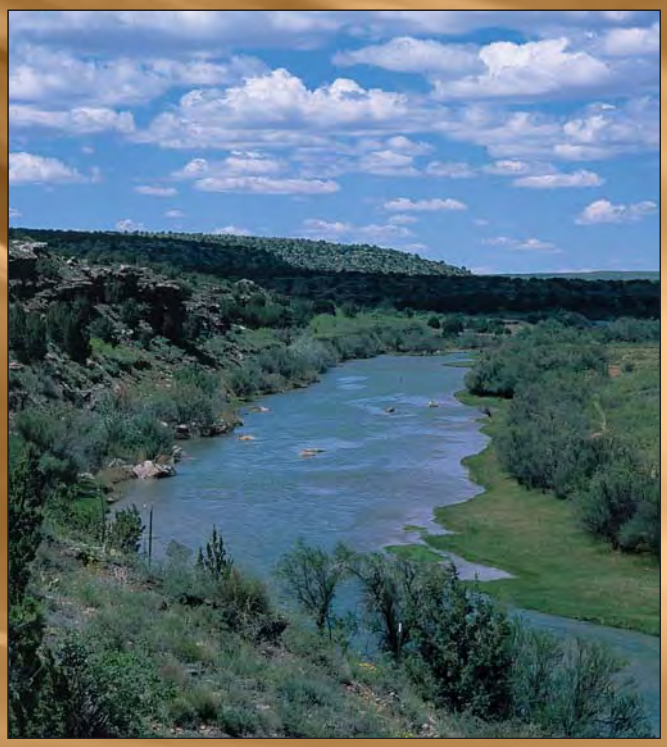
CHAPTER FOUR

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

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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

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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.

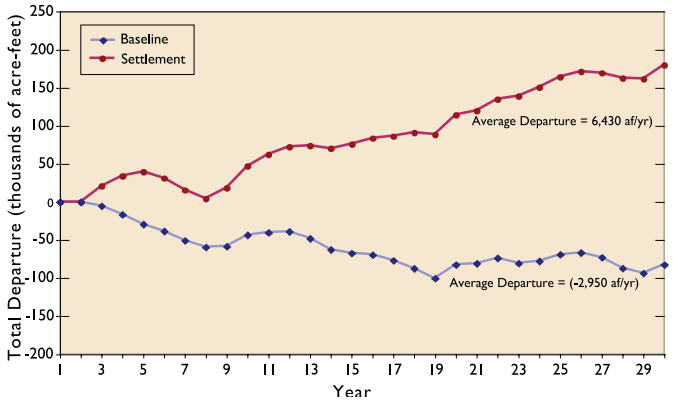
RESULTS

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:

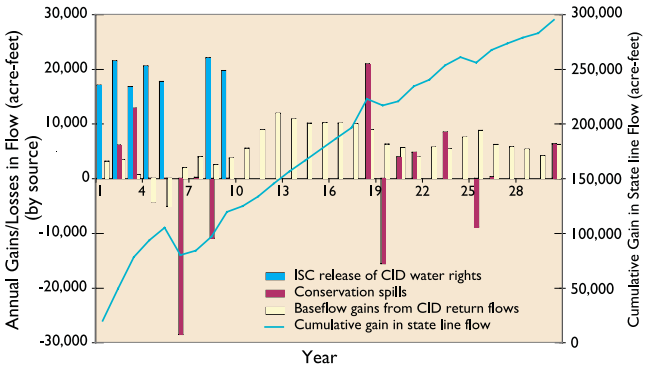
- Estimated Pecos River Compact deliveries and credits;
- CID surface water allotment and supplemental pumping rates;
- Augmentation pumping of purchased PVACD water rights.

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.

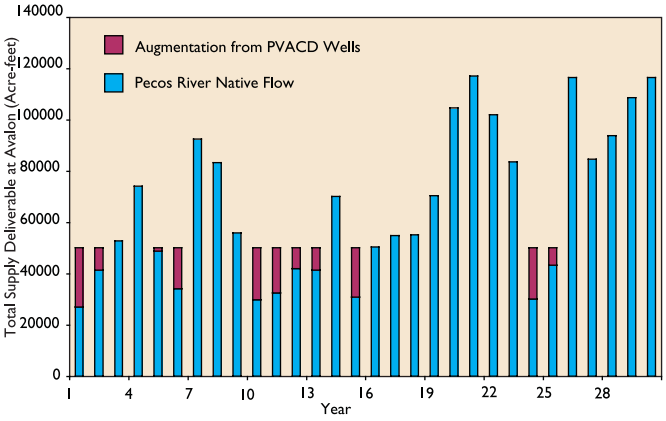


Comparison of Pecos River Compact departures for the two scenarios.



