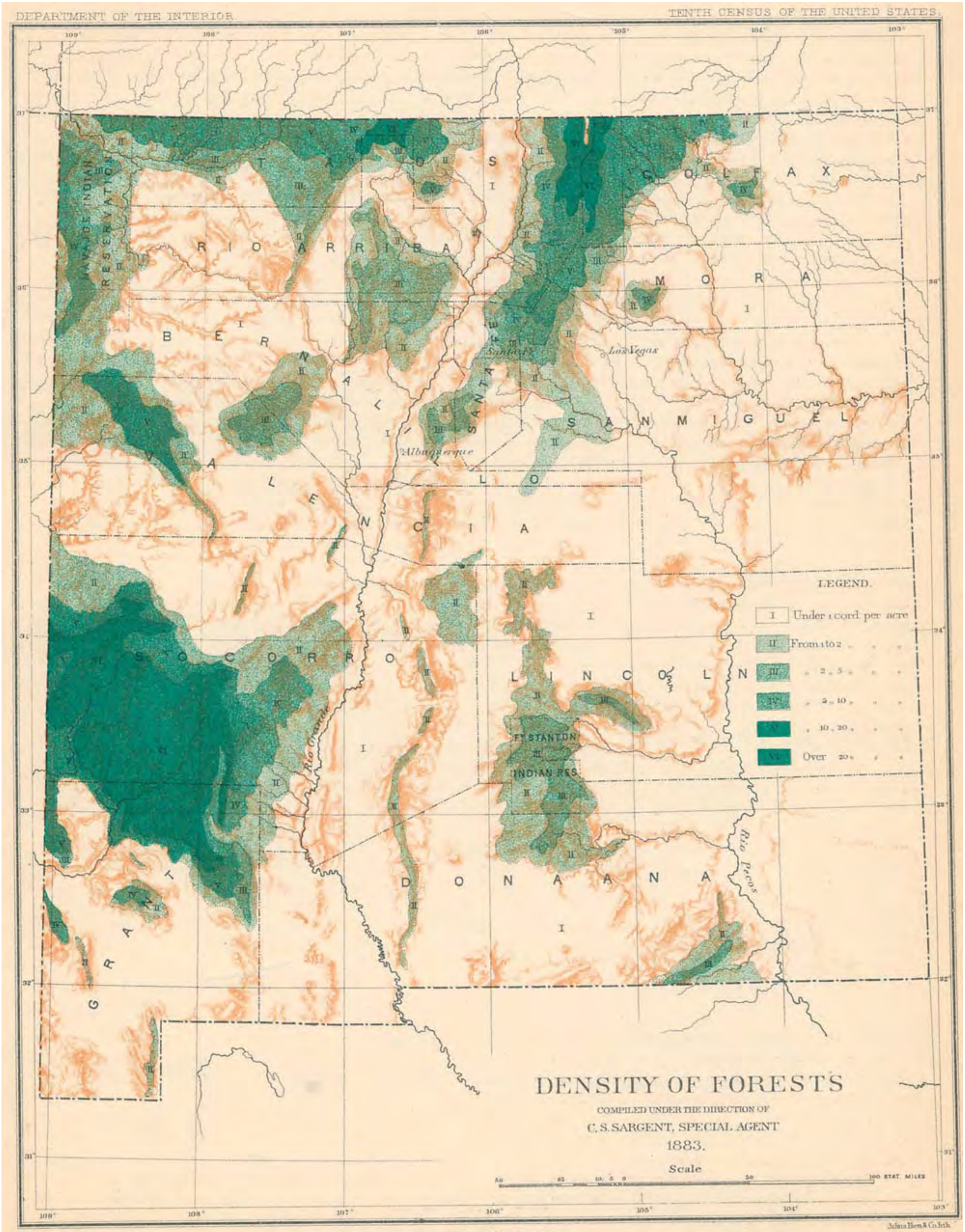
VEGETATION AND BIOLOGICAL DIVERSITY

During the early 1900s dramatic changes in the landscape of the Sacramento Mountains began to take place. Developers opened the mountains to the timber industry by building a railroad to Cloudcroft, with spurs up many of the adjacent canyons. The big, old trees were logged and removed. Settlers' livestock kept the grass short. With the removal of widespread, low-lying ground cover, low-intensity ground fires were no longer able to maintain the delicate balance between old-growth trees and open grasslands. The natural balance between trees, grass, animals, and water, developed over thousands of years, became skewed.

The most significant vegetation changes in the last 100 years have been marked by a reduction in species diversity and an increase in tree density. In the logged stands, each original tree has since been replaced by dozens of smaller trees. The intervening grassy savannahs have also been filled with trees, at the expense of the lush grasses of the open forest floor and the original biological diversity. Riparian plants along streams and wet areas have largely disappeared, as the forest vegetation shifts toward a monoculture of evergreen species. Most significantly, the change from open stands of large conifer trees and associated deciduous trees to dense stands of small, monotypic conifer trees has altered the water balance in mountain watersheds.

The territory occupied by fir trees has significantly expanded into lower elevations during the last century, and firs now dominate many hillsides where the majestic old ponderosa pines once reigned. The current drought, combined with pests, disease, and a thick understorey of juniper, has also displaced old ponderosa pines from lower elevations. Although these old pines were on the fringe of their adapted range in the Sacramento Mountains, they had prospered here for several hundred years.

The piñon-juniper zone has also undergone dramatic changes associated with the recent drought. Piñon pine has suffered a massive die-off in the foothills of the Sacramento Mountains, primarily because it is drought intolerant and less competitive than juniper. Its shallow roots generally extend no more than 21 feet into the ground, increasing its susceptibility to pests and disease during stressful drought periods.



This map showing availability of firewood in the territory of New Mexico was published in 1883 in the Tenth Census of the United States. The Department of the Interior survey depicts a landscape of low density, open woodland, and forest in the Sacramento Mountains.

Many trees that have lived and thrived here for over two centuries recently succumbed to the killer combination of drought, pests, and competition. The current drought will alter the composition of our woodlands. Small alligator junipers or one-seeded junipers are already positioned to fill the void left by dying piñon. As these junipers grow, they will eventually dominate the foothills, creating a monoculture and decreasing the habitat value for wildlife. Juniper trees also use more water than piñon pine, thus increasing consumptive use of water in this vegetation zone.

In this photo of piñon-juniper woodland, the dead trees are piñon, whereas the junipers are still healthy.

Changes in plant diversity affect the water balance in mountain watersheds. Evergreen trees use water in the winter because they never go dormant, as do grass and deciduous plants. The extensive root systems of evergreens allow them to use most of the summer and winter precipitation. Mature ponderosa pine roots can extend to a depth of 15–79 feet, and large pines use over 250 gallons of water per day in the summer. Juniper roots can extend to a depth of 80–200 feet. A 12-inch-diameter juniper can use 34 gallons of water per day in the summer and 14 gallons per day in the winter.

As conifer populations dominate the landscape, both deciduous trees and grasses are choked out. Conifers are displacing aspen and oak, deciduous species that use much less water than conifers and are dormant in the winter, allowing snow and precipitation to contribute to recharging the water table. Trees use from 4 to 17 times more water than grass to produce a pound of biomass. The transition from a mosaic of deciduous trees, grasses, junipers, and conifers to monotypic stands of conifers has sacrificed both water and biological diversity.

WATER AVAILABILITY

A forest is a living thing; changing one part will influence other parts. The tree-covered hills we see today are a result of unnatural forest growth that has followed logging and fire suppression during the last century. Water is an indispensable part of any healthy forest, and in the Sacramento Mountains its availability has steadily and dramatically decreased in our lifetimes. Many springs and streams that were perennial during the last century have become intermittent sources of water in the last 20 years, flowing seasonally and only during years with high precipitation. Several streams have completely dried up, including the Agua Chicuita, Cuevo, La Luz Creek, Three Rivers Creek, and the Sacramento River.

The Agua Chicuita stream has been dry for over ten continuous years. Investigations along its upper course reveal reservoirs and old ditches that were once used to store water for irrigation. Maps from the Office of the State Engineer show that many people have water rights along this ex-stream. Descendants of homesteaders describe it as a dependable source of water that had dried up only twice in their lifetimes. Photos taken in the early 1900s portray the Agua Chicuita as a substantial stream.

The Sacramento River played an important role in the development of the watershed. In the early 1900s a railroad company built a pipeline from the river above Timberon to Orogrande in the Tularosa Basin to supply water for its steam engines. The springs feeding this small river provided water for the Orogrande pipeline, as well as for fishing at Timberon, as recently as the 1970s. The U.S. Geological Survey stream gage on the Sacramento River was closed in 1989 when the river dried up. Orogrande is presently tying into a pipeline near Chaparral for its water supply because the spring at their water intake location on the Sacramento River is also dry.

Carrisa Spring, which once supplied the community of Timberon with water, dried up in September of 2000 for the first time since flow records have been kept for the spring. The spring yielded as much as 600 gallons of water per minute when the Sacramento River valley was settled in the late 1800s. A 10-inch flow meter was installed on the main spring in 1986, measuring its flow at an average of 108 gallons per minute that year. The flow during the 1990s ranged from a high of 124 gallons per minute in 1990 to a

	Piñon–juniper woodland		Ponderosa pine		Mixed conifer	
	circa 1900	circa 2000	circa 1900	circa 2000	circa 1900	circa 2000
Trees/acre	19–25	1,300 above 1”	20–50	180–220 >5” dbh	40–70	200–250
Basal area	Multi-aged	> 120	Multi-aged	110–120	Moderate, open stand	120–140
Site water	Limited seeps and springs	Depleted, minor water available	Seeps, springs, moderate ground water recharge	Diminished 10–30%	Active seeps, springs	Diminished 10–30%
Soil	Thin, but intact with dense grass	Very unstable, lack of cover	Dense grass, some shrub cover	Unstable, minimal ground cover	Intact and stable, dense grass and forbs	Unstable, minor grass cover
Fire interval	Low intensity, frequent 5–15 years	60% of stand at risk of crown fire	Low intensity frequent ground fire 3–10 years	65% of area at risk of crown fire	4–15 years	Larger crown fire potential

Summary of research findings by M3 Research relating to tree density and other forest components.

low of 66 gallons per minute in 1994. In early 2000 the flow was 69 gallons per minute, then the spring declined steadily until it dried up altogether.

Timberon residents are now trying to find more water by deepening existing wells, but they are having difficulty finding adequate water in a watershed already drained by acres of heavy timber. The aquifer in the San Andres Limestone that supplies Timberon is one that readily transmits water through enlarged fractures and holes in the rock, but it also has a relatively small storage capacity. In other words, it must be continually recharged. The combination of the current drought and thick timber on the upper slopes has altered the water balance dramatically and dried up springs, streams, and the ribbon of riparian habitat once used by both man and wildlife

INVESTIGATIONS AND RESTORATION

A historic reconstruction of vegetation type, size, and density has recently been completed for the Lincoln National Forest. Early logging records and other U.S. Forest Service records were used to recreate woodland landscapes present in the Lincoln Forest Reserve in 1902. These records indicate a tree density of 20–70 trees per acre, with trees ranging from 25–45 feet apart. Now average woodland densities are 200–250 trees per acre for trees measuring more than 5 inches in diameter at breast height. The average distance between trees is 3–10 feet if trees less than 5 inches in diameter are also counted.

The Otero Soil and Water Conservation District (Otero SWCD) and the Natural Resources Conservation Service (NRCS) recently completed a grant proposal for watershed investigations and restoration in the Sacramento Mountains. The principal component of the proposal is to map the hydrogeology in the Sacramento Mountains to determine where recharge zones for the springs and streams are located. The map will be used to delineate areas where vegetation thinning could have the most positive impact on restoring surface and ground water sources. Another component of the proposal includes the development of a watershed model to predict the effects of various resource alternatives on the water balance in these mountain watersheds.

A coalition of state, federal, and local government entities recently initiated a study of the Sacramento River and its watershed. The Otero SWCD, Otero County Commission, residents of Timberon, the U.S. Forest Service, and the NRCS have joined forces to participate in the endeavor. The hydrogeology, early written history, photographic reconstruction, and a watershed model are all components of the study. In addition, the Otero SWCD recently received a grant through the U.S. Bureau of Reclamation to monitor static water levels in six wells in the watershed.

Focusing thinning and restoration efforts in recharge zones for streams and springs has proven to be a successful approach for restoring surface water on Mescalero Apache tribal lands. In 1998 the Mescalero Apaches noticed that the flow of Whitetail Spring had diminished dramatically until it was barely able to fill the adjacent storage pond. This spring system supplies water through 25 miles of pipeline to both cattle and large wildlife populations. The tribe requested assistance from the NRCS to restore and conserve the spring. After mapping the recharge area for the spring, the U.S. Bureau of Indian Affairs immediately began timber sales in the recharge zone to replenish subsurface flow to the spring. The forest management plan identified 1,225 acres of the 2,400-acre recharge area to be thinned by Mescalero Forest Products crews. Trees were thinned to a density of about one 12-inch tree every 40 feet. Two 20- to 25-acre blocks were clear cut to make parks or forest openings. More sunlight in the parks has allowed grasses and shrubs used as browse by wildlife to increase. Thinning proceeded for about 18 months before flows in Whitetail Spring visibly increased. Thinning of the last units will be completed in 2003. Whitetail Spring is still flowing and filling the pond and pipeline system, even though the drought has intensified. The Mescalero Apache Tribe has asked that the same process be initiated for Encino Spring, which is now in jeopardy. Similar hydrogeologic surveys are planned for springs throughout the Sacramento Mountains.

SUMMARY

If we wait for watershed health to improve, it probably won't. All the streams in the Sacramento Mountains are now discharging substantially less water than they were during the 1980s. Springs have been disappearing for decades, but the rate has accelerated during the current drought. The communities of Cloudcroft, Ruidoso, and Alamogordo all have serious water supply problems that are intensified by declines in their watershed yields. Most municipal residents do not realize that they have traded their water for trees. At least 65 rural wells have also dried up, and in some instances, water was not available even when the wells were deepened. The impact to wildlife populations, livestock producers, and mountain residents has been substantial. Proactive management of tree stands is the only alternative available to sustain the lifeblood of these mountains—water.

SUGGESTED READING

Kaufmann, Merrill R., Huckaby, Laurie S., Regan, Claudia M., and Popp, John, 1998, Forest Reference Conditions for Ecosystem Management in the Sacramento Mountains, New Mexico: U.S. Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-19.

Garrett, Dave, and Garrett, Pamela, 2001, Evaluating Forest Restoration Opportunities on the Lincoln National Forest: M3 Research

Managing Forests and Woodlands for Increasing Water Yields

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Over the past century forest density has generally increased in New Mexico due to fire suppression, reduced grazing rates, and reduced harvest of timber for fuel wood and other products. The problem is that the increase in forest density may increase the risk of high-severity wildfires during unusually dry periods. High-severity wildfires generally have a much greater effect on runoff and water quality than forest harvest or thinning operations using best management practices. Data from the Cerro Grande and other fires show that such high-severity fires greatly increase surface erosion rates and the size of peak flows, induce channel scour and bank erosion, cause downstream sedimentation, and adversely affect water quality. Hence there is increasing interest in reducing forest vegetation density, but the justification and effects of these treatments will vary by forest type.

The effect of fire suppression is particularly marked in lower-elevation forests where fire historically was relatively frequent. Because annual precipitation in these lower-elevation forests is generally less than 18–20 inches, any reduction in vegetation to reduce fire risk will have little or no effect on annual water yields. The last century of fire suppression has had much less effect in higher-elevation forests because the several hundred-year natural fire recurrence interval in these forests is longer than the period of suppression. There is much less justification for thinning in these higher-elevation forests, but these are the forests where harvesting or heavy thinning has the potential to increase water yields.

Efforts to reduce fire risks in lower-elevation areas or alter the density of tree cover in piñon-juniper woodlands involve a variety of social, legal, and economic considerations, and these may make it difficult to implement larger-scale treatments. Similarly, social and physical considerations may severely limit efforts to increase water yields from the higher-elevation forests.

MANAGEMENT EFFECTS ON RUNOFF PROCESSES AND WATER YIELD

Piñon-Juniper Woodlands The historic record indicates that there has been an increase in the density of piñon pine and/or juniper in piñon-juniper woodlands and a corresponding decline in the abundance of broad-leafed plants and grasses. Although tree removal may reduce interception and transpiration losses, these are offset by a corresponding increase in soil evaporation and transpiration from the denser understory. Hence it is virtually impossible to increase water yields through tree removal in piñon-juniper woodlands, where annual precipitation is below the 18–20 inch threshold. Predicting the effects of management actions in piñon-juniper woodlands is particularly difficult because there can be such large differences in runoff processes and management effects between the canopy and intercanopy areas.

In some cases removing the tree canopy may affect the timing and quality of stream flow, even though there is no change in the annual water yield. A critical issue is how overstory removal affects the amount of surface cover and surface roughness. Runoff and erosion rates generally are much lower under the tree canopy than in the intercanopy areas. If removing the woody vegetation results in less surface vegetation, there can be an increase in the amount of overland flow and surface erosion, and this may reduce the amount of groundwater recharge and the magnitude of base flows. On the other hand, if management increases the amount of surface cover and roughness—especially in the intercanopy areas—the resulting increase in infiltration may reduce the size of peak flows and cause some streams to flow on a more regular basis. This shift in runoff processes may reduce total annual runoff while improving the timing and the quality of the runoff.

Similarly, a reduction in grazing intensity may increase herbaceous cover and reduce the amount of overland flow by increasing infiltration rates. Although most of this additional infiltration would be lost to evapotranspiration, this shift in runoff processes again could result in lower peak flows and more sustained stream flows.

The effects of wild and prescribed fires on runoff rates are difficult to predict. In general, a higher-severity fire should have a proportionally greater effect on runoff rates because of the greater loss of surface cover.

Forests Forests in New Mexico include lower-elevation ponderosa pine forests, mid-elevation mixed conifer forests, and higher-elevation spruce-fir forests. In areas where annual precipitation is greater than 18–20 inches it may be possible to increase water yields by large-scale reductions in the number and density of trees. The social, political, and physical constraints on forest harvest imply that water yield increases associated with removing forest vegetation will be relatively small.

In general, only a small portion of a watershed can be subjected to forest harvest, and this limits the potential increases in water yields. For example, only 24 percent of the 4,100-acre Coon Creek basin in Wyoming's Medicine Bow National Forest could be harvested due to various management constraints, and the observed initial increase in annual water yield was 3.0 inches per unit area harvested, or 0.7 inches when averaged over the entire watershed. This increase in annual water yield is consistent with the results of other watershed studies in the central Rocky Mountains. At a yet larger scale, intensive management of national forest lands in the California Sierra Nevada was predicted to cause a sustained water yield increase of only 0.1 inch, as much of the land is not suitable for timber harvest or is subject to other management constraints.

A more recent study estimates that the increase in forest density since the late 1800s on national forest land in the North Platte River basin in Colorado has decreased water yields by approximately 160,000 to 185,000 acre-feet per year. This is slightly less than 2.0 inches of water per unit area of forest land or approximately 1.6 inches of water over the entire watershed. Approximately 54 percent of the total area, or 66 percent of the forested area, is classified by the USDA Forest Service as land suitable or potentially suitable for timber harvest. Intensive forest management on these lands could yield an average of 55,000 acre-feet of additional water per year. The 55,000 acre-feet converts to 0.9 inch per unit of suitable forest land, or 0.5 inch per unit of total forest land. This is slightly more than one-third of the "losses" that are currently occurring as a result of the increase in forest density.

The values from the North Platte River basin study probably represent the upper boundary on water yield changes that might be expected from forested areas, as two-thirds of the national forest in the North Platte River basin were classified as suitable or potentially suitable for timber harvest. Furthermore, forest types with a high potential for increasing water yields (spruce-fir and lodgepole pine) accounted for nearly 85 percent of the forested area; while forest types with a lower potential for increasing water yields (ponderosa pine and aspen) occupied only 13.5 percent of the forested area.

In most cases, a reduction in forest density by prescribed burning will not increase water yields. Most prescribed burns are designed primarily to remove brush and suppressed trees, and are not intended to kill a significant proportion of the overstory. There is little reason to expect an increase in water yields unless there is a substantial reduction in vegetation density over the entire watershed.

Though field data from New Mexico are scarce, hydrologic response to forest treatment in New Mexico is expected to follow the patterns seen in studies of similar forest types elsewhere. Importantly, in New Mexico only small portions of the larger river basins are occupied by the higher-elevation forests that have sufficient annual precipitation to even consider the potential for increasing annual water yields.

MANAGEMENT EFFECTS ON EROSION, WATER QUALITY, AND FOREST HEALTH

Piñon-Juniper Woodlands Management goals for piñon-juniper woodlands are typically to increase the amount of forage and vegetative ground cover, reduce erosion, and re-establish native riparian species. Aggressive treatments such as chaining are generally not acceptable because of excessive ground disturbance and potential increases in erosion. The most significant management issue in the piñon-juniper zone is the intensity, timing, type, and location of grazing activities. Although the effects of grazing can be highly variable, the scientific literature generally indicates that high-intensity grazing causes a significant reduction in plant cover and infiltration rates, potentially leading to an increase in runoff and surface erosion, and a decrease in site productivity and water quality. Light to moderate grazing has much less effect in terms of soil compaction, surface erosion, the degradation of riparian areas, and adverse changes in water quality and stream channel characteristics.

Cattle tend to concentrate in riparian areas because of the better forage, water for drinking, and shade. The concentration of cattle in riparian areas usually causes a more direct and largely adverse effect on aquatic resources than high-intensity grazing outside the riparian area, as a much higher proportion of sediment and animal wastes is likely to be delivered directly into the stream network. If cattle or other animals concentrate in the riparian areas, the resultant trampling and reduction of riparian vegetation can destabilize the stream banks and further increase the amount of sediment being delivered to the stream.

Some of the adverse effects of grazing can be alleviated by simply reducing the number of animals, but the total number of animals is often not as much of a problem as the distribution of animals within the areas being grazed. A combination of fencing, herding, and providing salt, shade, and watering points away from streams can help ensure a more even distribution of grazing pressure and reduce the concentration of animals in the riparian zone.

Forests The primary forest management options include commercial harvest, commercial and non-commercial thinning, and prescribed burning. An extensive program of forest harvest or thinning could increase erosion rates and adversely affect water quality as a result of increased turbidity and sediment loads. The magnitude of these effects will depend more on the methods used to gather and remove the woody material than on the harvest itself, as roads and skid trails are the primary sources of sediment from well designed and carefully executed forest management programs. The increase in erosion from harvested areas and the accompanying adverse impacts on water quality usually can be minimized by applying Best Management Practices. The design, construction, and post-harvest treatment of the road and skid trail system is critical to minimizing the generation and concentration of overland flow, and hence the amount of surface erosion. The use of buffer strips along both ephemeral and perennial streams can greatly reduce the delivery of overland flow and sediment to the stream network. Maintaining riparian vegetation is the best means to minimize increases in water temperatures.

The primary advantage of reducing forest density is the lower risk of high-severity fires. In the absence of any effort to reduce forest density, one can expect a continuing (or gradually increasing) risk for high-severity wildfires in forested areas. Such fires are of considerable concern because of the potential to destroy property and greatly increase runoff and erosion rates. The increase in runoff from wildfires is usually regarded as a negative effect because high-severity fires can increase the size of peak flows by as much as a factor of 10. Erosion rates from forested sites burned at high severity can increase by a factor of 100 or more. These changes can have severe effects in terms of downstream flooding, reservoir sedimentation, and degradation of aquatic habitat.

Prescribed fires generally have minimal effects on runoff and water quality, as the fire severity is mostly low to moderate, resulting in much less soil water repellency than high-severity fire. Areas burned at moderate or low severity also have much lower percentages of bare ground; recent research shows that erosion rates are strongly correlated with the percent of bare ground. As long as the percent bare ground is less than approximately 20–30 percent, post-fire erosion rates should be very low and therefore pose little threat to water quality and downstream aquatic resources.

REGULATORY AND LEGAL CONSIDERATIONS

High-elevation forests present greater opportunities for increasing water yields than piñon-juniper woodlands or riparian zones. Two different sets of laws affect the potential to manage these forests for increased water yields.

The first set of laws governs land management practices and the protection of surface waters. Most of the constraints placed by these laws relate to the planning, studies and administrative procedures for deciding what management activities are appropriate. The National Forest Management Act restricts the methods and locations of logging and road building on national forest lands. The National Environmental Policy Act requires federal agencies to consider the potential environmental impacts of any proposed policy or action. The Clean Water Act may limit activities through state-specific water quality criteria. The Endangered Species Act may limit actions in areas with threatened or endangered species, or in areas that might be suitable habitat for these species. The National Historic Preservation Act and the American Indian Religious Freedom Act may limit land disturbance near sites of historical, cultural, or religious significance.

The second set of laws governs the use and ownership of water. Water use generally is subject to the prior appropriation doctrine, which means the person with the most senior water right has the first claim, and the most junior claim can receive water only when all senior water rights have been satisfied. Any "additional" runoff created by watershed management becomes part of the public water supply and is subject to the prior appropriation system. Hence a person or entity that increases the amount of runoff would not be able to claim that water except by obtaining a new and very junior water right, so there is no direct incentive for a person or agency to manage for increasing water yields. Some states explicitly preclude anyone from claiming the rights to water generated by a reduction in vegetation density.

ECONOMIC AND SOCIAL CONSIDERATIONS

The costs of a program to manage or restore piñon-juniper woodlands will be much greater than the direct economic benefits. Piñon-juniper woodlands are used primarily for fuelwood and livestock production. Past practices included chaining followed by seeding, but this was costly, induced severe erosion in some areas, and engendered considerable public resistance. Broadcast burning often is not feasible because there is not enough fuel to carry the fire during the conditions conducive for controlled burns. Overall, the costs of trying to alter or intensively manage piñon-juniper woodlands have far exceeded the potential returns, so many efforts have been discontinued.

Efforts to reduce vegetation density and increase water yields in forested zones generally will require a net investment of public funds. Commercial forest harvest or thinning is more economically feasible in areas with less than 30 percent slope and an existing road network. In other areas, thinning is much more difficult unless it also includes some harvest of the larger trees that have more economic value. In some areas the thinned material may be used for poles, posts, or fuelwood, and this can help offset some of the costs of the thinning. If there is not a commercial market for the harvested material, the thinnings have to be chipped and scattered, piled and burned, or broadcast burned. In the Upper South Platte watershed southwest of Denver, thinning costs for ponderosa pine are approximately $1600 per acre.

Local residents may support efforts to manage and restore woodlands and forests because of the potential to improve watershed conditions, reduce fire risks, and provide short-term employment. However, some of the management actions may encounter local opposition. Piñon and juniper are the preferred fuel wood in many areas, and any program or action that would limit access or supply might encounter local opposition. Grazing of sheep and cattle is a tradition and a source of livelihood in many communities, and efforts to restrict or control the number of animals in piñon-juniper woodlands may be opposed by local communities. Efforts to harvest or thin public forests often engender considerable opposition, even though these actions may reduce the risk of high-severity wildfires and improve wildlife habitat while having few negative effects on water quality.

An important concern in the case of prescribed fire and broadcast burning is the effect on air quality. Fires in forested areas produce a large number of particulates that are a hazard to human health, and the regulatory agencies may limit the number of permits for prescribed burning because of the temporary reductions in air quality. Smoke is visually unappealing and this can be an important concern for communities dependent on tourism. For these reasons prescribed burning programs often encounter considerable public resistance.

To be successful, restoration and management plans must be designed in collaboration with local communities to generate local support. Local communities can directly benefit from restoration and management efforts through contracts for forest harvest and thinning, prescribed burning, erosion control, and other stewardship work. If much of the cost has to be met by public funds, these efforts will require broad public support.

SUMMARY OF POTENTIAL AND PITFALLS OF FOREST MANAGEMENT

Advantages of manipulating the vegetative cover in forests and woodlands include the following:

- Reduced risk of wildfires;
- Reduced surface runoff, surface erosion, and channel incision in piñon-juniper woodlands;
- Improved range and riparian conditions in piñon-juniper woodlands and possibly improvements in water quality;
- Increased amount and quality of forage;
- Improved habitat for native riparian and aquatic species at lower elevations;
- Potential for small increases in water yield from higher-elevation forests, especially in wetter years.

Disadvantages of actively managing the vegetative cover in forests and woodlands include:

- Limited potential to increase water yields; coupled with the need to store a water yield increase until it is needed;
- Smaller water yield increases in dry years;
- Poor cost/benefit ratios;
- Potential declines in air quality and threats to human health from increased particulates from prescribed fires;

- Considerable public opposition to forest harvest and thinning;
- Difficulty of balancing the needs of different resources and user groups.

SELECTED READING

Blackburn, W. H., Knight, R. W., and Wood, M. K., 1982, Impacts of grazing on watersheds—A state of knowledge: Texas Agricultural Experiment Station: Texas A&M University, College Station, 30 pp.

Brown, H. E., Baker, Jr., M. B., Rogers, J. J., Clary, W. P., Kovner, J. L., Larsen, F. R., Avery, C. C., and Campbell, R. E., 1974, Opportunities for increasing water yields and other multiple use values on ponderosa pine forest lands: U.S. Department of Agriculture Forest Service Research Paper RM-256, Fort Collins, Colorado, 36 pp.

Troendle, C. A., Wilcox, M. S., Bevenger, G. S., and Porth, L. S., 2001, The Coon Creek water yield augmentation project—Implementation of timber harvesting technology to increase streamflow: Forest Ecology and Management, v. 143, pp. 179–187.

Surface Water Quality Monitoring in the Lower Pecos River Watershed

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New Mexico recognizes the value of surface waters as a public resource. Surface waters irrigate croplands, water livestock, and, as live streams (the "thin green lines" in the desert), support a variety of wildlife and places where people can fish, swim, watch and photograph wildlife, or simply find peace and relaxation. These "designated uses" are the management goal of the Surface Water Quality Bureau of the State of New Mexico. Our mission is "to preserve, protect and improve New Mexico's surface water quality for present and future generations."

The lower Pecos River and some of its tributaries (including the Rio Peñasco) do not currently support these goals. The causes include disruption of both hydrologic and sediment regimes. These kinds of impairments can be seen throughout New Mexico. Disruption of the hydrologic regime includes changes in the runoff characteristics of the watershed, such as unnatural changes in the vegetation (like forest overgrowth), increased impermeable surfaces (like asphalt), or poorly designed bar ditches along roads. These changes tend to make watersheds more "flashy," resulting in less water soaking into the ground—ground waters that would otherwise support stream flow in dry times. Flashy streams also tend to downcut. Excessive diversion of stream flow such as for irrigation is another way to disrupt the hydrologic regime; the diminished flows can jeopardize the survival of the fish in these streams.

Rio Peñasco below the mouth of Cox Canyon (showing recent channel excavations and levee rebuilding).

Rio Peñasco below the mouth of Cox Canyon (showing recent channel excavations and levee rebuilding). Recent flood debris in side channel from burned area.

Disruption of the sediment regime involves changes to the stream's sediment supply. Watershed impairments such as those described above often increase the supply of fine-grained sediment or silt. A gravel stream bed by its very nature usually has spaces between the gravels that serve as habitat for and support aquatic insects (which fish eat) and even fish eggs. Oxygenated water usually circulates through these gravels. When these spaces are filled with silt, this habitat and (eventually) the fishery are destroyed.

TOTAL MAXIMUM DAILY LOAD

One measure of the standards that are set for water quality throughout the state is "total maximum daily load" (TMDL), which can best be described as a watershed or basin-wide budget for pollutant influx to a watercourse. TMDLs may also be established for a portion or segment of a watershed. A TMDL, in actuality, is a planning document. Through scientific study the allowable budget—the amount of pollutants that can be assimilated without causing the stream to exceed the water quality standards set to protect the stream's designated uses—is first determined. Once

Some Background on TMDLs

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The federal Clean Water Act requires states to determine whether water bodies meet water quality standards and protect beneficial uses. In instances where water bodies do not meet a particular water quality standard, states must identify that water body as impaired and determine the total maximum daily load (TMDL) of the pollutant that the water body can receive and still meet water quality standards. The state then allocates that TMDL among both point and nonpoint sources discharging to the water body, with the objective of reducing pollutants and improving water quality. However, because states lacked data and resources to accomplish this objective, neither the U.S. Environmental Protection Agency (EPA) nor the states historically used the TMDL program to address water quality problems—until the EPA was barraged by citizen lawsuits.

In 1997 one such lawsuit in New Mexico (*Forest Guardians and Southwest Environmental Center v. Carol Browner*, Administrator, U.S. EPA, Civil Action 96-0826 LH/LFG) resulted in a federal court monitored consent decree and settlement agreement between the EPA and environmental groups concerning development of TMDLs in New Mexico. This consent decree laid out an ambitious schedule for the development of TMDLs throughout the state. TMDLs summarize identified wasteload allocations for known point sources and load allocations for nonpoint sources at a given flow. TMDLs must also include a margin of safety to account for uncertainty in the calculation of the pollutant allocations.

A TMDL is not a regulatory document; it is a planning document that contains recommended actions intended to protect or restore the health of the water body. In 1999 the New Mexico Environment Department, Surface Water Quality Bureau developed 26 TMDLs on 11 different reaches in four watersheds throughout the state. These TMDLs were determined for a variety of pollutants such as stream bottom deposits, turbidity, total phosphorous, total ammonia, fecal coliform, and temperature. After TMDLs are developed, there is a legitimate expectation that they will be implemented. The Surface Water Quality Bureau has started implementing TMDLs in several watersheds.

—Excerpted from *Water, Watersheds, and Land Use in New Mexico*, Peggy S. Johnson, editor, 2001 Decision-Makers Field Guide, New Mexico Bureau of Geology and Mineral Resources.

Lower Pecos River (main stem) 2003 Intensive Water Quality Survey.

this is done, sources of the pollutants are considered. Both point and nonpoint sources must be included. Once all the sources are accounted for, the pollutants are then allocated or budgeted among the sources in a manner that will describe the limit (the total maximum load) that can be discharged into the river without causing the stream standard or budget to be exceeded. Nonpoint sources are grouped into a load allocation and point sources are grouped into a wasteload allocation. By federal regulation, the budget must also include a margin of safety. TMDLs can therefore be described by the following equation:

TMDL = sum of nonpoint sources + sum of point sources + margin of safety

TMDL ASSESSMENT FOR THE LOWER PECOS RIVER WATERSHED

An intensive water quality survey for the lower Pecos River watershed is in progress and will be finished in early fall 2003. The lower Pecos River watershed is defined for this survey as the Pecos River from Fort Sumner Dam south to the New Mexico–Texas border; it includes the Rio Ruidoso, Rio Hondo, and Rio Peñasco drainages. The data from the survey are expected to be back to the Surface Water Quality Bureau by summer 2004. The data will undergo a thorough check to ensure that the results are not erroneous. Once this is done, the watershed will be assessed for impairment and listing on the State's 303(d) list, which is a compilation of all impaired surface waters statewide. If it is determined that portions of the lower Pecos River watershed are impaired by one or more pollutants, then TMDLs will be written for those pollutants in 2006–2007.

Drought in New Mexico: History, Causes, and Future Prospects

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Ecosystems and human societies have adapted to New Mexico's desert climate. During prolonged drought periods, however, life in the desert can become extraordinarily harsh and difficult. Drought in New Mexico causes dry riverbeds, widespread plant and wildlife mortality, failed crops, and may have contributed to the collapse of prehistoric civilizations in the not-so-distant past. It behooves us to study the history of drought to get an idea of what is in store for us when the next major drought event befalls us.

We don't have a thorough understanding of what causes long-term drought episodes. Recent research on the variability of the world's oceans offers insights into possible causes of drought, but our limited knowledge is not yet sufficient to provide reliable forecasts of when the next huge drought will occur, or (perhaps more importantly) to predict when an existing drought might end. As we will discuss, however, there are ominous signs that the current dry conditions may not abate soon and that New Mexico could be in for dry times for the next few years.

DROUGHT INDICES

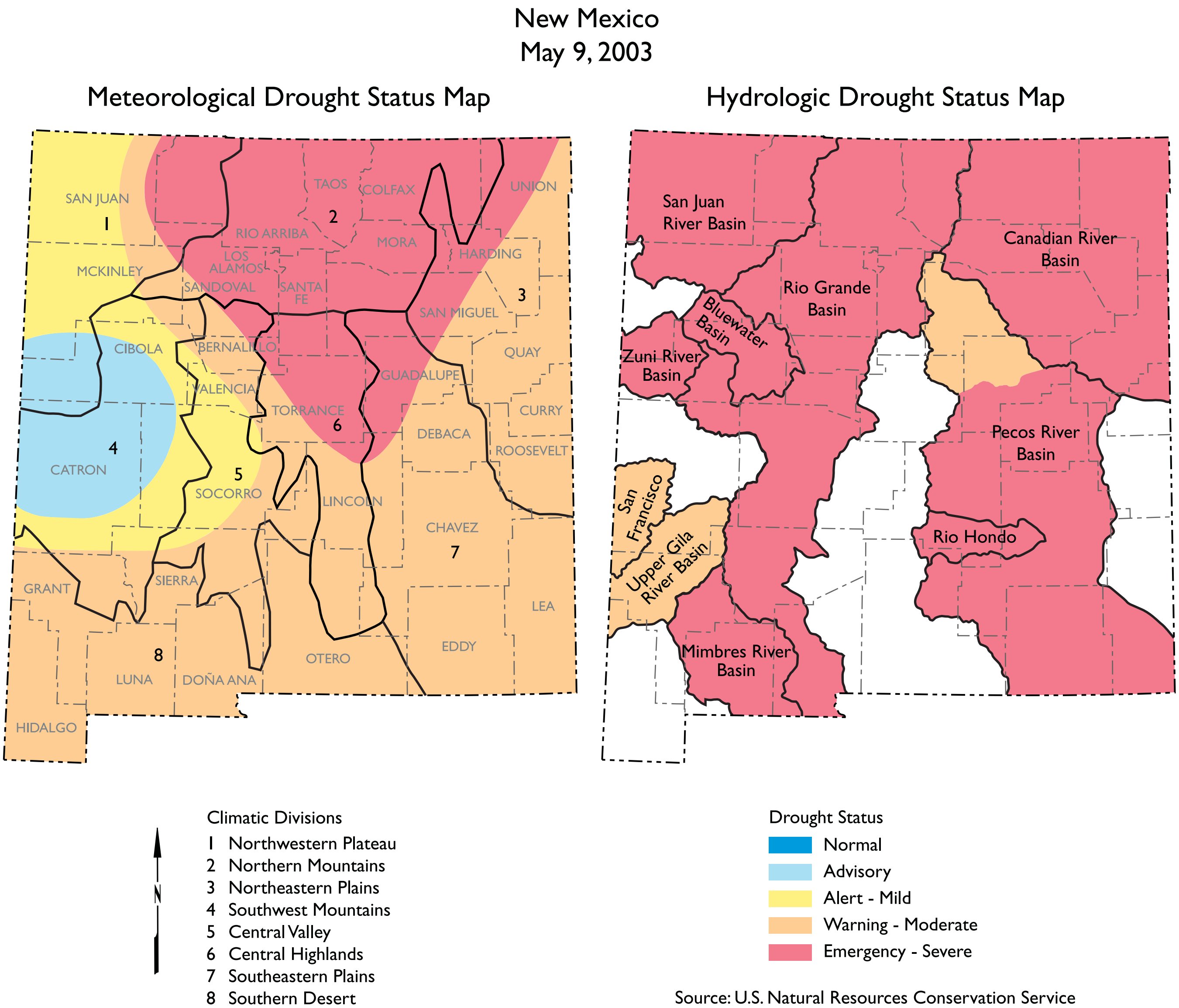
There is no standard quantitative or legal definition of "drought." The term refers to an extended period of time of below-normal precipitation, generally long enough to have pronounced effects on plants, rivers, or reservoirs. Thus, drought refers not just to persistent dry weather, but also to the various impacts that go along with dry weather. These impacts vary regionally. Three weeks without rain in a desert, coniferous forest, or wheat-growing region would have different effects in different seasons; they would have quite different consequences in a place that depends on precipitation replenishing a local reservoir than they would on a major, snow-fed river in a different location.