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."

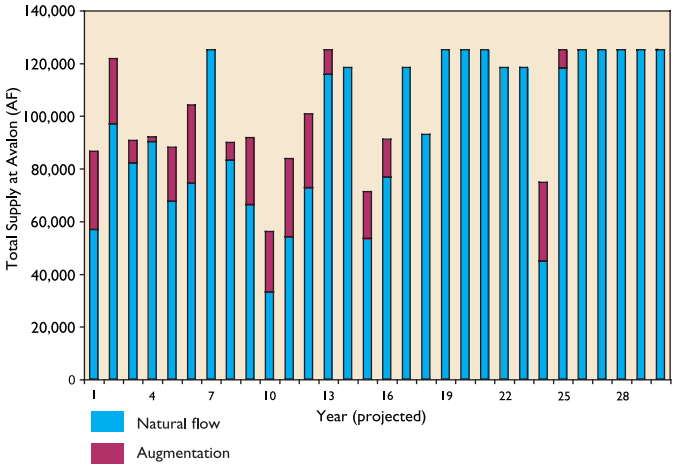
The impacts of the settlement on CID water supply are shown in the next two figures. Under the settlement terms, CID will not attempt a priority call on Pecos River basin water rights if they have at least 50,000 acre-feet of divertable supply each year. This means in practice that a need for a priority 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

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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:

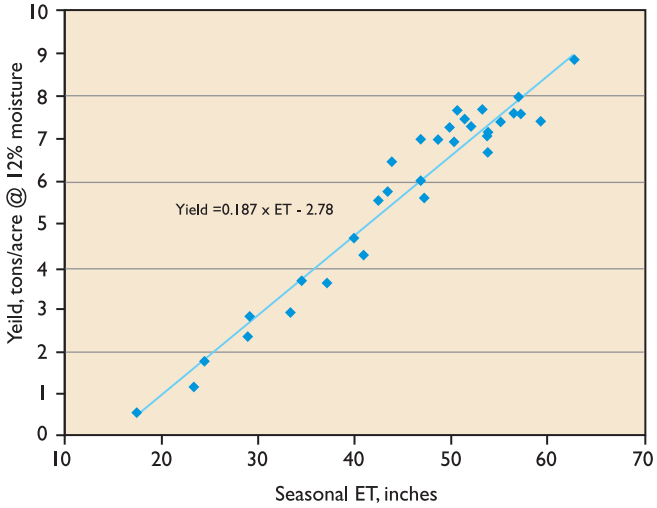
Drip-irrigated strawberries.

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.

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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.