The National Drought Mitigation Center at the University of Nebraska defines three different "types" of drought: *meteorological* drought, defined strictly in terms of less than normal precipitation; *agricultural* drought, defined in terms of water-stressed crops or rangeland and anomalously dry soil; and *hydrologic* drought, measured in terms of shortages of surface water supplies (low reservoir levels and/or diminished stream flow). Meteorological drought affects ecosystems and economic activities that depend directly on local precipitation. Forested hillslopes, non-irrigated agriculture, and landscape watering in cities are examples. Agricultural drought generally refers to longer time scales than meteorological drought. Hydrologic drought affects large-scale waterworks and river flows, taking into account factors such as reservoir levels (which are affected by consecutive years of drought) and winter snowpack at the headwaters of large river drainages.

At present (June 2003) most of New Mexico has received near-normal precipitation for the water year that began in October 2002, hence in a formal sense we are not suffering from short-term meteorological drought. The Palmer Drought Severity Index, probably the single most commonly cited measure of drought conditions, is currently near zero (i.e., normal conditions) across most of New Mexico.

However, the Palmer Index is based entirely on local weather history. Dry conditions prevailed for several years before last autumn, and neither rangelands nor reservoirs have recovered from very poor conditions. Thus, indices of agricultural drought (such as soil moisture estimates) or hydrological drought (such as reservoir levels) indicate that New Mexico is deep in a long-term drought.

Recognizing the multiple components of drought, in spring 2003 the New Mexico Drought Task Force (which reports to the governor) switched from using the Palmer Index as its principal drought indicator to a two-component set of maps on the next page. The task force regards parts of the state to be in the midst of a long-term meteorological drought (the map on the left), emphasizing the multi-year precipitation deficit that has built up since the late 1990s. The map on the right shows the absolutely dire situation in the state with regard to hydrological drought in both the Rio Grande and Pecos drainage basins. Reservoir levels are very low (as a result of very dry years in 2001 and 2002), and current forecasts call for minimal river flows in the Rio Grande and Pecos River following a deficient winter snowpack in northern New Mexico and southern Colorado.

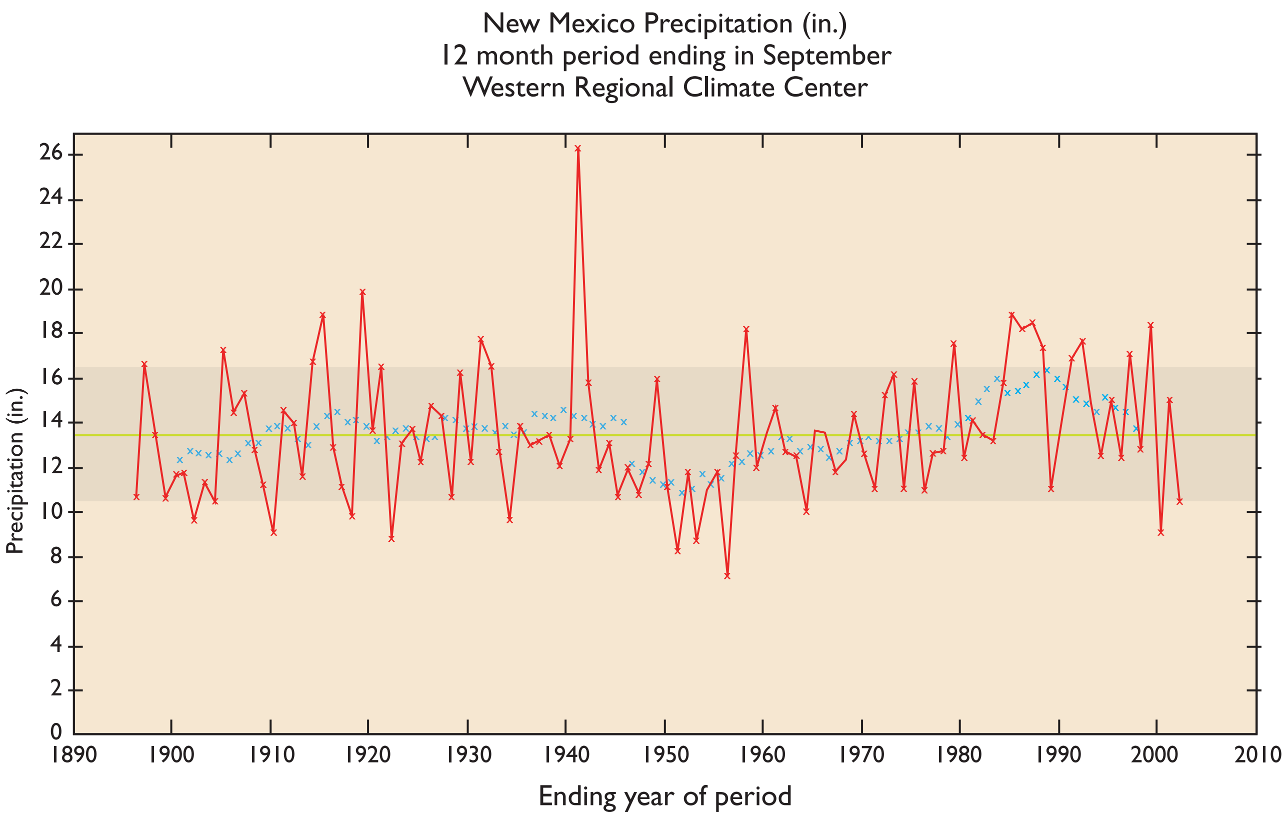


Drought status maps (issued May 9, 2003) from the New Mexico State Drought Task Force, available online from the New Mexico Climate Center at http://weather.nmsu.edu/drought/ (a) Status of "meteorological drought"; (b) Status of "hydrological drought." Color scheme is the same in both maps, ranging from blue ("normal" or no drought) to deep red ("emergency" or severe drought). Hydrologic drought is defined only for selected river basins; areas between these basins are left blank.

PREVIOUS DROUGHTS IN NEW MEXICO

Instrumental precipitation records in New Mexico extend back to the nineteenth century. A time series of annual precipitation averaged over the entire state since 1896, shown in the figure on the opposite page, is based primarily on a network of several hundred volunteer "cooperative observers" spread throughout the state organized by the U.S. National Weather Service. (Even today this network of citizens—ranchers, park rangers, backyard weather enthusiasts, etc.—none of whom receives payment for this effort—forms the backbone of our nationwide climate observing system.) Each annual value contains considerable uncertainty: there are large gaps between weather stations, and high mountain regions are undersampled, so the data in this figure probably underestimate the "true" statewide average. The solid green line shows the century-average annual precipitation in the state, about 13.5 inches.

Large inter-annual fluctuations of precipitation occur routinely. However the severe drought of the



Time series of annual water-year (October–September) precipitation averaged across New Mexico from 1896 to 2002. Red line shows annual data points; blue x's show 10-year running average; yellow line shows average annual precipitation for the entire period of record. Data and plotting routine are available online from the Western Regional Climate Center at http://www.wrcc.dri.edu

1950s clearly stands out as something unique in the twentieth century. For seven consecutive years, 1950–1956, annual precipitation was less than 12 inches. In three of those years (1951, 1953, 1956) the annual value was less than 9 inches, an amount lower than any year in the half century since then (although 2001 came close).

The 1980s and 1990s were years of plentiful rainfall by comparison. Precipitation failed to exceed 12 inches only one year in those two decades. These were decades of explosive population growth in the state. It is imperative for policy makers to understand that recent climatic conditions in the 1980s and 1990s were not "normal" by any standard. The 1980s and 1990s were just as anomalously wet as the 1950s were anomalously dry.

To put the drought of the 1950s and the wet spell of the 1980s and 1990s into long-term perspective, plots like the figure on this page can be extended backward in time using biological or geological indices that are known to correlate with climate in recent data. The most common such proxies for continental climate variability of the last 1,000–2,000 years are the annual growth rings in old trees, analyzed using a technique called dendrochronology. Trees in New Mexico have yielded a wealth of information on droughts and wet spells during the past millennium.

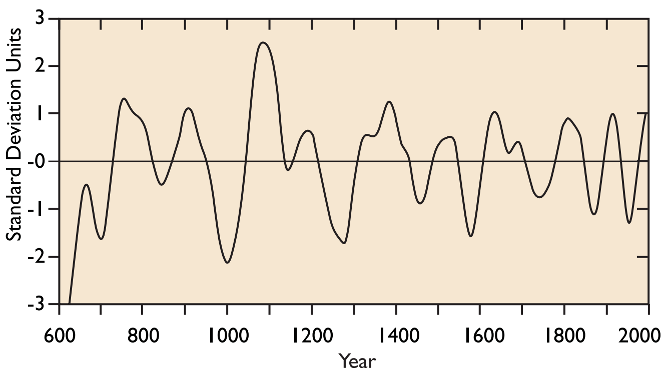
The dendrochronological record shown on the next page, for the period from A.D. 622 to 1994, is from a set of trees in south-central New Mexico. The graph shows the time series of reconstructed annual precipitation anomalies after a low-frequency smoother has been applied to emphasize long-period fluctuations, so short-term (one- or two-year) dry or wet spells are smoothed out. Several features are worth emphasizing:

- The 1950s drought was very substantial, but previous droughts (e.g., around A.D. 1000 and in the late thirteenth and sixteenth centuries) were both longer and drier.
- The late twentieth century wet spell is truncated by the smoothing function, but it is clearly a wet spell of historic proportions.

- Frequency analysis of this curve indicates that severe droughts occur at least once every century, with an average of approximately 60–80 years between droughts. An average drought periodicity between 50 and 100 years is observed in similar records throughout the Mountain West, suggesting that the next severe drought episode in New Mexico is due anytime within the next couple of decades.

CAUSES OF MULTI-YEAR CLIMATE ANOMALIES

What could cause precipitation to remain lower than normal for months, years, or a decade or more? The dendrochronological record shows that droughts have occurred in New Mexico for centuries, long before people were plentiful enough to disrupt the climate system. Research during the past several decades has



Reconstructed precipitation in south-central New Mexico, A.D. 622–1994, derived from tree ring records obtained in the Magdalena, San Mateo, and Organ Mountains. The annual precipitation values have been smoothed to emphasize multi-decadal fluctuations. From Grissino-Mayer, H., C.H. Baisan, and T.W. Swetnam, 1997, *A 1,373 year reconstruction of annual precipitation for the southern Rio Grande basin*: Final report for the Legacy Program.

pointed to slow variations in ocean temperature and currents, especially in the Pacific Ocean, as a major cause of wintertime climate variability across North America. The causes of prolonged summer droughts are not well understood at this time, but severe long-term winter droughts seem to span the seasons.

The El Niño cycle is the best known, and best understood, oceanic phenomenon that modulates drought in New Mexico. El Niño is an enormous tongue of anomalously warm Pacific Ocean surface water extending along the equator westward from the South American coast. The mirror-image cold phase is typically called La Niña. The cycle is not periodic, but extreme warm and cold phases each tend to occur several years per decade, reaching maximum amplitude in the Northern Hemisphere winter season.

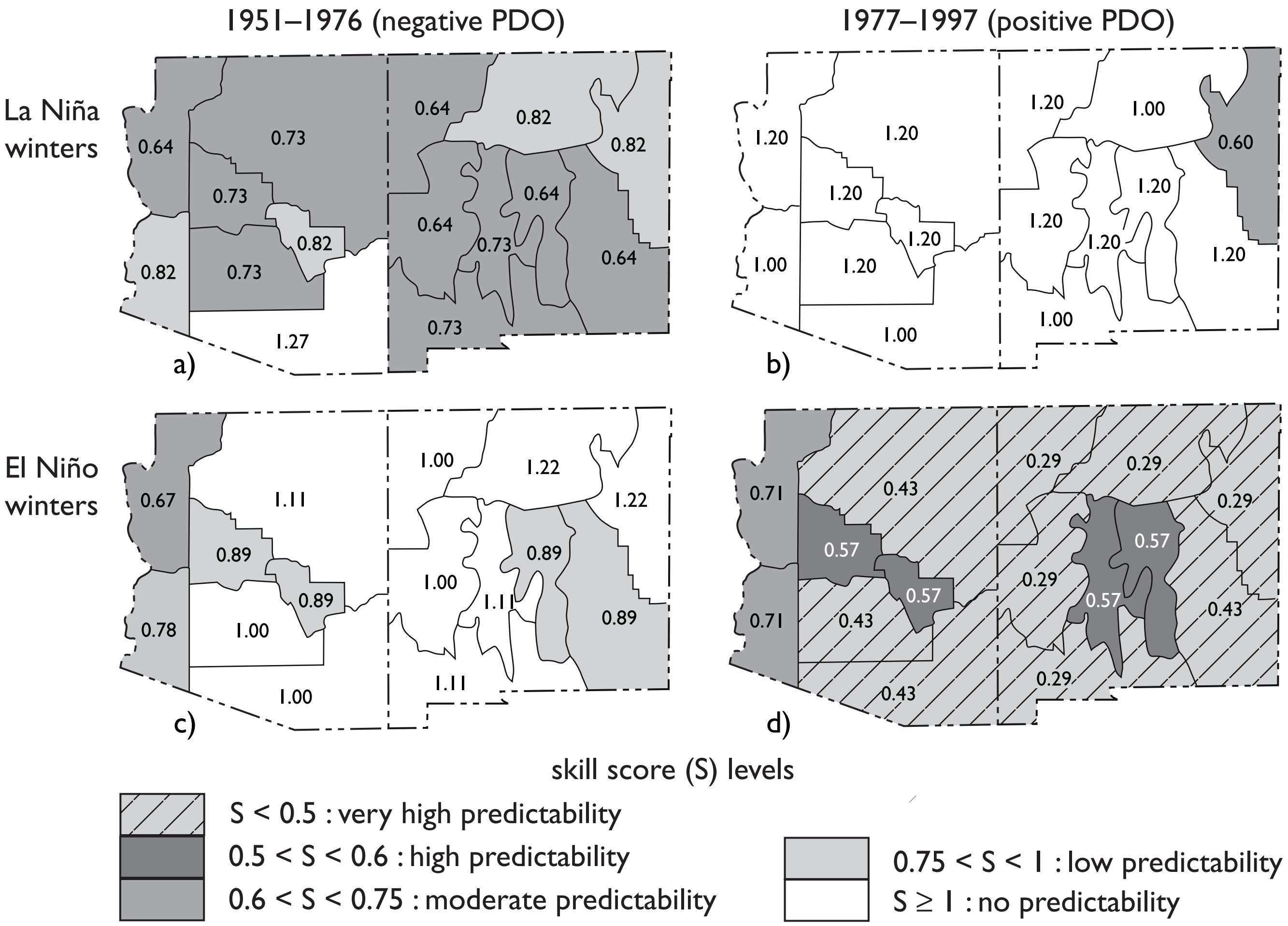
El Niño affects winter and spring precipitation by influencing the atmospheric jet stream across the Pacific Ocean. El Niño pulls the Pacific jet stream, and the storms that spawn off it, southward toward California and the southern U.S. Thus New Mexico tends to receive more precipitation than normal during an El Niño winter. La Niña has the opposite effect, pushing the jet stream northward and leaving New Mexico drier than normal.

Recent research shows that longer multidecadal fluctuations in the North Pacific Ocean also affect precipitation across southwest North America. In particular, North Pacific Ocean temperatures seem to vary more slowly than El Niño-related anomalies. This “Pacific decadal oscillation” (or PDO) seems to modulate the effects of El Niño, such that in its negative phase the effects of La Niña are amplified and the effects of El Niño are suppressed, whereas in the PDO’s positive phase the opposite modulation occurs. The PDO was in a negative phase during the 1950s (when persistent drought plagued New Mexico), then abruptly flipped in 1977 so that the wet decades of the 1980s and 1990s took place during a PDO-positive period.

El Niño / La Niña extrema are the principal source of skill for current seasonal forecasts. When we see El Niño or La Niña forming in the summer and autumn we can be nearly certain that the ocean anomalies will persist through the winter. The PDO is currently not predictable, but it appears to have flipped back to a negative phase following the huge El Niño event of 1997–98. This ominous development may have contributed to the failure of last winter’s El Niño event to generate abundant snowpack and break the current drought. Major research initiatives now in progress seek to gain better understanding of El Niño and PDO variability with the aim of improving long-range predictions of continental climate a year or more in advance.

CURRENT STATUS OF DROUGHT: SUMMER 2003

At the time this chapter is being written (June 2003) New Mexico is poised on the cusp of what could become the worst drought since the 1950s. Reservoir levels, streamflows, and rangeland-quality indices all indicate that the state is deep in agricultural and hydrological drought already. Unfortunately, current Pacific Ocean conditions are consistent with continuation of



Predictability of winter precipitation across Arizona and New Mexico derived from knowledge of El Niño or La Niña conditions the previous autumn (Gutzler et al., 2002). The plotted values represent a statistical measure of predictive skill, with 0 representing perfect predictability and 1 or greater representing no predictive skill at all. The top row of maps (maps a,b) show predictive skill associated with La Niña; the bottom row (c,d) depicts predictive skill associated with El Niño. The left column (a,c) is based on years between 1951 and 1976, when the PDO was in its negative phase. The right column (b,d) is based on years between 1977 and 1997 during a positive phase of the PDO. Thus La Niña effects (dry winters) were enhanced in the earlier period (a), and El Niño effects (wet winters) were enhanced in the later period (d). Pacific Ocean data since 1998 suggest that the PDO may have flipped back into its negative phase, whence the Southwest could be especially vulnerable to dry La Niña winters. From Gutzler, D., D. Kann, and C. Thornbrugh, 2002: Modulation of ENSO-based long-lead outlooks of Southwest U.S. winter precipitation by the Pacific Decadal Osicillation, Weather and Forecasting, vol. 17, pg. 1163–1172.

drought in New Mexico: Initial hints of the next La Niña event have been observed in the tropical Pacific, and the Pacific Decadal Oscillation seems to have shifted back into the phase that reinforces La Niña when it next occurs. Decision makers should anticipate the increasing likelihood that drought conditions in New Mexico will get worse in the near future.