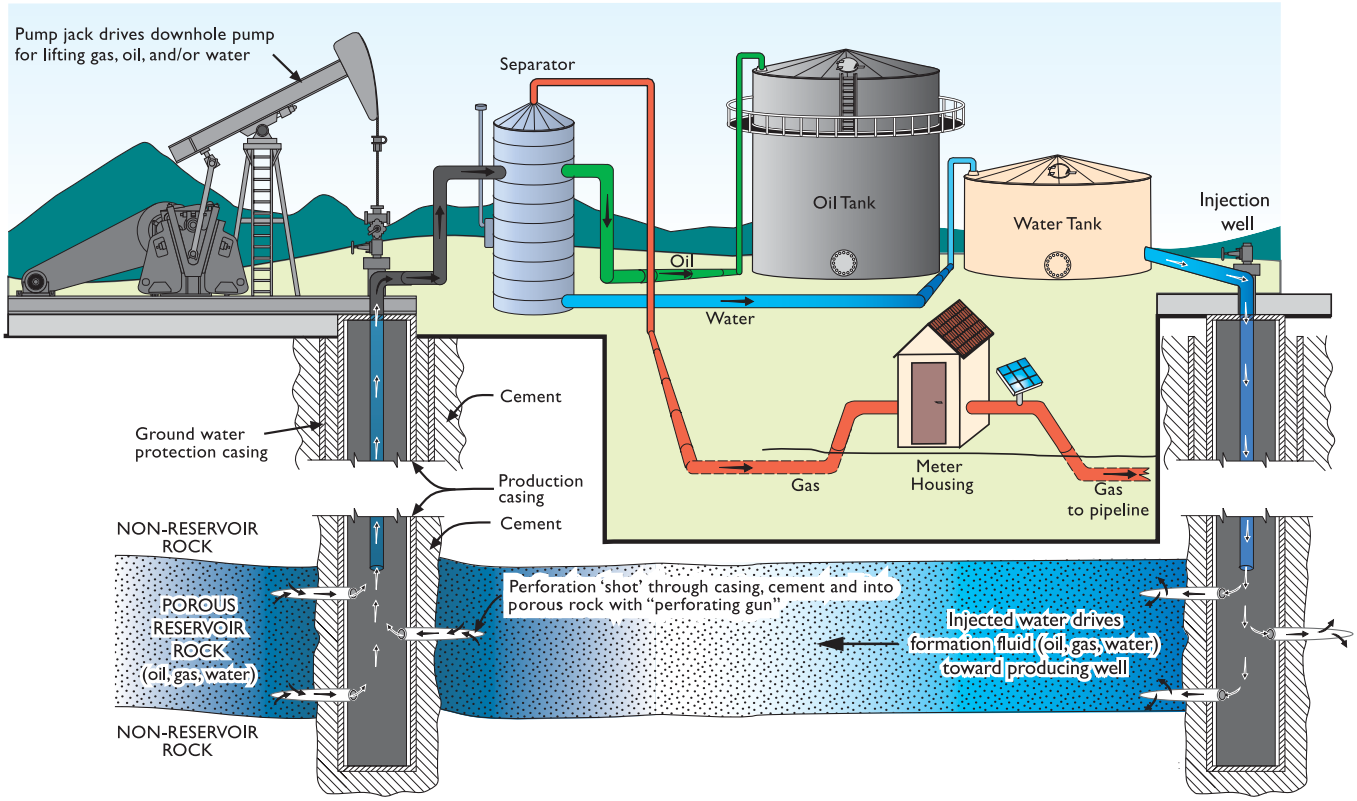
Injection well in the Indian Basin gas field south of Artesia.

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?

Brian Brister
New Mexico Bureau of Geology and Mineral Resources

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

Joel M. Carson
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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

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

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.

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Salt Cedar Control and Riparian Habitat Restoration

John P. Taylor, *Bosque del Apache National Wildlife Refuge*
Kirk C. McDaniel, *New Mexico State University*

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 waterborne 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.

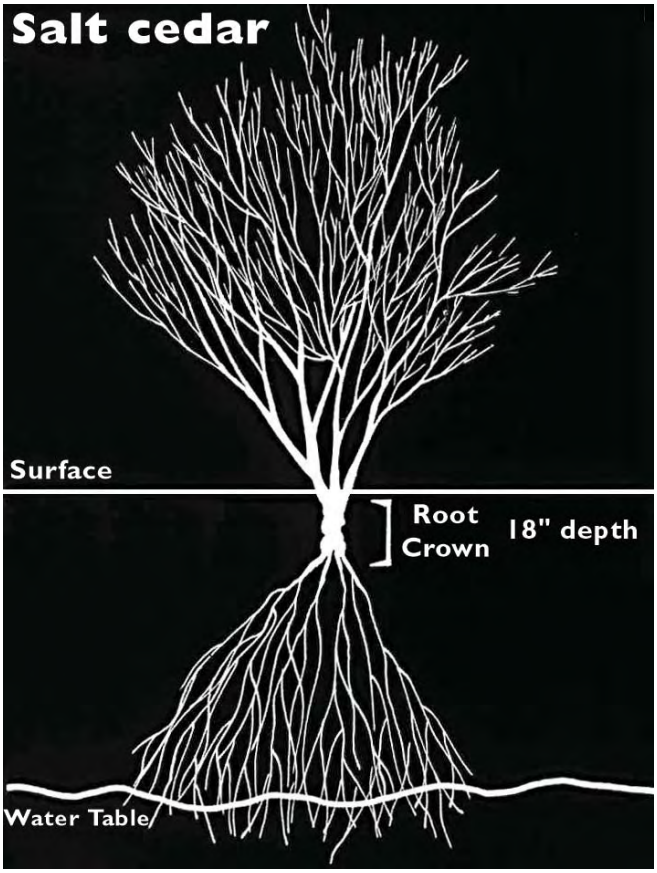

Diagram of the aboveground and belowground root system of salt cedar showing the location of the root crown.