SUGGESTED READING

Wilhite, D., editor, 2000, Drought—A global assessment (in 2 volumes): New York, Routledge.

SOLUTIONS, TECHNOLOGY, AND A LOOK TO THE FUTURE

DECISION-MAKERS
FIELD CONFERENCE 2003
The Lower Pecos Region

The Pecos River just south of Sumner Dam.

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Building Consensus: A Plan for Long-term Management

Reese Fullerton, *Santa Fe, New Mexico*

A rapidly growing number of collaborative decision-making processes are happening throughout the world. They involve bringing stakeholders involved in conflicts or making decisions to the table to discuss, shape, and often help decide the course being chosen. These collaborative processes are producing some dramatic results:

- Consensus agreements or decisions reached by stakeholders are more durable than decisions made solely by agencies or just approved by affected groups.
- The participation and buy-in by stakeholders (citizens, groups, businesses, and agencies) has led to the successful implementation of the agreements made through consensus.
- The commitment to each other and to the consensus agreements is best maintained if those involved continue to assist in the implementation of the agreements.
- Finally, the work of building consensus for a particular plan of action profoundly enhances the chances for long-term management success and future positive working relationships.

COMPLEX CONFLICTS AND CHALLENGES

In the face of rising challenges to environmental resources, communities and governmental agencies throughout the world have increasingly explored and chosen processes that would break the pattern of cyclical or intractable conflict. These processes occur around issues of pollution, water usage and rights, endangered species, siting of waste dumps, timber cutting, grazing, etc. Winning one day, only to lose in court or at the ballot box or because of reactive vigilante-like actions, is not what communities, agencies, and leaders hope for as consequences to their decisions. What could have been stable and long-term management plans instead often end up jeopardized, in chaos, or in disruption and ruin.

Because of these negative experiences, community and agency leaders are increasingly using consensus-building and collaborative problem-solving processes early on in the decision-making process, or early in a conflict, in order to raise issues critical to stakeholders. With all the important participants at the table, the group can begin exploring possible alternatives that will address and resolve potential conflicts and come to consensus around desired goals and ways to reach them. An example of the various helpful ways that such a process can infuse solutions into problems is the U.S. Bureau of Land Management's Rio Grande Corridor Management Plan. The involvement of the public, self selected by coming to a series of public meetings, resulted in the bureau's ability to select alternatives that it could not have otherwise afforded. Because there were community volunteers built into many of the long-term management provisions, the bureau and its involved public chose several action steps that resolved some difficult problems that members of the community would otherwise have had with the plan. Another indirect product was that groups and individuals with a history of adverse relationships with the bureau joined the effort in a positive and helpful way, which resulted in removing several major stumbling blocks.

Successes with these processes have shown that the earlier the consensus building begins before a decision must be made, a problem resolved, or a goal achieved, the more effective the process is in achieving consensus and sustainable results. It is worth noting, however, that the consensus process is often difficult to start unless a fearful threat looms over the stakeholders.

THE HARD WORK

As a society we think of litigation as tough, and sitting down to talk as softer. The work at a table among persons who have different needs and values, who have diverging traditions and goals, and often who have difficult histories with each other is real and usually very tough. It takes time to work through many of these dynamics. But compared to protracted litigation, especially in the area of water, this time is typically filled with direct and indirect progress and creative ideas that would otherwise not have surfaced. The time spent at the table is also often valuable for its own sake. The much-heralded Catron County process is a good example of this. Many participants felt that the critical success was not the particular agreement reached, but the fact that the community knew that it could come together again and again as difficult issues arose. Before the consensus-building process, there was very little communication among the persons in conflict. In fact, the tension in the community had become a real health problem.

When a group is involved in consensus building, there is no judge who makes a decision for everyone. In the final analysis it involves the difficult work of exploring ways of discovering shared values and needs, exploring common goals, getting on with the important work of the future, and letting go of the past.

THE LOWER PECOS RIVER BASIN EXAMPLE

The Lower Pecos River Advisory Committee to the New Mexico Interstate Stream Commission is an example of just such a consensus-building process. Stakeholders throughout the basin convened for the purpose of developing a plan that would achieve compliance with the Pecos River Compact of New Mexico and Texas, in annually delivering the required amount of water to Texas. This compact has a United States Supreme Court order affirming it and a federal River Master is in place to guarantee compliance. If New Mexico violates the compact, it will suffer extreme consequences. The stakeholders are cities, counties, the dairy industry, oil and gas, farmers, ranchers, irrigation districts, the state and federal agencies, and community members. Every stakeholder invited to participate had something that potentially might be lost. The group was empowered by the New Mexico Interstate Stream Commission to develop by consensus both short- and long-term comprehensive plans that would meet compact requirements, and, if they achieved that goal, plans that could be supported by the Interstate Stream Commission. As with many collaborative problem-solving processes, the will and commitment to meet the challenge grew as relationships improved, trust developed, and potentially productive ideas began to emerge.

There was much give and take, much going over old ground, and slowly moving to new ground. There was both good and questionable data that the group had to evaluate and discuss. Government agencies had to push sometimes and catch up at other times. The threat of a socially and economically disastrous priority call on water by the state, or the taking over of the river by the federal River Master, provided everyone with the incentive to stay at the table. Another real incentive, which is often present when people choose to come and talk about issues that impact their lives and the lives of their communities, was and remains "good will" and a sense of a shared destiny for their region and for their communities.

The persons at the table represented constituents to whom each owed a duty: a duty to report to, to listen to, to educate and be educated by, to represent as leaders in the most profound meaning of that word. Trust and credibility were at stake; these representatives had been given trust, and their credibility was on the line. As with each other, full, honest, and open communication had to occur with each participant's own constituents. This was true for the Lower Pecos River Advisory Committee, and it is true for every consensus-building process if long-term success is going to be achieved.

Consensus was reached, and it was supported by the state legislature—but with additional difficult conditions beyond those agreed to by stakeholders. The participants, spurred on by the potential positive consequences of their comprehensive solution, met and agreed to the conditions, settling many decades of litigation.

The purchase of farm land with its water rights, augmentation pumping, reclamation of water, and conservation activities, among other alternatives, are all part of this agreement. Without buy-in and support of community members and their leaders, successful long-term implementation and management would be a pipe dream. With continued advice, involvement, and commitment, the implementation and follow through is much more likely to occur. The duties of state and federal agencies have not been abrogated—in fact, quite the opposite. Long-term management of this resource, the Pecos River, is likely now to be successful, because there are literally thousands of people who are more educated and more involved in its health.

CONSENSUS DECISIONS

Consensus decisions do not guarantee perfection, they do not always please everyone, nor are they always technically the best decision. So why not go to court and get a judge to order the (technically) best decision on the issue or for the region? Or should the state or federal agency involved simply make the decision as it is authorized to do? Yes, but someone's "right" is someone else's "wrong." In trying to achieve what is the "right" decision, another 50 years may go by if the "right" decision is challenged in court. Or in just four years, when a new president or governor may arrive, the decision may well be overturned. A government agency should explore the use of a consensus process in every possible situation. But the equal protections guaranteed by the constitution and state and federal laws, which set out standards for and protect our environment, should not be violated. Rather, they should be used as parameters. The decision should be made with the input of the communities and citizens that are involved.

LONG-TERM MANAGEMENT AFTER A CONSENSUS BUILDING PROCESS

If you win in court but the community (or part of it) fights you, if an executive order gives you a victory but the populace is against it, if an agency says do this and it makes no sense to those affected, then long-term management, long-term goals, and long-term success are at risk from the beginning. Over and over again throughout the U.S. we are seeing lasting results from agreements reached collaboratively and by consensus.

Is this hype, a fad, or just common sense, that if people impacted by a decision have been involved in making it and support it, then it is likely that managing the implementation of it will be more successful? When unexpected and unforeseen challenges arise, participants in the consensus-building process are committed to searching for new common goals and new creative solutions that will achieve the original agreed-upon goals. It is simply the common sense habits that we are returning to, where neighbors talked over problems and communities sought out those who had some balance and wisdom to help them through tough times.

Consensus building and collaborative problem solving are just new phrases for old-fashioned cooperation based on a desire to serve the common good. It is not new, nor is it peculiar to the United States. If you read history you discover that, when societies and communities talked things out together, they flourished, and when they lost this ability, they experienced frequent crises and decline or disappeared.

Evaluating the Consensus/Adjudication Settlement Plan: Application of the Pecos River Decision Support System

Beiling Liu, *New Mexico Interstate Stream Commission*
John Carron and Jim McCord, *Hydrosphere Resource Consultants, Inc*

The primary challenge facing New Mexico in the Pecos River basin is compliance with the requirements of the Pecos River Compact and Amended Decree.
—Thomas C. Turney, former New Mexico State Engineer, April 11, 2002

Since the U.S. Supreme Court's 1988 Amended Decree ruling on the Pecos River Compact, New Mexico has achieved compliance largely through short-term leasing of irrigation water rights. In 2001, faced with the prospect of a potential compact delivery shortfall and the possibility of a priority call, a committee of water users and stakeholders in the Pecos River basin began discussions on a long-term solution to the compact compliance problem. These discussions led to the "consensus plan," an allocation of $34 million from the New Mexico legislature to implement the plan, and ultimately to an Adjudication Settlement Agreement on the Carlsbad Project water rights, agreed to by the participating parties in March of this year.

The Adjudication Settlement Agreement incorporates the key components of the consensus plan: land purchases and retirement of appurtenant surface and ground water rights, ground water pumping to augment Pecos River flows, and deliveries of purchased water to the New Mexico–Texas state line. To evaluate the effectiveness of the Adjudication Settlement Agreement terms in complying with the compact and Amended Decree, augmenting the Carlsbad Irrigation District (CID) water supply, and avoiding priority calls, the New Mexico Interstate Stream Commission performed hydrologic simulations of the proposed settlement terms using the Pecos River Decision Support System, described in the paper in this volume by Barroll and Keyes.

THE CONSENSUS/SETTLEMENT PLAN

The goals of the settlement terms are to comply with the Pecos River Compact and Amended Decree and to avoid the need for a priority call. To achieve these goals, the settlement terms anticipate the purchase and retirement of as many as 18,000 acres of irrigated lands (primarily within the Pecos Valley Artesian Conservancy District [PVACD] and CID), ground water pumping from the retired PVACD lands to augment Pecos River flows as needed to supplement CID's surface water supply and avoid a priority call, and release of the Interstate Stream Commission's shares of CID water from Lake Avalon directly to the state line for compact compliance. Historical records indicate that on average, New Mexico under-delivers water to the state line by about 10,000 acre-feet annually (not including leased water offsets). The intent of the settlement is not just to offset this under-delivery, but also to allow New Mexico to accumulate a credit "buffer" against future under-deliveries.

This will be achieved in two ways. First, the terms anticipate direct deliveries of water from Lake Avalon to the state line. These deliveries may be used to accumulate a net compact credit, or to avoid violation of the Amended Decree if New Mexico's net credit is very low. Second, the terms implement measures that will augment CID's surface water supply. Keeping CID "whole" is a key component of the plan because of the interdependence of CID surface and ground water supplies and their impact on return flows to the Pecos River (which ultimately contribute to New Mexico's state line deliveries under the Pecos River Compact). CID irrigators receive surface water deliveries based on an allotment, which is determined based on existing surface water supplies in CID reservoirs. In periods of low surface water supply, CID irrigators may pump ground water to supplement their surface water supplies. The combination of reduced surface water delivery plus increased ground water pumping has a direct and significant impact on return flows and base flows into the Pecos River below Avalon Dam. These gains to the river form a significant component of the annual state-line deliveries that New Mexico must make to comply with the compact.

The key components of the consensus plan include:

- Purchase and retirement of appurtenant water rights for 6,000 acres of land within CID;
- Purchase and retirement of 11,000 acres of land within PVACD;

- Purchase and retirement of 1,000 acres outside of PVACD, somewhere north of Acme;
- Delivery of the Interstate Stream Commission's purchased CID water from Lake Avalon directly to the state line, subject to limits described below;
- Pumping from wells in the Roswell artesian basin to supplement Pecos River flows and CID's surface water supply in low-supply years,up to the supply target levels shown below, subject annual limit of 35,000 acre-feet and 5-year accounting period limit of 100,000 acre-feet.

Target date	Target volume (acre-feet)
March 1	50,000
May 1	60,000
June 1	65,000
July 15	75,000
September 1	90,000

CID surface water supply target volumes.

The distribution of the Interstate Stream Commission's CID rights is conditioned on two competing objectives: to eliminate a default condition with respect to the compact, and to maximize water available for agricultural production. Distribution of water from the 6,000 acres of CID land purchased by the Interstate Stream Commission (ISC) is thus based on a tiered schedule of delivery and redistribution, as follows:

- If CID supply is less than 50,000 acre-feet on March 1, ISC water is realloted to CID.
- If compact credit is less than 50,000 acre-feet, deliver ISC water to the state line on each of 5 CID allotment dates.
- If compact credit is between 50,000 and 115,000 acre-feet, and the CID supply is less than 90,000 acre-feet, ISC shall make its CID water available for re-distribution to CID irrigators up to 3.5 acre-feet/acre (90,000 acre-feet total).
- If compact credit is between 50,000 and 115,000 acre-feet, and the CID supply is greater than 90,000 acre-feet, ISC gets all water greater than 90,000 acre-feet, up to 24,696 acre-feet. Beyond 114,696 acre-feet (90,000 + 24,696), water is allotted to all CID shareholders equally (including ISC) up to the decreed limit of 3.697 acre-feet/acre.
- If compact credit is greater than 115,000 acre-feet, ISC shall make its CID water available for re-distribution to CID irrigators up to the decreed limit (3.697 af/acre); if CID irrigators have full allotment, excess water is to be held over in storage for future years.

EVALUATION OF THE PLAN

The Pecos River Decision Support System (DSS) consists of three physical-process-based models, numerous pre- and post-processing tools, and analysis and accounting spreadsheets. The models use historical hydrology records from 1967 to 1996, including river gages, pumping records, and meteorologic data, as inputs. The physical system characteristics (reservoirs, diversion structures, etc.) and the system management policy (reservoir management, irrigation demands, etc.) are based on current (or proposed future) conditions. The models thus represent current development and operational conditions superimposed on historical hydrology. As such, they are not intended to predict future hydrologic conditions in the basin at any particular time, but instead to predict the expected differences in hydrologic conditions in the basin resulting from two different management actions.

Using the Pecos River DSS, the key operational features of the settlement terms were implemented and evaluated. The evaluation process involves two simulations of the DSS: a "baseline" scenario and a "settlement" scenario. The baseline scenario provides a "no-action" simulation of the basin hydrology and water operation, assuming in essence that the current water management actions within the basin will continue into the future. The baseline scenario model is then modified to reflect the conditions of the settlement terms. Results of this settlement scenario are then compared to the baseline results to estimate the impacts of implementing the proposed terms. In addition to the settlement terms described in the previous section, other key modeling assumptions used in evaluation of the scenarios include:

- Augmentation of CID surface water supplies;
- Supplemental well pumping in CID limited to 3.0 feet per acre per annum for the baseline, and 3.697 feet per acre per annum under the settlement scenario;
- CID allotments based on decreed 25,055 acres, deliveries to 20,000 irrigated acres (baseline), or 19,055 irrigated acres + 6,000 equivalent acres of ISC rights (settlement);
- PVACD alluvial ground water pumping rates based on recent (1991–2000) historical use patterns, extrapolated back to 1967, artesian

aquifer pumping rates use historical data 1967–1996;

- Permanent land retirements, such as ISC purchases of Harroun Farms, Willow Lake, and PVACD retirements, are represented in both scenarios;
- Temporary lease programs for Endangered Species Act (ESA) compliance and Pecos River Compact compliance are not included in either scenario.

The process of running each scenario involves a sequential simulation of the various models and analysis tools. Model scenario runs typically take 8–12 hours to complete including all model data pre- and post-processing and analysis.

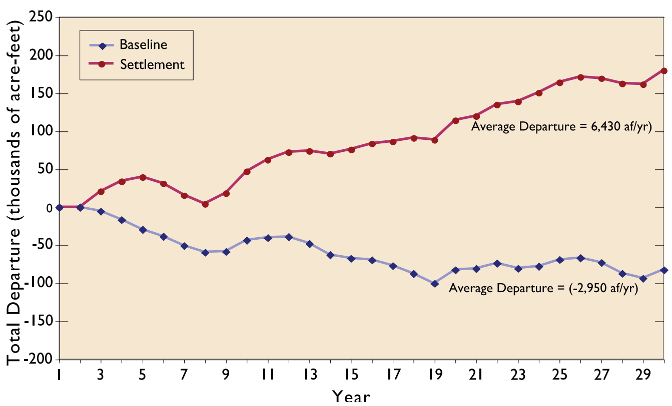
RESULTS

Evaluation of the model scenario outputs provides decision makers with estimates of the benefits that would be realized by implementing a particular management policy. Again, evaluation of the benefit of a proposed action is in comparison to the baseline or "no-action" scenario. For evaluation of the settlement scenario, the specific model results of interest—referred to here as "resource indicators"—include:

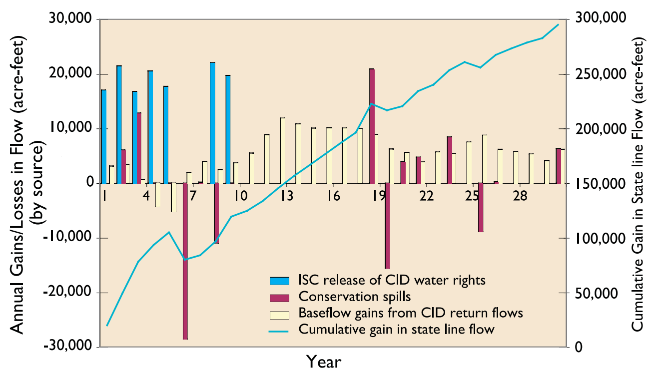
- Estimated Pecos River Compact deliveries and credits;
- CID surface water allotment and supplemental pumping rates;
- Augmentation pumping of purchased PVACD water rights.

Results of the scenario evaluation indicate that the settlement terms would likely increase state-line flows by approximately 10,000 acre-feet annually. That 10,000 acre-foot increase in state-line flow would translate directly into an additional 10,000 acre-feet of compact delivery. The figure below, on the left shows the estimated Pecos River Compact cumulative departure for both scenarios. Note that although the baseline results show a net deficit, this is not necessarily an indication or prediction of future non-compliance. Rather, we want to focus on the net gain in deliveries, as indicated by the difference in compact departure between the two scenarios.

The figure below, on the right illustrates the various sources of water that would contribute to the roughly 10,000 acre-foot increase in state-line flows, and how they vary in magnitude and in time. The bars in this figure show the three sources of additional water reaching the state line under the settlement terms scenario, and the single line (on the right-hand y-axis) shows the cumulative increase in state-line flows relative to the baseline scenario. It is clear how the settlement terms provide for delivery of ISC's CID water. Early in the scenario when there is very little compact credit, the State is releasing much of its shares of CID water directly to the state line. After about year 10, when the compact credit exceeds the 50,000 acre-foot threshold, the State often redistributes its shares of CID water to CID irrigators. This redistribution reduces the need for supplemental well pumping, and generally increases return flows to the Pecos. Finally, conservation spills increase slightly over the simulation period as well, although on a year-to-year basis they may actually be less than under the baseline scenario.

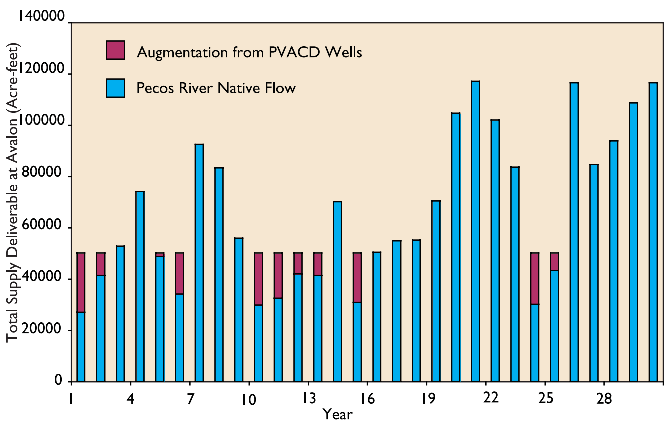


Comparison of Pecos River Compact departures for the two scenarios.



Sources of increased state-line flows under the settlement scenario. The line shows cumulative gain in state-line flow (settlement vs. baseline) using the right-hand axis. The bar charts show year-by-year gains (or losses) from three water "sources."

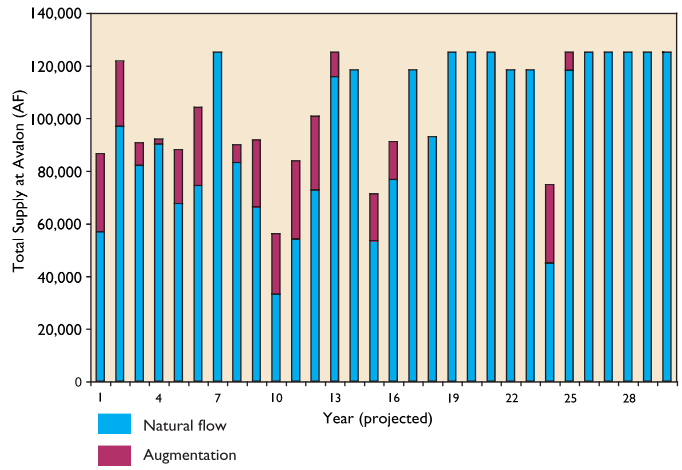
The impacts of the settlement on CID water supply are shown in the next two figures. Under the settlement terms, CID will not attempt a priority call on Pecos River basin water rights if they have at least 50,000 acre-feet of divertable supply each year. This means in practice that a need for a priority call is circumvented if CID's water supply reaches 50,000 acre-feet by March 1 (the beginning of the irrigation season) of each year.



March 1 CID divertable supply. The settlement terms provide for augmentation pumping to meet a March 1 divertable supply target of 50,000 acre-feet.

The figure above shows the estimated CID water supply on March 1, and illustrates the potential importance of augmentation pumping to the Pecos River in avoiding a priority call.

The figure below shows total annual divertable CID supply as of October 31, with both natural and augmentation sources. Note that although augmentation pumping does not occur when the CID supply exceeds 90,000 acre-feet, there are several years when the natural supply is less than 90,000 acre-feet early in the year and augmentation pumping occurs, but summer storm events cause the total annual supply to exceed 90,000 acre-feet.



Total annual CID divertable supply based on total diversions and water in storage on October 31.

The Pecos River DSS has proven to be an invaluable tool for simulating and evaluating various actual or proposed management policies in the Pecos River basin. In addition to the application described here, the tools are currently being used to evaluate short and long-term impacts of other land retirement options, bypass flows for the Pecos bluntnose shiner, and annual accounting of lease/purchase programs to offset depletions caused by bypass operations.

Technical Advances in Water Use Efficiency

J. Phillip King and A. Salim Bawazir, *New Mexico State University*

Advances in irrigation technology over the past 40 years have enabled farmers to produce crops of higher quality with greater yields, and have allowed the productive use of water of marginal quality. One of the largest benefits has been the increase in the efficiency of irrigation water use, but managers and policy makers must understand the complex and often over-simplified hydrologic cycle in which water conservation exists.

Efficiency is one of the most used and abused terms in discussion of irrigation and water conservation. It is used to convey some concept of quality of performance of an irrigation system, but unless it is specifically defined and examined in a broad context, the term efficiency is ambiguous and misleading. Efficiency generally is defined as an output divided by an input. In irrigation terms, the output may be delivery, consumptive use, or beneficial use of water. Input may be release from a reservoir, diversion from a river or aquifer, or delivery to the farm. The implications of the various forms of efficiency vary according to hydrology of the irrigation system.

Conveyance efficiency is the proportion of water diverted from a river or aquifer that is delivered to farms. Mathematically, it is the ratio of farm delivery to diversion, generally expressed as a percentage. Diversion is always larger than (due to seepage and evaporation losses) or equal to delivery (if diversion occurs on the farm), so the conveyance efficiency is less than or equal to 100 percent. High values are common in lined or piped conveyance systems due to the reduced seepage. High values also indicate that excessive water is not being diverted and returned to the system as operational spills. In fact, if a system operator under-delivers water, there will be a very high demand for the water he does divert, and he may have a high conveyance efficiency but some unhappy irrigators who are not getting adequate deliveries. Low conveyance efficiency is not necessarily wasteful, if downstream users can recapture operational spills and canal system seepage.

Application efficiency refers to the efficiency of the irrigation application system. It is the ratio of irrigation water consumed by the crop to the water applied to the crop from the farm ditch or pipeline. The term is somewhat complicated by the fact that crops get some of the water they consumptively use from precipitation, though this is a relatively small amount in New Mexico. Application efficiency varies from 50 percent in rather poorly managed surface irrigation systems to over 90 percent with drip irrigated fields. It is possible to achieve 100 percent in deficit irrigated systems, but the crop will likely show a reduced yield because of moisture stress.

Irrigation efficiency is the ratio of beneficially used irrigation water to water applied to the field. This beneficial use includes the consumptive use plus a leaching fraction, recognizing that leaching is a necessary function of applied water. Only water infiltrated in excess of a specified leaching fraction is considered a deep percolation loss in the determination of irrigation efficiency, but it should be remembered that deep percolation is not necessarily a loss to the system as a whole, because in some settings, such as stream-connected aquifers, deep percolation is either captured and returned to the source, or it may act as ground water recharge. The required leaching fraction is a function of irrigation water quality (higher water salinity requires higher leaching fraction), soil type (soils with more clay require more leaching), crop (more salt-sensitive crops require more leaching), and yield goal (higher yield requires higher leaching fraction). In practice, water availability typically determines leaching fraction, as one cannot apply excess water to leach if one doesn't have the water to apply.

On-farm efficiency is the percentage of delivered water that is consumptively used by the crop. Mathematically, it is the ratio of consumptively used irrigation water to water delivered to the farm. The consumptive use is smaller than delivery, making on-farm efficiency less than 100 percent. Losses or inefficiencies that affect on-farm efficiency include losses in on-farm ditches or pipelines and incidental evapotranspiration. Application efficiency differs from on-farm efficiency in that the former does not include losses in on-farm conveyance systems, whereas the latter does.

Application efficiency, irrigation efficiency, and on-farm efficiency are similar to each other. For simplicity in discussion, application efficiency will be the indicator of efficiency at the farm level, as an improvement in application efficiency will generally produce an improvement in the other two. Various other combinations of outputs and inputs are sometimes expressed as efficiencies, but conveyance efficiency and application efficiency capture the essence of conveyance and farm application, and will be the basis for discussion of water conservation measures.

On-farm water conservation measures range widely, but can generally be classified by application system type. The two major divisions of water conservation application systems are surface and pressurized systems.

SURFACE SYSTEMS

The oldest and most widely used class of irrigation is surface irrigation, including basin, furrow, border, and other techniques that apply water to the soil surface at the head of the field and allow the flow to advance to the tail, wetting part or all of the soil surface. Because the soil is used both to infiltrate and store water and to convey the water across the field, there are inherent inefficiencies in the irrigation process. Generally, the objective of surface irrigation conservation technologies is to advance the water from the head of the field to the tail as rapidly as possible without eroding the soil surface, thereby minimizing the differences in infiltrated water between the head and tail of the field. Common conservation technologies used in surface irrigation systems are:

- Laser leveling, where the field is precision-graded to allow uniform advance of water and eliminate high and low spots in the field. This is very commonly practiced in New Mexico; it can improve application efficiency from 10 to 20 percent.
- High-flow turnouts are used to provide rapid advance. These turnouts are most commonly used in conjunction with laser-leveled fields, and the combination can produce application efficiencies in excess of 80 percent.
- Surge irrigation is used to improve the infiltration uniformity, and therefore efficiency by advancing the water down the field in pulses. It is best suited to very long furrow or border runs and has not seen wide application in New Mexico.
- Alternate furrow irrigation allows some improvement in uniformity, because the available flow is directed into every second furrow, thereby doubling the flow per furrow over conventional furrow irrigation.
- Tailwater recovery and recycling systems capture runoff from the tail of the field and recirculate it to the head of the field. This also is rarely applied in New Mexico.

High flow turnout on pecans.

PRESSURIZED SYSTEMS

Whereas surface systems rely on the soil to convey water from the head of the field to the tail, pressurized systems rely on pipes. Pressurized systems also lend themselves to automation. The two main classifications of pressurized systems are sprinkler and trickle (or drip), though these descriptions represent ends of a spectrum rather than distinctly different systems.

Sprinkler systems can be either solid set, with permanently fixed sprinkler head positions, or moving. Moving systems are moved mechanically or by hand. In New Mexico mechanical moving systems are widely used, with center pivots being the most common.

Center pivot irrigation of alfalfa.

Center pivot sprinklers reduce the amount of applied water necessary to irrigate a field because they apply water more uniformly than surface irrigation systems typically do. Center pivots are also capable of irrigating gently rolling land, reducing the need for leveling. Drawbacks are the wetting of the plant during irrigation, evaporative losses, and wind drift. Low pressure systems can reduce these losses by applying water near, within, or below the crop canopy. Typical application efficiencies with center pivots are 75–80 percent.

Drip is the racehorse of irrigation. Managed correctly, this type of system can produce the highest yield, and the highest quality, for a wide variety of crops. Drip proves in many cases to be economically quite viable. Unfortunately, like a racehorse, anything less than the highest level of management can create serious problems. Clogging of emitters is the biggest problem faced by most growers, particularly when using sediment-laden surface water. Clogging may result from sediment, precipitation of minerals at the emitter outlet, and biological growth within the drip lines. An acid flush will generally take care of precipitants and biological growth, but removal of sediment requires multi-stage filtration and frequent cleaning of filters.

In identifying potential water conservation measures in New Mexico, one must look at conservation from two perspectives:

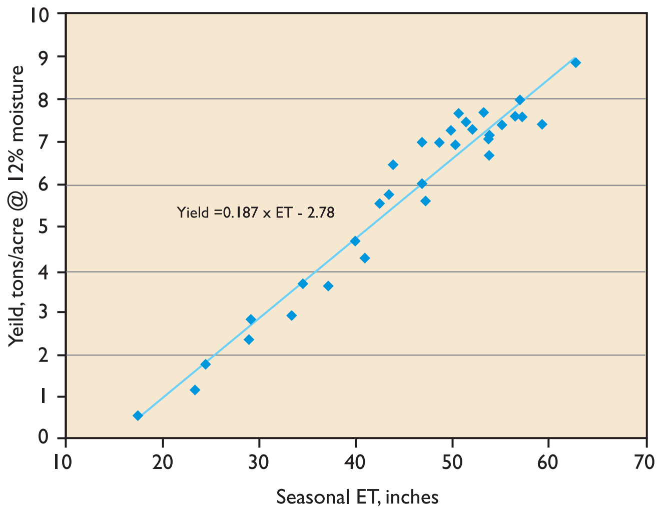
Drip-irrigated strawberries.

Characteristic	Surface	Sprinkler	Drip
Irrigation efficiency	50–85%	70–85%	90–100%
Yield potential	low-mod	moderate	high
Depletion/acre	low-mod	moderate	high
Diversion/acre	high	moderate	mod-low
Capital investment	low	moderate	high
Labor requirement	high	low	low
Labor skill level	low	moderate	high
Soil types	fine	mod to coarse	any
Topography (slope)	0–2%	0–5%	0–15%+

Irrigation system characteristics: general performance characteristics of improved surface, sprinkler, and drip irrigation systems. Note that the actual performance of an irrigation system has a great deal more to do with the operation and scheduling of irrigations than does the hardware.

- The farm perspective, where water use and water accounting is based on application of water to the crop. The primary goal is to reduce application of irrigation water and to conserve allocated water for later use.
- The system perspective, where the system manager has a responsibility to deliver water to irrigators while meeting obligations to downstream water users. In order to meet downstream obligations, the primary long-term concern is depletions rather than farm application of water. Depletion and application are certainly related, but they are not one in the same, as application efficiency is generally less than 100 percent.

Crop yield is related to seasonal evapotranspiration, and therefore depletion. As a crop consumptively uses more water, the yield will increase. In Rio Arriba County in northern New Mexico, for example, the average yield of alfalfa is approximately 2.4 tons per acre (12 percent moisture content). In the Middle Rio Grande Conservancy District (MRGCD), located south of Rio Arriba County, the warmer weather and higher solar radiation allow growers to produce an alfalfa yield of approximately 4.5 tons per acre. Still farther south in Elephant Butte Irrigation District (EBID), farmers achieve a yield of approximately 7.5 tons per acre, three times that of their Rio Arriba counterparts.



Water production function for alfalfa at 12 percent moisture (from Abdual-Jabbar, 1983).

From this relationship, one may infer that the yield of 2.4 tons per acre Rio Arriba County consumptively used 2.3 feet of water, MRGCD's yield of 4.5 tons per acre consumptively used 3.2 feet, and EBID's yield indicates a consumptive use of 4.6 feet of water. These yields reflect irrigation management, as well as other cultural practices. Pressurized irrigation systems allow more frequent watering of crops than surface irrigation, thereby reducing moisture stress, and may increase both yield and consumptive use of water. The increased efficiency and operational advantages of pressurized systems may actually allow increased consumptive use while decreasing application and diversion of water.

Weather is not the only factor affecting a given crop's evapotranspiration and consumptive use. Timing of irrigation affects the moisture stress on a crop. As a crop's root zone soil moisture is depleted, evapotranspiration is decreased, thereby producing a reduction in yield. Diseases, pests, and nutrient stress may similarly reduce a crop's vigor, hence reducing its evapotranspiration and yield.

AGRICULTURAL WATER CONSERVATION

Seckler (1996) examined water conservation efforts in various parts of the world and pointed out a relevant distinction in conserved water. In systems where return flows produced by processes traditionally considered to be losses (such as canal seepage and deep percolation from irrigated fields) are recaptured and reused by downstream users, reduction in these losses does not actually create more water to the system. For example, if a canal lining project were to reduce the quantity of water "lost" to seepage, conveyance efficiency would increase, but return flows would be reduced. Although less water would need to be diverted, the savings essentially came out of the return flow, which is not a loss term. This is a local savings but a system-wide break-even proposition. Seckler termed this "dry water" conservation, because it does not provide a net reduction of water use for the system as a whole.

"Dry water" conservation may produce significant benefits when water is kept in irrigation, as farmers can use seepage and deep percolation reduction to increase their available supply in times of drought, essentially borrowing from the ground water system. Keeping water upstream in storage also allows the active management of that water to match supply to crop demands, rather than allowing it to return as drain flows, which can be managed only passively, and may not reach the river at a useful time.

Reduction in depletion is a different matter. If depletions (which in the case of irrigation are primarily associated with evapotranspiration) are reduced, more water becomes available to other users in the study area. For example, if a farmer who has been growing alfalfa switches to onions, he reduces the amount of water his crop is depleting, and the savings actually results in more water available for delivery and depletion by another user. This is what Seckler termed "wet water" conservation.

In some circumstances the distinction between wet and dry water conservation is irrelevant. For example, irrigators pumping water from the Ogallala aquifer in eastern New Mexico can improve on-farm efficiency by reducing deep percolation losses and extend the life of their resource. Because the deep percolating water does not return to the aquifer in any operational time frame, deep percolation is functionally a loss to the system, and reducing it (and making a higher percentage of the applied water available to the crop) reduces the required diversion from the aquifer.

This distinction between wet and dry water conservation is critical in evaluating conservation measures intended to provide additional water. Wet water conservation truly frees up water that may then be assigned to another use whether considered from the farm or district perspective. Dry water conservation, from the district perspective, has less impact on increasing the water supply, but may offer management advantages that justify investment of resources.

There may be unforeseen negative consequences to water conservation measures, along with the positive ones. For example, on-farm conservation measures that increase application efficiency reduce the required application of irrigation water to achieve a given level of yield (and depletion). Although this is generally a benefit, it will also reduce the return flow to drains, which may provide important habitat. Although the return flows may be reduced, their salinity and the salinity in the shallow ground water will likely become more concentrated. It is, therefore, important to examine direct and indirect consequences of conservation measures to ensure that they are consistent with specific conservation objectives that fit the local hydrology and institutional setting of both the farm and the larger system.

SUGGESTED READING

Abdual-Jabbar, A. S., Sammis, T. W., Lugg, D. G., Kallsen, C. E., and Smeal, D., 1983, Water use by alfalfa, maize and barley as iInfluenced by available soil water: Agricultural Water Management, v. 6, pp. 351–363.

Cuenca, R. H., 1989, Irrigation system design—an engineering approach: Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 552 pp.

Seckler, D., 1996, The new era of water management—from “dry” to “wet” water savings: CGIAR Issues in Agriculture No. 8.

Beneficial Use of Oil-field Produced Waters: One Company's Efforts

Frank Yates, *Yates Petroleum, Artesia, New Mexico*

Oil and gas companies, in their production of oil and natural gas, also produce water as a waste byproduct. The New Mexico Oil Conservation Division (NMOCD) regulates the proper disposal of this produced water, requiring oil companies to use either downhole disposal, such as salt-water injection wells, or a surface waste management facility. However, these methods of disposal can be expensive, accounting for as much as 30 percent of operating costs at a particular well. If a company can reduce that cost, it enhances their ability to focus on the exploration and production of oil and gas. To that end, Yates Petroleum Corporation (YPC) is exploring the use of new, more economical technologies that treat, rather than dispose of, oil field wastewater.

Today, over 90 percent of produced water is injected into downhole disposal wells or into wells used in secondary oil recovery. Among even the most economical disposal wells, such as those in Dagger Draw and Indian Basin in southeast New Mexico, capital costs can range from $600,000 to $1,300,000, and operating costs can range from $.02 per barrel to $.09 per barrel. These wells are generally non-commercial oil wells that have been deepened to reach Devonian strata, at approximately 12,000 feet deep, which consists of highly porous and permeable limestone. Operators can inject as much as 25,000 barrels of produced water per day over the lifetime of a well, generally 12–16 years. Toward the end of a well's life, operating costs begin to increase and injection volumes decrease as a result of increasing injection pressures as the reservoir fills. Commercial injection facilities can accept and inject a third-party operator's water at a cost of 25–50 cents a barrel. Trucking of water to a disposal well can cost from around $1.10 to $1.50 per barrel in New Mexico and as much as $5.00 per barrel in southwest Wyoming.

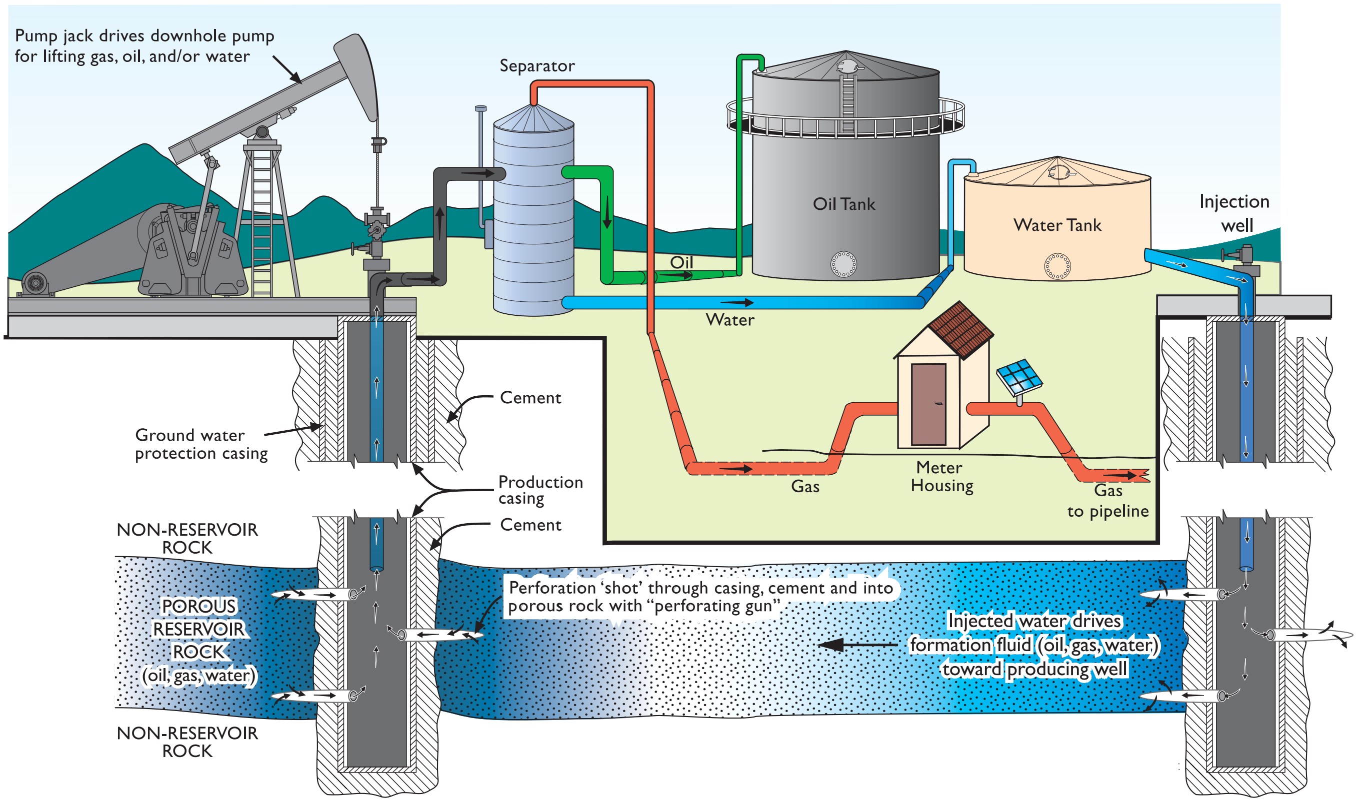
Injection well in the Indian Basin gas field south of Artesia.

YPC's costs are consistent with the industry average. Hence, we have been looking for economic alternatives to downhole disposal for several years. Potential options include membrane filtration technology, separation technologies, and open-air aeration ponds, all of which focus on treatment of produced water rather than injection. The advantages to treatment include:

- Flexibility of location. If we can avoid having to dispose of a "reject fluid waste stream," we can build a facility practically anywhere and not be constrained by proximity to downhole disposal.
- Longer lifetime. As long as equipment is maintained, a treatment facility has the potential for a life at least twice that of conventional downhole disposal.
- Generation of fresh water and possibly other valuable byproducts.

However, each of these alternatives has certain drawbacks. For instance, membrane filtration technology is improving and becoming less expensive, but it is corrupted by the hydrocarbons and metals that are prevalent in produced water. Existing separation technologies remove hydrogen sulfide (H_2S) and BTEX (volatile aromatic hydrocarbons that are found dissolved in most produced water), but these technologies don't address dissolved solids. Open-air aeration ponds are cost effective but pose certain risks to the environment.

There is another, more promising treatment alternative that has arisen in just the last year. YPC has committed to testing this technology, which is based on proprietary intellectual property and has not yet been tested on a meaningful scale in the oil field. We have recently completed construction of a 10,000-barrel per day pilot facility, and we are operating under a confidentiality agreement with the owner of the intellectual



Reinjecting produced water into the subsurface in order to enhance the recovery of oil and gas is one alternative for disposal of produced water. Another option is downhole disposal in an approved subsurface reservoir. New methods seek to reduce downhole disposal by generating fresh water that is usable at the surface.

property. This pilot project will not be a single-purpose treatment facility used solely for waste disposal. Emphasis will also be placed on developing operating limits, strategies, manuals, training procedures, and studying simulated failures, etc.

In addition to beginning the test phase of this facility, YPC has several other operating goals. For example:

- We plan to process 10,000 barrels per day (1.3 acre-feet per day, or approximately 420,000 gallons per day) of produced water.
- We plan to be a fully automated, unmanned facility that requires minimal human opera tional or maintenance inputs.
- We plan to have the ability to completely cir cumvent downhole disposal and remove only solid wastes to industrial landfills.

ECONOMIES OF SCALE

It became clear during the design phase of the pilot project that the incremental costs of building larger facilities would decrease with increasing size. For instance, it is estimated that a 10,000-barrel per day (b/d) facility will cost $1 million, or $100 per barrel per day capacity. A small, mobile facility capable of treating 500 b/d could cost $600,000 or $1,200 per b/d capacity. Conversely, construction costs for a 50,000 b/d facility are estimated to be approximately $2,500,000 or $50 per b/d of capacity.

The operating cost target for the pilot facility is $.07 per barrel during steady-state operation. These costs include electrical, labor, and maintenance costs. The target for a 50,000 b/d facility is approximately $.04 per barrel. By contrast, a smaller 500 b/d facility may incur operating costs as high as $1.00 per barrel.

PROBLEMS AND SOLUTIONS

Two potential obstacles stand in the way of private companies investing in newer technologies for disposal of produced water, while continuing to produce oil and gas. One obstacle is the risk of losing their investment. Fortunately, tax incentives are available through

What Is Produced Water?

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Produced water is water that is produced during the extraction of petroleum (crude oil and gas) from underground reservoirs. These reservoirs are found in the subsurface in porous rock formations that are filled with petroleum and water. As the petroleum is pumped to the surface, produced water is an inevitable natural byproduct.

Oil and water don't mix, even in reservoirs. In some reservoirs, water and oil or gas naturally segregate by buoyancy forces so that the lighter hydrocarbons float on the water. Thus, it is possible in some cases to pump water-free petroleum to the surface when water is present in the reservoir. Under these circumstances a well can be engineered to avoid the water at the bottom of the reservoir. As the petroleum is produced, however, the surface between oil or gas and water in the reservoir will rise, eventually intersecting the well. Typically, the amount of water produced increases with time.

Even in reservoirs with no water horizon beneath the oil or gas, there is still plenty of water in the reservoir. The walls of each pore are usually coated with a thin film of water. This water may occupy 20-60 percent of the pore volume. Because the water adheres to the pore wall it is initially resistant to movement through the pore system, whereas the oil is free to flow toward the well. With time, the oil is drained and the ratio of water to oil increases, so that more water is produced with the oil. In advanced stages of depletion, a reservoir that initially produced water-free petroleum may yield more than 90 percent water.

As a reservoir is depleted of its petroleum and water, its internal pressure is reduced. This pressure is an important force for moving fluids and gases to the well and then to the surface. Often produced water is recycled under pressure back through water-injection wells to the same reservoir from which it came. This "enhanced recovery" technique repressurizes the reservoir and serves as a mechanism for sweeping oil from pores toward producing wells.

The quality of produced water ranges from fresh to concentrated brine. Presently there are a variety of options for disposing of (or reusing) produced water. For highly saline water, options include reinjection into the producing reservoir for enhanced recovery operations or disposal into an approved underground saline aquifer. For less saline water, options include evaporation in ponds or use in road dust abatement. With the proper permit, fresh water could be discharged to streams. If water can be chemically treated or filtered for beneficial use, it becomes "manufactured water."

Whatever option is applied, it must be cost-effective or it will never be implemented. Transportation by truck or pipeline, disposal well and storage tank construction and maintenance, re-pressurization for injection or transportation, chemical treatment or filtration, environmental protection, and regulatory compliance—all of these add considerably to the capital spent in simply lifting the water to the surface as a byproduct. The economically preferred option depends upon the volume of water to be processed, water quality, technical options locally available, and the political climate controlling those options.

House Bill 388. For operating companies that treat produced water to Interstate Stream Commission water-quality standards for the purpose of meeting delivery obligations to Texas, HB 388 offers tax credits of $1,000 per acre-foot, not to exceed $400,000 per year. (An acre-foot of water is equivalent to 7,758 barrels or 325,851 gallons.)

The second obstacle is overlapping jurisdiction. In brief, this issue concerns water rights, which are created by an individual or a company establishing a beneficial use of a source of water. The Office of the State Engineer (OSE) has the power to create a newly designated ground water basin and then grant permits for new water wells in that basin. Water rights can be lost after a period of non-use, and applications for permits can be denied by the OSE if it determines that the water is not being put to beneficial use. The New Mexico Oil Conservation District has jurisdiction over

Some Policy Considerations From An Industry Perspective

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House Bill 388, passed in the 2002 session of the New Mexico Legislature, describes the procedures for putting water produced in refining and natural gas processing as well as water produced from below a depth of 2,500 feet into the Pecos River. (Sponsored by Representative Bob Burpo, it is sometimes referred to as "the Burpo Bill.") The bill gives an operator (a refinery, natural gas processor, or person who operates an oil or gas well) a New Mexico income tax credit of $1,000 per acre-foot of produced water, not to exceed $400,000 per year. The tax credit is intended to help defray the cost of building infrastructure and processing the produced water so that it meets the standards of the Environmental Protection Agency and the New Mexico Oil Conservation Division (OCD).

Ownership of the produced water is one important issue. H.B. 388 requires the operator to deliver the water to the Interstate Stream Commission (ISC) at the Pecos River, at which point title to the water is transferred to the ISC. The industry views processing of the water and its delivery to the ISC as an alternative disposal method, subject to approval by the OCD. The operator does not sell water to the ISC but, in order to claim the tax credit, is required to process the water so that it meets stream standards at the Pecos River. If, on the other hand, the operator processes produced water so that it meets the environmental and disposal requirements of the OCD but does not deliver it to the ISC at the Pecos River, the water belongs to the operator and may be disposed of in a manner approved by the OCD.

H.B. 388 does not address the issue of whether water that has been processed for introduction into the Pecos River, by being delivered to the river, is being put to a beneficial use. The water from the only refinery on the Pecos that is available for introduction into the river comes (a) from wells for which the refinery owns water rights, (b) from water purchased from the City of Artesia, or (c) from water produced in the refinery as part of the refinery processes. Water from the Dagger Draw and Indian Hills fields is produced in conjunction with the production of oil or gas from depths below 2,500 feet and historically has not been subject to regulation by the Office of the State Engineer.

If the tax credit is to be claimed, produced water delivered to the ISC at the Pecos River, must be delivered in a manner such that it contributes to delivery obligations to Texas pursuant to the Pecos River Compact. This statutory requirement raises two issues. First, does delivery of water to the ISC at the Artesia bridge, for example, require that the water barrel for barrel reach the Texas line? The statute merely requires that the water "contribute" to the delivery obligation to Texas. It was contemplated that some water would be lost in the Pecos River by natural processes during stream flow.

The Carlsbad Irrigation District (CID) believes that water placed in the Pecos River above its works becomes subject to appropriation to meet its needs, presumably relying on rules such as those stated in *State ex rel Reynolds v. Luna Irrigation Co.*, 80 N.M. 515, 458 P.2d 590 (1969). CID also contends that, for hydrological reasons, produced water that reaches their works will necessarily contribute to the obligation to Texas because it will help recharge the river. From the industry view, once the water is delivered to the ISC at the Pecos River in a manner that meets the applicable environmental rules, it belongs to ISC. Any argument involving the volume of water delivered to Texas is between CID and ISC, not between the producers and CID.

A second issue raised by H.B. 388 involves indemnification. From an industry view, no produced water will be delivered to the Pecos River unless the ISC agrees to indemnify the operator from future liability. Although legal title to the water delivered to the ISC in compliance with the applicable environmental permits belongs to the ISC and not the operator at the time of delivery to the river, the industry believes it is entitled to indemnification from the State under H.B. 388.

H.B. 388, therefore, addresses a number of important issues. Without H.B. 388, many questions remain unanswered. If H.B. 388 provides a plan for meeting the obligation to Texas with produced water, the scheme outlined above is one simple solution.

disposition of oil field wastes, including produced water. However, if the produced water is put to beneficial use (for example, helping to meet the state's compact obligations to Texas), does jurisdiction of the water now devolve to the OSE?

If a private company cannot produce and subsequently treat or dispose of this wastewater, then it cannot produce oil and gas from its wells, because the oil, gas, and water are all produced simultaneously. Individual companies and the NMOCD have worked together to establish rules protecting the environment from improper disposition of oil field wastes. If the State Engineer's Office overlaps the NMOCD's jurisdiction, competing priorities will result, namely environmental protection vs. beneficial use. We must ensure that existing environmental protections are not circumvented in the state's desire to use this water.

A study is currently being conducted by Natural Resources Consulting Engineers, Inc., paid for by a grant from the U.S. Department of Energy to the Carlsbad Department of Development. The study's objectives include, but are not limited to, assessing the state's water supply, evaluating water demands, addressing ownership and jurisdictional issues, and describing the regulatory environment. This study will apprise legislators of the risks that overlapping jurisdiction poses, both to environmental quality and to the ability of private companies to produce oil and gas.

Riparian Evapotranspiration and Vegetation Management

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Riparian vegetation that flourishes along the water courses in New Mexico includes salt cedar, cottonwood, willow, Russian olive, and salt grass. During the last century or so the density of indigenous riparian vegetation such as cottonwood and willow has diminished, whereas non-native species such as salt cedar and Russian olive have continued to flourish and dominate. Salt cedar is the most common of these, well known for its dominance of riparian regions throughout the southwestern United States. It was introduced here in the late 1800s from Europe and Asia as an ornamental, for windbreaks, and for erosion control. The exact acreage of salt cedar along the water ways throughout the U.S. is not known, but recent studies indicate that approximately 1.5 million acres of floodplain in 23 states are covered by salt cedar. A survey in 1992 by the U.S. Bureau of Reclamation to identify and quantify land use trends in the Albuquerque Basin reported that 55,051 acres along the middle Rio Grande, from north of Cochiti Dam to the south near San Acacia Dam, were covered by riparian vegetation; salt cedar presumably constituted the bulk of this riparian vegetation. In 1993 it was reported that salt cedar covered nearly 300,000 acres along the Pecos River from Sumner Dam south to the Texas state line. While conducting evapotranspiration studies of riparian vegetation in the middle Rio Grande we observed that salt cedar and Russian olive are growing not only along the river but also near conveyance canals and irrigation drainages. Because salt cedar continues to dominate the riparian regions of New Mexico and the Southwest in general, its consumptive use of water (evapotranspiration) and its management are crucial to the management of water, a scarce resource in the Southwest.

QUANTIFYING RIPARIAN EVAPOTRANSPIRATION

Direct measurement of evapotranspiration is difficult, expensive, and (under certain conditions) impractical due to the complex physical processes involved. Many methods have been developed based on measured quantities such as ambient and soil temperatures, solar radiation, wind speed, relative humidity, and amount of vapor above and inside the vegetation. These methods apply basic principles such as the conservation of mass and energy. The most currently used method is based on conservation of energy where *sensible heat* (flow of energy through air) and *latent heat* (energy required or absorbed per unit area to evaporate a unit mass of water) are measured using a technique known as *eddy covariance*. The sensors used measure vertical wind speed, air temperature, and humidity accurately. Sensible and latent heat (this is evapotranspiration) is then determined as a covariance of temperature and wind speed, and humidity and wind speed, respectively. Other measurements in the energy budget that are measured include net radiation flux (considered as available energy to the system) and soil heat flux (energy that is lost into ground during day time or released from ground during night). Other minor energies that are not usually considered in this method include energy stored in the vegetation and energy used by plants in photosynthesis. The energy stored in the vegetation during day time is counterbalanced by energy released during night time; on a daily basis this energy is often ignored, as it is very small. Evapotranspiration measurements by the eddy covariance method are considered to be "actual" measurements because they are based on a sound theoretical foundation. Eddy covariance techniques using a more rugged OPEC (one propeller eddy covariance) system and highly sensitive three-dimensional sonic eddy covariance systems have been used successfully to measure evapotranspiration of dense salt cedar and sparse cottonwood sites at the Bosque del Apache National Wildlife Refuge (NWR) since 1999.

POTENTIAL FOR WATER SALVAGE ALONG THE LOWER PECOS RIVER

Maintaining a riparian ecosystem with native plants that use less water than the invasive salt cedar in order to salvage water for other uses is a challenge. It is necessary to understand the physical environment of the riparian regions and the factors that allow the growth and sustainability of native riparian vegetation. Many of these factors were reported at the Bosque del Apache NWR on the Rio Grande by Taylor and McDaniel in 1998 in their efforts to restore cottonwoods and willows in the floodplain. They successfully used an approach that mimics a natural flood event. Understanding the physical environment of riparian regions on the Pecos River is crucial for proper management of salt cedar and the establishment of cottonwood, willow, and other native vegetation, with the objectives of sustaining a riparian ecosystem as well as salvaging water for other use.

Many factors such as meteorological conditions, soil water availability, soil chemistry, type of vegetation, and other factors are known to affect evapotranspiration rates. In order to salvage water and minimize cost and time, the root of the problem has to be understood. For example, a successful study on salt cedar and cottonwood riparian vegetation on the middle Rio Grande (sponsored by the U.S. Bureau of Reclamation in 1999) showed that evapotranspiration of a dense salt cedar stand, measured at Bosque del Apache NWR, was approximately 3.9 feet per acre during its growing period (from budbreak to fall senescence, generally mid-March through the beginning of October) and approximately 0.6 feet per acre during the dormant period, a total of approximately 4.5 feet per acre per year. By comparison, alfalfa evapotranspiration during normal conditions in southern part of New Mexico ranges from 4.2 to 4.9 feet per acre per year. Sparse cottonwood at the Bosque del Apache NWR measured during the same period was approximately 3.0 feet per acre per year. The salt cedar measured at the Bosque del Apache NWR compared reasonably well with previously published data, but cottonwood evapotranspiration measurements did not compare well to those published (5–6 feet per acre per year). This discrepancy may be due to current conditions such as high soil salinity (observed at the Bosque del Apache NWR in 1999), decline in ground water table (cottonwood does not extend its roots as deep as salt cedar), lower soil moisture, and most probably the variety of cottonwood grown at the Bosque del Apache NWR. Conditions are probably similar on the Pecos River. If salt cedar were to be replaced by cottonwood with the “same conditions” there would be a savings of 1.5 feet per acre per year (33 percent). Although the same conditions may not be possible, in general there would be a salvage of water for other use. There has not been a similar effort to understand the physical environment of the riparian regions along the Pecos River and the factors that would allow the growth and sustainability of native riparian vegetation along the river corridor, but a similar strategy might result in water salvage and a better management of the riparian ecosystem here, as well. Evapotranspiration data from the Bosque del Apache NWR during years 2000 thru 2002 are being analyzed, and the results are pending. The models developed from that study may be applicable to riparian regions of the Pecos River.

SUGGESTED READING

Brown, J. P., Peters, A. J., and Pieper, R.D., 1993, Vegetational history of the Pecos Basin in New Mexico: Las Cruces, New Mexico State University, 46 pp.

Taylor, J. P. and McDaniel, K. C., 1998, Riparian management on the Bosque del Apache NWR: New Mexico Journal of Science v. 8, 219–232 pp.

Salt Cedar Control and Riparian Habitat Restoration

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Riparian communities of the Rio Grande and Pecos River historically were dominated by mosaics of cottonwood and willow forests, mesquite and wolfberry brushlands, saltgrass and alkali sacaton meadows and grasslands, and annual and emergent marshes. These vegetative communities were established and maintained by spring flooding events that scoured the floodplain and provided soil disturbance and moist areas for germination of aerially dispersed or water-borne seed. Today, throughout the western United States, less water is available to maintain low-elevation riparian areas due to agricultural and urban water demands. Catastrophic flooding is now less frequent, and historic river flow patterns have been altered, impacting native vegetation recruitment and maintenance. In this void, exotic species such as salt cedar and Russian olive have spread rapidly, further degrading these once rich riparian habitat mosaics.

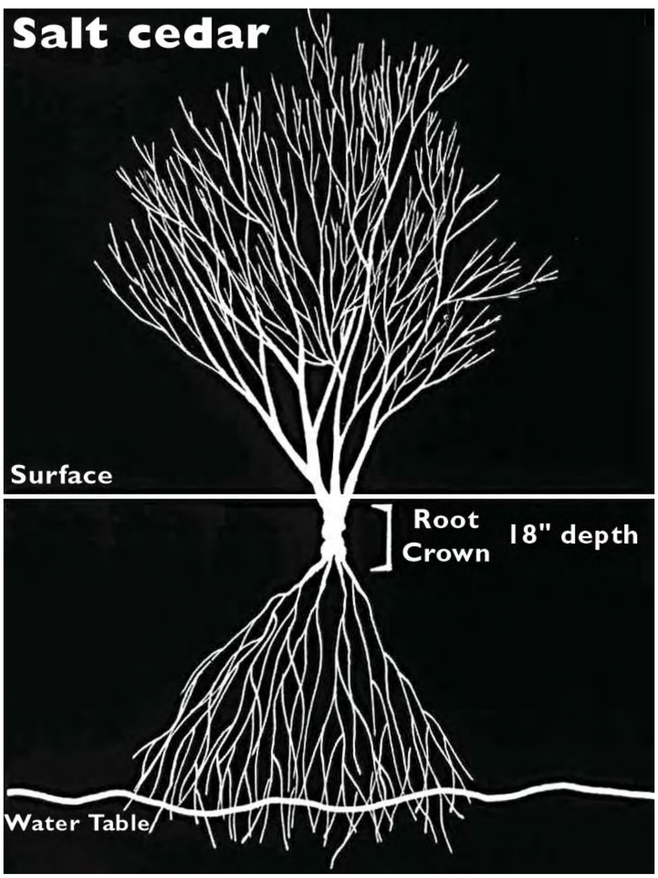

Diagram of the aboveground and belowground root system of salt cedar showing the location of the root crown.

High wildlife diversity, particularly for bird species, characterizes native dominated habitat mosaics. This diversity has been compromised with the expansion of exotic species and is the motivating force behind extensive efforts to control salt cedar and restore native riparian vegetation at the Bosque del Apache National Wildlife Refuge near Socorro. Limited water resources present serious challenges to these restoration efforts and have led to the development of innovative control and re-establishment approaches. Sites have been restored under a variety of circumstances ranging from flood management mimicking natural river hydrographs for the recruitment of native species, to artificial revegetation on sites where flood management is not possible. The techniques outlined below are commonly combined, depending on the success of salt cedar control and the requirements of site preparation for restoration using controlled flooding or revegetation.

SALT CEDAR CONTROL

Salt cedar is an exotic deciduous woody shrub or tree that can survive under conditions where ground water is inaccessible. Similar to native riparian woody species, salt cedar releases thousands of short-lived seeds after flowering. These seeds germinate on moist open mudflats usually associated with flooding events. Unlike native species, however, salt cedar blooms over the entire growing season; one plant can produce over half a million seeds per year. Seedlings can reach 2–3 feet in height in a single growing season with root growth characterized by the development of a single primary root before initiation of lateral root growth. Average heights of mature salt cedar trees are 7–12 feet. Mature root systems are dominated by a root crown extending 12–18 inches below the soil surface from which stems resprout following aerial trunk and stem removal. The presence of this root crown beneath the surface makes salt cedar particularly difficult to control.

MECHANICAL SALT CEDAR CONTROL

Mechanical control of dense salt cedar stands uses a two-phase approach whereby aerial trunks and stems are first cut at the soil surface and piled using a D-7 class bulldozer equipped with a front-mounted brush blade. A 3-yard-capacity articulating loader equipped with a brush rake, working in tandem with bulldozers facilitates piling. Piles are allowed to dry for a month or longer before burning. This work is usually accomplished during winter months, to avoid both harsh hot summer conditions that contribute to equipment overheating and summer nesting seasons for bird species.

Root plowing and raking, the second phase of control, are done during hot and dry summer months, usually May and June when root material is subject to desiccation as it is removed from the soil. A 12-foot wide root plow, pulled by a D-7 class bulldozer, is used to sever the root crown from the remaining root mass approximately 12–18 inches below the soil surface depending on the maturity of the salt cedar stand. A D-8 class bulldozer equipped with a 21-foot-wide hydraulic root rake containing 4-foot-long teeth spaced 15 inches apart is recommended to rake root material from the soil surface. Root material is later piled using the articulating loader. Piles are subsequently burned.

An experienced operator can clear a typical salt cedar stand with plant populations of 3,000–4,000 plants per acre averaging 10–12 feet in height at the rate of approximately 6 acres per day. Root plowing is accomplished at a slower rate of approximately 3 acres per day, while root raking can progress rapidly at a rate of approximately 15 acres per day. Costs for mechanical salt cedar control can vary depending on stand characteristics. Generally, shorter stature, dense stands that are not fully mature will take longer to complete control work than larger trees with fewer stems. Satisfactory control before site restoration must reduce plant densities to less than 20 plants per acre (99 percent control). To achieve this level of control, sites typically are root plowed and raked twice in opposite directions. Follow-up individual plant control treatments (grubbing or herbicide application) are advised for a 2-year period following initial control work. Costs per acre and percent control for various projects on the refuge, based on contracted equipment and labor are provided in the table above.

Site	Year	Cost per acre	% Control
Unit 28	1989	$419/acre	98
Unit 29	1990	$525/acre	98
Unit 30	1992	$302/acre	99
Unit 33	1995	$595/acre	97
Unit 26	1997	$690/acre	99

Mechanical salt cedar control costs and plant mortality at sites on the Bosque del Apache National Wildlife Refuge

Typical root plow used at Bosque del Apache National Wildlife Refuge.

HERBICIDE-BURN SALT CEDAR CONTROL

The herbicide-burn salt cedar control program is relatively new and has emerged from an experimental phase to use as a practical control tool on large, dense continuous tracts. The herbicide treatment includes a mix of imazapyr and glyphosate herbicides with added agents to enhance adhesion and to control spray drift. Application can be made with either a fixed-wing or helicopter aircraft in August or September before fall color change when plants are actively storing carbohydrates in root systems in preparation for winter dormancy. Moderate temperatures (60–70°F), high relative humidity (65–90 percent), and light winds (less than 5 mph) are important to maximize herbicidal activity. Applications should be made only to mature salt cedar stands. Herbicide applications to recently burned or disturbed stands will result in poor control because of disproportionate

Dead salt cedar resulting from aerial herbicide application at Bosque del Apache National Wildlife Refuge.

aboveground to belowground biomass ratios. For maximum control, sites receiving herbicide treatment should not be disturbed for 3 years to allow maximum plant herbicidal effectiveness.

A prescribed burn follows herbicide treatment to remove aerial trunks and stems. In order to carry the fire and maximize fuel consumption, the vegetation canopy coverage should be at least 60–70 percent. Moderate temperatures (64–85°F) and relative humidity (30–40 percent), and light winds (3–7 mph) are important environmental conditions for burning standing dead (herbicide treated) salt cedar to ensure fuel consumption (over 98 percent) and safe burning conditions. Such conditions coincide with the summer rainy season primarily in August. With preparation of 50-foot firebreaks surrounding treated areas, prescribed burning can be conducted safely due to the high moisture content of adjacent untreated salt cedar. Long-term salt cedar control using the herbicide-burn control technique has been 93 percent or greater. Costs per acre and percent control for various projects on the refuge are provided in the table on this page.

Site	Year	Cost per acre	% Control
Unit 33	1995	$114/acre	93[1]
Unit 34C	2001	$182/acre	76[2]
Unit 34B	2001	$225/acre	91[3]

[1]Control after 6 years with application made using a fixed-wing aircraft applying an imazapyr/glyphosate mixture in a 7 gallon/acre total spray volume.
[2]Control after 2 years with application made using a helicopter applying an imazapyr/glyphosate mixture in a 15 gallon/acre total spray volume.
[3]Control after 2 years with application made using a helicopter applying imazapyr in a 15 gallon/acre total spray volume.

Herbicide-burn salt cedar control costs and plant mortality at sites on the Bosque del Apache National Wildlife Refuge.

CUT-STUMP SALT CEDAR CONTROL

Salt cedar infestations commonly develop within remnant stands of desirable native trees, shrubs, or herbaceous cover. The use of mechanical or herbicide-burn salt cedar control techniques is therefore limited by the need to preserve these remnant vegetative communities. The cut-stump control method is currently being evaluated within refuge gallery cottonwood forests to surgically remove unwanted salt cedar while preserving native species. Removal of salt cedar vegetation and other dead woody debris also eliminates the threat of wildfire. The technique requires the removal of salt cedar aerial growth during the winter season using chainsaws and the immediate (within 10 minutes) application of triclopyr herbicide mixed with vegetable oil using a backpack low volume sprayer. The remaining trunks and stems are usually chipped on site and/or removed as firewood by the public. A typical hand crew consists of about 15 personnel including 4 sawyers, 3 swampers (to move aerial trunks and stems to chippers), 2 sprayers, and 6 personnel feeding debris into 2 chipping machines. At least 75 percent control is expected from initial trials, therefore, a follow-up application in late August of 1 percent imazapyr and 0.25 percent nonionic surfactant by volume in water using a low-volume backpack sprayer will be required to approach full control. Typical progress made by one crew is approximately one acre per day in stands averaging 3,500 plants per acre. Costs are very high, and on a contractual basis average $2,500 per acre.

NATIVE RIPARIAN RESTORATION

Native riparian vegetative communities can be successfully restored using either natural flooding processes or artificial seeding and planting. Several key characteristics of riparian vegetative communities, including depth to water table, flood frequency, soil texture, and soil salinity, dictate restoration potential.

RESTORATION USING CONTROLLED FLOODING

Controlled flooding coinciding with the natural seed rain of native species closely emulates natural flooding and regeneration processes. This technique is particularly effective when used in combination with mechanical salt cedar control, which removes competing vegetation and provides light, soil minerals and nutrients for developing seedlings. Native seed germination and plant growth are stimulated by soil disturbance and are influenced by key soil characteristics and hydrologic conditions inherent to the site. Flooding is also the natural process whereby soil salinity is reduced through leaching. Sites with shallower ground water levels and more frequent surface water flow naturally develop vegetation suited for these conditions such as willow. Soil salinity is generally well leached at such locations. Sites with shallower ground water and limited surface flow are more characteristic of saltgrass meadows or mesquite brushlands.

On the Rio Grande and the Pecos River, peak flood periods historically occurred in late May and early June as snow melted at higher elevations. Flood peaks were followed by precipitous drops in river flow as runoff moved through the river system. Native vegetation evolved to cope with these drying river conditions by quickly developing root systems to main contact with declining water tables. Although both native plants and salt cedar are established using controlled flooding, native plants are better able to survive dry conditions following flooding. For example, cottonwood mortality can be 70 percent after one year whereas salt cedar mortality can be over 90 percent. These mortality rates result in a balanced mixture of native vs. exotic plants by the second year of growth. Cottonwoods are better able to compete for available soil nutrients and water; growth rates can be twice those of salt cedar. The resulting plant community is characterized by robust native species growth and salt cedar suppression in the understory.

	Cottonwood			Salt cedar		
Site	1st year	2nd year	% Survival	1st year	2nd year	% Survival
Rio Grande[1]	5	1	20	112	5	4
Unit 30[2]	30	16	47	69	6	9
Unit 26[1]	26	9	22	22	3	14

[1]median values
[2]mean values
[3]Dellorusso, 1999

Cottonwood and salt cedar plant recruitment using controlled flooding and percent survival after one year on the Bosque del Apache National Wildlife Refuge.

Often, salt cedar can be easily controlled while preserving native seedlings through light discing in September following spring establishment. Native seedlings, particularly cottonwood, have deeper roots and heavier root structure than salt cedar seedlings allowing for high native seedling survival following light discing to control salt cedar. On more saline sites such as developing saltgrass meadows, light discing in July following spring seedling establishment can also control salt cedar while enhancing saltgrass growth by cutting and spreading remnant saltgrass rhizomes in moister soil conditions.

River flooding still occurs on some major southwestern river systems although less frequently than what once occurred historically. Overbank flooding events are now managed by river regulatory entities through a network of flood control dams and levees to protect irrigation infrastructure and urban communities. During cyclical periods of abundant snowfall in mountain watersheds water may be available in excess of agricultural and urban needs. Riparian restoration can occur concurrent to water delivery from upper storage reservoirs to those farther downstream by matching historic river flow patterns within existing levee systems. In a more controlled setting, flooding for riparian purposes is possible on areas such as state and federal wildlife refuges or tribal lands outside river levees using appropriated irrigation water.

RESTORATION USING ARTIFICIAL PLANTINGS AND SEEDING

Many sites along the Rio Grande and Pecos River have no natural or controlled flooding potential and must be revegetated artificially. Weed competition can often limit the survival and growth of planted materials. Managers should therefore consider treating salt cedar monocultures using herbicide-burn control practices that result in limited growth of competing weeds. Factors influencing revegetation potential have been documented for more common plant species. For example, some species can survive through contact with the water table, therefore it is important to know water table depth and its annual fluctuation. Plant species also have thresholds for survival and growth based on soil and salinity conditions. Many sites have not benefited from the leaching effects of flooding for many years and salinity levels are quite high. Some sites have such high salinities that revegetation is not possible. Clay soils should be avoided as planting substrates. Considering the high costs associated with salt cedar control and revegetation, some preliminary information on soil, depth to ground water, and salinity conditions should be gained before the selection of areas for salt cedar control.

Following salt cedar control, detailed information is required to develop accurate planting prescriptions in the field to ensure restoration success. The most practical method involves development of a grid system across the area, with each grid cell consisting of one-half acre. Soil samples are taken at the center of each grid, 15 inches below the soil surface and 18 inches above the water table and sent to a soil laboratory specializing in riparian revegetation for analysis of soil texture and electrical conductivity. From this information, a series of contour maps are generated outlining water table depth, soil texture, and salinity. Field planting crews are provided with grid sheets outlining plantings based on species survival and growth tolerances to water table depth, soil texture, and soil salinity

Cottonwood and willow trees and shrubs are planted using dormant poles augered to the water table to establish forested areas. This technique requires cutting saplings of sufficient length and small butt diameter during winter months. All lateral branches are trimmed leaving only 2–3 branches, and the butt ends are soaked in water for a 10-day period before planting. On average, a 3-person crew is able to auger and plant 150–180 poles per day using a large production auger drilling machine.

Understory plantings can be made using 30-inch container nursery stock augered into water tables of generally 5 feet or less and at locations where electroconductivity readings are less than 8.0. This technique relies on root development to the water table. Plantings are usually in August and require supplemental water for 1–2 months. Planting density is about 100 trees or shrubs per acre, a density shown to benefit wildlife. Plant survival for both techniques is about 90 percent after 4 years with about a 24 percent annual growth rate.

Planted cottonwoods after 6 years at Bosque del Apache National Wildlife Refuge.

Where water tables are deep or electroconductivity readings are high, other establishment techniques must be used. Rainfall harvest is one such method for establishing seedling shrubs where electrical conductivity levels are below 8.0. A road grader is used to construct a long shallow V-shaped water catchment. Seedlings are planted at 5-foot intervals at the bottom of the catchment, and the banks are lined with plastic. Seedlings obtain supplemental water from surface rainfall or undersurface condensation funneled from the plastic to seedling root zones. Survival and growth rates are comparable to poles and containerized stock.

In areas of higher electroconductivity (8–14), seeding mixtures of four-wing saltbush and salt-tolerant grasses such as alkali sacaton are prepared and seeded following the onset of summer rains. Sites where electroconductivity levels are above 14.0 cannot be revegetated

Species	Depth to water table (feet)	Soil texture	Soil electric conductivity (dS/m)
Cottonwood	5–13	sandy-loamy	< 1.0–2.0
Black willow	3–6	sandy-loamy	< 1.0–2.5
New Mexico olive	< 5	sandy-loamy	< 1.0–2.5
Screwbean	< 5	sandy-loamy	2.5–8.0
Wolfberry	< 5	sandy-loamy	2.5–8.0
4-wing saltbush	< 15	sandy-loamy	8.0–14.0

Water table depth, soil texture, and soil electroconductivity requirements for revegetation on the Bosque del Apache National Wildlife Refuge.

Riparian plant establishment using the rainfall harvest method at Bosque del Apache National Wildlife Refuge.

successfully. Seed can take as long as 4 years to germinate, and growth can be slow depending on the timing and amount of late summer and winter precipitation.

Overall revegetation costs can range between $1,100 and $1,500 per acre. These costs include site suitability potential analysis, plant materials, and labor. Over 80 percent of costs associated with revegetation are plant materials. Costs for plant materials can often be reduced for cottonwood and willows through harvest at natural nursery sites along rivers and ditches. Only 5 percent of total costs are associated with site suitability determination, quite low when the importance of this activity is considered.

Lasting salt cedar control requires a long-term commitment by agencies and individuals to some base level of maintenance following initial control to avert re-infestation. At least 2 years of follow-up individual plant treatments should be planned to control salt cedar resprouts on an individual plant basis. A proven long-term strategy to avert widespread re-infestation is the establishment of native riparian vegetation following control. If sites are subject to periodic flooding, care should be taken to closely follow historic natural river flooding patterns that coincide with the dispersal of native seed. Research has shown that native riparian trees and shrubs are better able to survive harsh river wetting and drying periods associated with historic flood patterns. Once established, native riparian seedlings are able to out-compete salt cedar seedlings, and the resulting vegetative community will be dominated by native plants.

The Future of Water in New Mexico

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Two decades of greater-than-average rainfall and a desire to postpone tough choices have enabled the laissez faire approach of the past to persist.

This introductory statement from the New Mexico Interstate Stream Commission's 2002 Framework for Public Input to a State Water Plan, Appendix B, prompts one to think about the water management choices New Mexico faces and the alternative futures that will result. Many people recognize that drought has brought—and will continue to bring—dramatic controversies and changes regarding our uses, distribution, and administration of the state's finite water supplies. Advocates with diverse perspectives and interests seek changes in all three areas. Many of these changes are highly controversial. Regardless of what we do, we will experience substantial water management change, and it is these changes that will define the future of water in New Mexico.

The approach taken in this paper, to describe alternative water futures in New Mexico, is based on a number of premises. Many of these premises imply alternative future conditions. Some premises represent my understanding of the facts; many reflect my observations and conclusions. Collectively they describe my thinking on the reasons and imperatives that are driving changes in New Mexico water management.

PREMISES

- Virtually nowhere in New Mexico is there sufficient water to satisfy all needs, wants, and wishes.
- New Mexico's water is not over appropriated —it is under administered.
- New Mexico's jobs, economy, and future are jeopardized by the lack of certainty regarding the future of its water.
- Much of New Mexico's growth occurred during the unusually bountiful water years of the 1980s and 1990s. With a return to normal conditions—to say nothing of drought conditions—shortages of water across much of New Mexico will become acute.
- New Mexico has obligations to limit its water use on most interstate streams in order to comply with interstate compact requirements. If New Mexico does not meet these obligations they will be externally enforced, probably with severe penalty and imposition of undesirable rules.
- Water use without measurement or accountability is somewhat like giving taxpayers access to the state bank vault with the message "take what you need and leave the rest."
- Even though New Mexico law says that all beneficial uses of water are equal, the New Mexico legislature in fact has created priorities of use. Domestic wells, stock wells, and stock tanks have the higher priority. All other uses share the lower priority.
- Despite our wishful thinking, there are no magic solutions, no painless remedies. Water resources solutions will always involve either distribution of available supplies in priority, or sharing the water and the shortages in some manner, or water anarchy, where the upstream users take it all. *Win big, lose big* is the law. *Lose less, lose less* is an alternative reality. *Win, win* is rare except when some water users accept money in lieu of water and others are willing to pay for it.
- Adjudications will not be completed for decades to come, and therefore adjudicated water rights cannot serve as the basis of water resources administration. The state engineer legally can use best available information as the basis of water-use administration, but determining what that information means and applying it to practical use is an immense task and will have imperfect results.
- Ground water use in some areas of New Mexico by some water users, particularly from aquifers in the middle Rio Grande, is like a pyramid con-game. Some municipal water users depend on ever-increasing ground water pumping with commensurate increases in return flows to the river in order to avoid having to acquire and transfer valid surface water rights to offset their river depletions. If ground water use stabilizes for whatever reason, the pyramid scheme collapses. But the continuing depletion of the river to refill the hole in the ground water table will continue. Not even federal judges can change that.

- Strict application of the priority administration in a river basin where there are both direct surface water uses and delayed depletions of the river due to ground water pumping from adjacent aquifers creates a poor and undesirable result. Additional tools, such as forbearance, water banking, and dry-year agreements, are necessary to avoid poor results.
- Administration is not easy or cheap. It requires water masters to oversee the distribution of water in accordance with priorities and operating rules. It also requires accounting water uses against water rights or agreed distribution arrangements. Colorado has more water masters in the field than New Mexico water management agencies have employees.
- Technology is necessary for managed solutions and may marginally augment our available supplies, but no magic bullets are in sight here, either. Technology for supply augmentation and for water resources management and adminis tration will require substantial increases in funding.
- Allowing water banking to be implemented in a river or aquifer system where all the water uses are not measured and administered is like printing cash to solve an income problem. Water banking must not result in net increases in water depletion.
- Water users from a common river or aquifer system, if they are motivated and have both technical and mediation help, can develop and agree to implement a superior solution to the allocation of limited water supplies as compared to implementation of priority administration in accordance with the State's legal authorities.
- The State should help, financially and technically, those water users who help or wish to help themselves.
- Water is scarce and essential, and therefore it has very high inherent economic value. It also has deep and diverse non-economic values. We need to find a way to reflect those values in our stewardship and management of water.
- Whereas uses need to reflect economic value, changes in use need to reflect the public welfare of both the state and the affected regions. This is much easier said than done.
- Virtually all of New Mexico's surface water was allocated to irrigation a century ago. New Mexico's well-being requires that some of this water be reallocated to municipal, industrial, and environmental uses. Irrigation districts must not be allowed to veto reallocation through the market of reasonable amounts of specific willing farmers' water to satisfy the water requirements of other valid but junior uses. Barriers that prevent market reallocation of some irrigation supplies to municipal, industrial, and environmental uses require state policy-maker attention.
- The State of New Mexico should prioritize and fund water resources investigations and development of models to serve as the basis of administration of complex water resources systems.
- Environmental uses of water are important to us all and are valid. Some environmental water uses are required under federal environmental law.
- Federal preemption may occur in the absence of other solutions to provide water for compliance with federal environmental law. Balance is needed. It's not appropriate or smart to deny the validity of environmental water needs or the preemptive ability of the federal agencies and courts. It's also essential to resist overweening, unsupported, and unrealistic demands, and attempted takings of water.
- The State of New Mexico needs to be able to administer and protect water that is legitimately acquired and dedicated for riparian and riverine uses. A statewide system to acquire and administer water for environmental purposes is required to avoid federal preemption and to provide for environmental quality.
- The state and local districts have distinct and complementary roles in the governance and administration of water use. Administration of water and maintenance of systems within local districts, such as acequias or irrigation districts, is best accomplished by local districts, but the state will need to see that river diversions and maintenance functions of the districts don't unlawfully diminish downstream supplies.
- Much of New Mexico's water use is from ground water aquifers that are being depleted. Planning is needed to realistically address solutions that ameliorate the current "race to the bottom."

FOUR ALTERNATIVE WATER FUTURES

Based on these premises, I offer four basic alternative futures for water in New Mexico. Different futures will occur in the different river basins and aquifers of New

Mexico in response to the various circumstances, issues, problems, priorities, and players.

1 Solutions through meaningful planning and negotiations New Mexico will find the wherewithal to face these very difficult problems. Water users will work out their preferred and workable solution. The state will do the very best it can to facilitate and provide matching funding for workable, realistic solutions. These compromises may not be pleasing to some but will be far superior and less costly than a laissez faire or unrealistic approach.

Implementation will require, for each river basin, stream system, or major aquifer, the following:

- Convening representatives of the water users within the stream system and connected aquifers.
- Motivating them to negotiate. Serious, unavoid able consequences of failing to negotiate may be a necessary factor to create the necessary motivation. In some cases water users may not be motivated to or may refuse to negotiate, leaving this approach unworkable.
- Developing the best available tabulation of water rights—amounts, priorities, points of diversion, and places of use.
- Providing OSE/ISC participation and guidance to assure that the negotiated solution is in accordance with water supplies that are legally and physically available to the geographic area—e.g., in accordance with hydrologic reali ty. The OSE/ISC must also prepare and adopt rules and procedures for distribution of water by a water master.
- Providing skilled facilitators/mediators to help get through the substantial controversies that inevitably will be involved.
- Requiring measurement of all water diversions, on-the-ground systems to limit uses in accor dance with water rights and priorities or nego tiated settlements, and accountability for illegal or excessive uses.
- Creating the practical capability and political willingness to revert to priority administration where required by the interests and obligations of the State of New Mexico and where locally derived negotiated solutions are not forthcoming.
- Assessing local water use to fund local water administration and solutions or finding alterna tive means of funding.
- Political willingness to allow existing water management systems or anarchic lack thereof to continue where local water uses may be unfair or are incorrect but which do not have a material adverse impact on the state and where local entities are unable or unwilling to help implement and fund the necessary systems of administration.
- Substantial investment in water resources investigations: models, systems of water resources and water use measurement, monitoring, improved efficiency of water use, and accounting.

This approach will be facilitated by changes in law to provide tools and resources and to authorize solutions.

2 Priority administration This is conceptually simple but difficult, costly, and controversial. However, in many cases, it may be the least costly solution for the state, much cheaper than the costs that eventually will result under a laissez faire approach. The state must determine the available supply, determine the amount and priority of water rights to use the available supply, distribute it in priority, and cut off water users that are out of priority. It can and does work in limited areas of New Mexico but requires an effective method for timely enforcement that does not now exist. Priority administration probably will engender litigation, particularly where water rights being administered have not been adjudicated and claims settled. It may be required to motivate superior solutions that the state cannot develop and implement without the participation and cooperation of major water-user groups.

3 Deny or ignore New Mexico may continue to not solve these problems until required to do so by the courts, one by one. New Mexico will be forced to accept the results, regardless of how insensitive or damaging they may be and how onerous the imposed penalties, which range from lost opportunities to fines and loss of jurisdiction imposed by the U.S. Supreme Court.

4 Local control New Mexico may delegate water management to local districts. This has two potential outcomes. The result may be good if the local district operation appropriately distributes its water within the district, fulfills its maintenance responsibilities, doesn't take water that belongs downstream, and has appropriate external constraints and accountability. The result will be poor if the accountability for failure reverts to the state or is absorbed by others external to the district.

CONCLUSIONS

The New Mexico Interstate Stream Commission, in the preparation of the State Water Plan, should evaluate and prioritize the problems and issues in the state's various river basins and aquifers and consider which of the alternative water futures are appropriate and realistically achievable for each. Substantial public input and review of the draft conclusions is essential.

The Office of the State Engineer should develop and be funded to implement a system of administering wet-water use in addition to administering a system of applications, permits, and files.

Both agencies should increase their capacity to engage in the development of solutions through meaningful planning and negotiations in multiple areas of New Mexico.

Executive and legislative leadership engagement and support will be essential—except, of course, for alternative future #3.

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29 *left*	Paul Tashjian
29 *right*	Michael Roedel, New Mexico Department of Game & Fish, 2003
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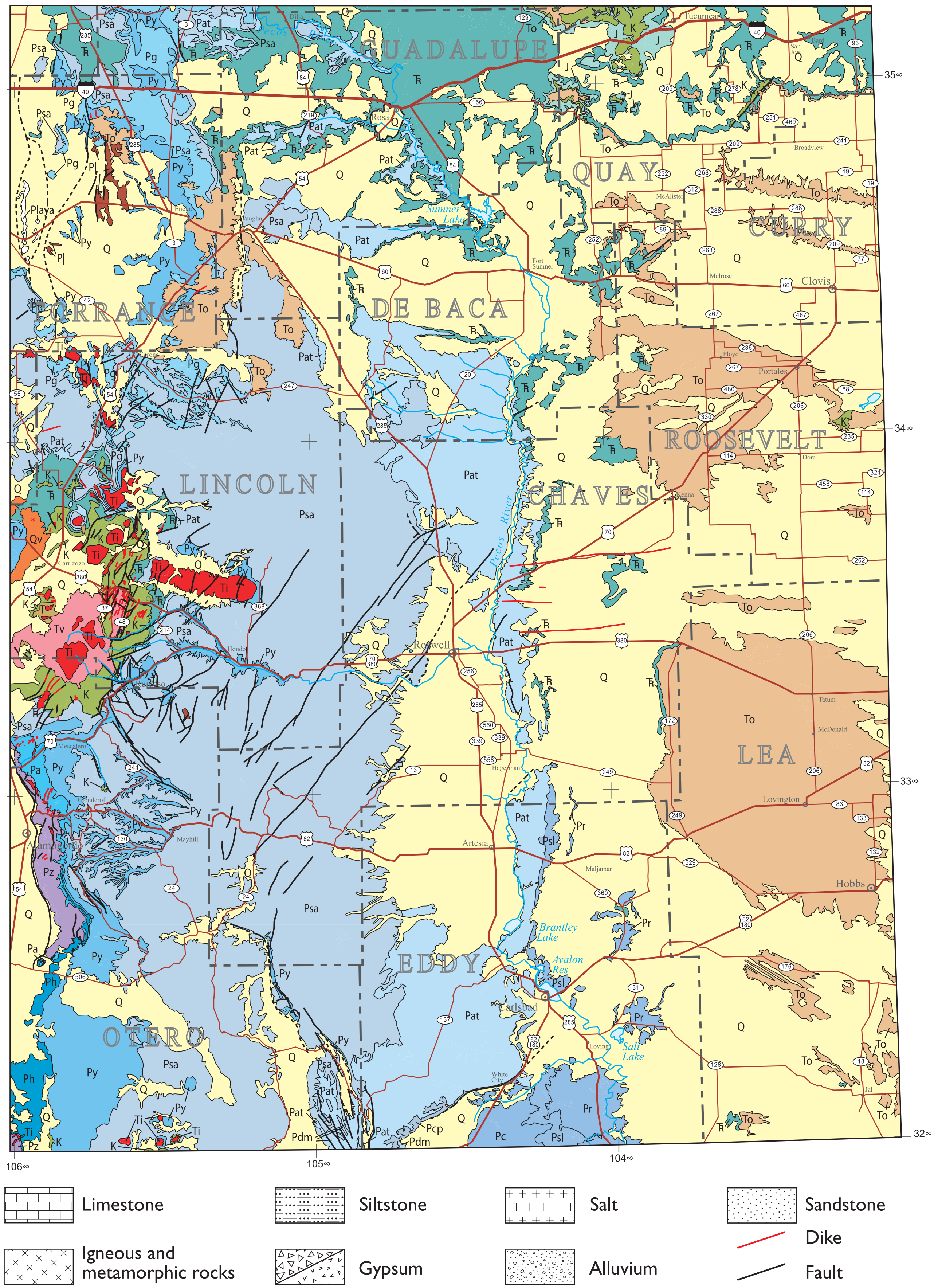
Acronyms

ARM	active river management
BOR	U.S. Bureau of Reclamation
CAFO	concentrated animal feeding operation
CAGW	Carlsbad Area Ground Water Model
CID	Carlsbad Irrigation District
CMA	Critical Management Area
DPT	data processing tool
DSS	Pecos River Decision Support System
EIS	environmental impact statement
EPA	U.S. Environmental Protection Agency
EBID	Elephant Butte Irrigation District
ESA	Endangered Species Act
ET	evapotranspiration
FSID	Fort Sumner Irrigation District
GWQB	Ground Water Quality Bureau of the New Mexico Environment Department
HIC	Hagerman Irrigation Company
ISC	New Mexico Interstate Stream Commission
MRGCD	Middle Rio Grande Conservancy District
NEPA	National Environmental Policy Act
NMDA	New Mexico Department of Agriculture
NMED	New Mexico Environment Department
NMEMNRD	New Mexico Energy, Minerals and Natural Resources Department
NMOCD	Oil Conservation Division of the New Mexico Energy, Minerals and Natural Resources Department
NRCS	Natural Resource Conservation Service
NWR	National Wildlife Refuge
OSE	New Mexico Office of the State Engineer
PDO	Pacific decadal oscillation
PVACD	Pecos Valley Artesian Conservancy District
RABGW	Roswell Artesian Basin Ground Water Model
RBAM	Red Bluff Accounting Model
SWCD	Soil and Water Conservation District
SWQB	Surface Water Quality Bureau of the New Mexico Environment Department
TMDL	total maximum daily load
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WIPP	Waste Isolation Pilot Plant
WQCC	New Mexico Water Quality Control Commission
YPC	Yates Petroleum Corporation

Age (M.Y.)	Era	Period	Symbol	Lithology	Formation	Notes
	Cenozoic	Quaternary	Q		Quaternary sediments - including alluvium, piedmont, landslides, etc.	Shallow alluvial aquifer
	Cenozoic	Quaternary	Qv		Quaternary volcanics (including basalts, tuffs, etc.)	
	Cenozoic	Tertiary	Tv		Tertiary volcanics (including basalts and tuffs)	
	Cenozoic	Tertiary	Ti		Tertiary intrusives	
	Cenozoic	Tertiary	T		Tertiary sediments exclusive of the Ogallala Formation	
65	Cenozoic	Tertiary	To		Ogallala Formation	Major aquifer
	Mesozoic	Cretaceous	K		Cretaceous	
	Mesozoic	Jurassic	J		Jurassic	
240	Mesozoic	Triassic	Tr		Triassic	
	Paleozoic	Permian	Pr		Rustler Formation (including Culebra dolomite)	Minor aquifer; source of salt below Malaga Bend
	Paleozoic	Permian	Psl		Salado Formation (salt)	WIPP repository
	Paleozoic	Permian	Pc		Castile Formation (gypsum)	
	Paleozoic	Permian	Pat Pcp Pdm		Artesia Group, Capitan Reef Formation (including Goat Seep) and Delaware Mountain Group	The Artesia Group (Pat) is the confining unit (aquiclude) in the Roswell artesian basin and, in places, an oil producer The Capitan Reef (Pcp) is a major aquifer in the Carlsbad area and the host rock for Carlsbad Caverns
	Paleozoic	Permian	Psa		San Andres Formation	The San Andres Formation is the major aquifer in the Roswell artesian basin and a major oil producer on the northwest shelf
	Paleozoic	Permian	Py		Yeso Formation	
	Paleozoic	Permian	Pa		Abo Formation	These formations are oil and gas producers in southeast New Mexico
	Paleozoic	Permian	Ph		Hueco Formation	
570	Paleozoic	Older Paleozoic	Pz		Older Paleozoic rocks	Oil producers
	Precambrian		P€		Precambrian	

(Not to scale)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Santa Rosa
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Clovis
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Roswell
Pecos River
Artesia
Carlsbad
Hobbs
Lovington
Brantley Lake
Avalon Res
Salt Lake
35∞
34∞
33∞
32∞
106∞
105∞
104∞
Limestone
Siltstone
Salt
Sandstone
Igneous and metamorphic rocks
Gypsum
Alluvium
Dike
Fault

NEW MEXICO BUREAU OF GEOLOGY AND MINERAL RESOURCES

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- Salt cedar control and riparian habitat restoration

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