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 flood-

ing 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.

Site	Cottonwood 1st year	Cottonwood 2nd year	Cottonwood % Survival	Salt cedar 1st year	Salt cedar 2nd year	Salt cedar % 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

Norman Gaume, *Santa Fe, New Mexico*

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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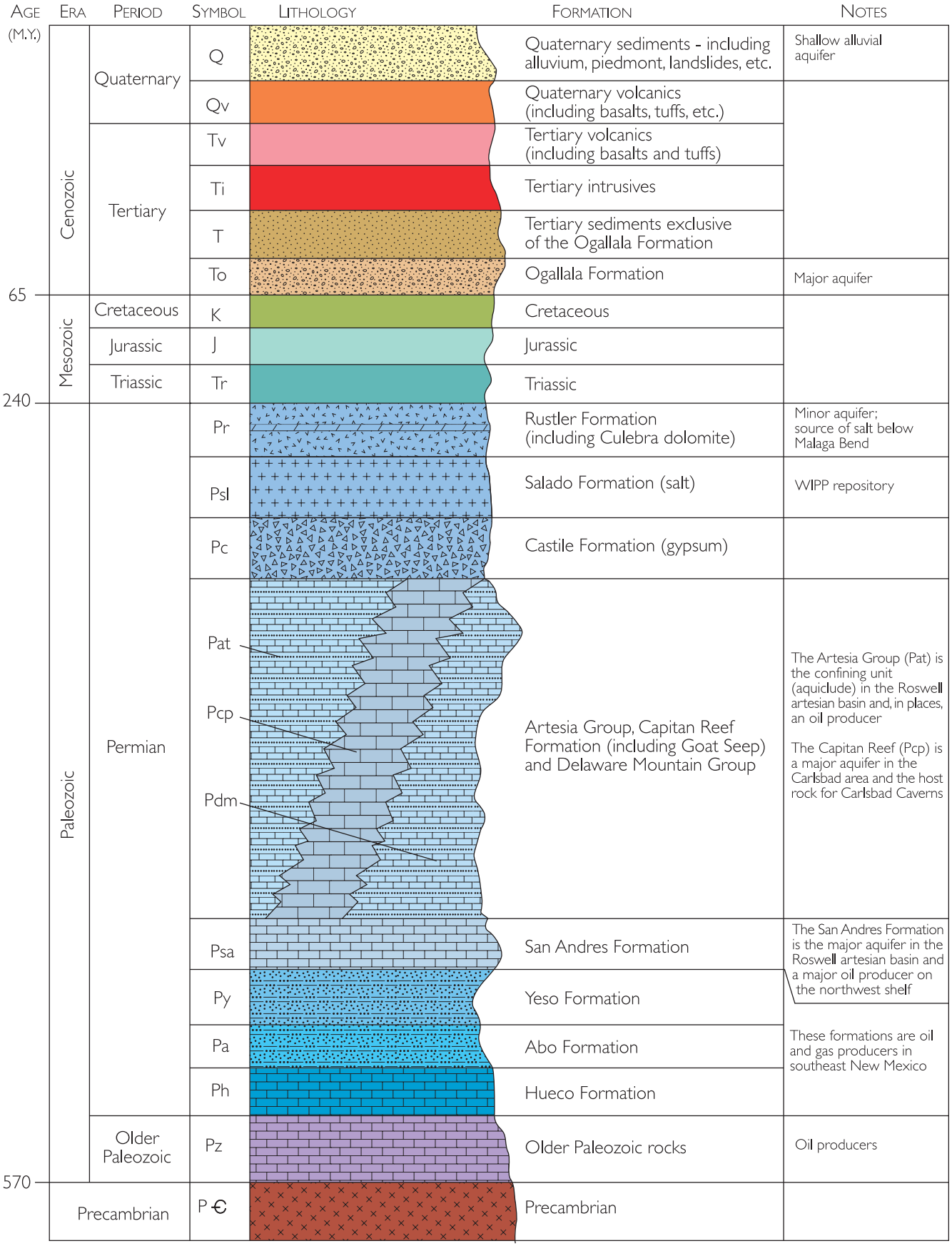
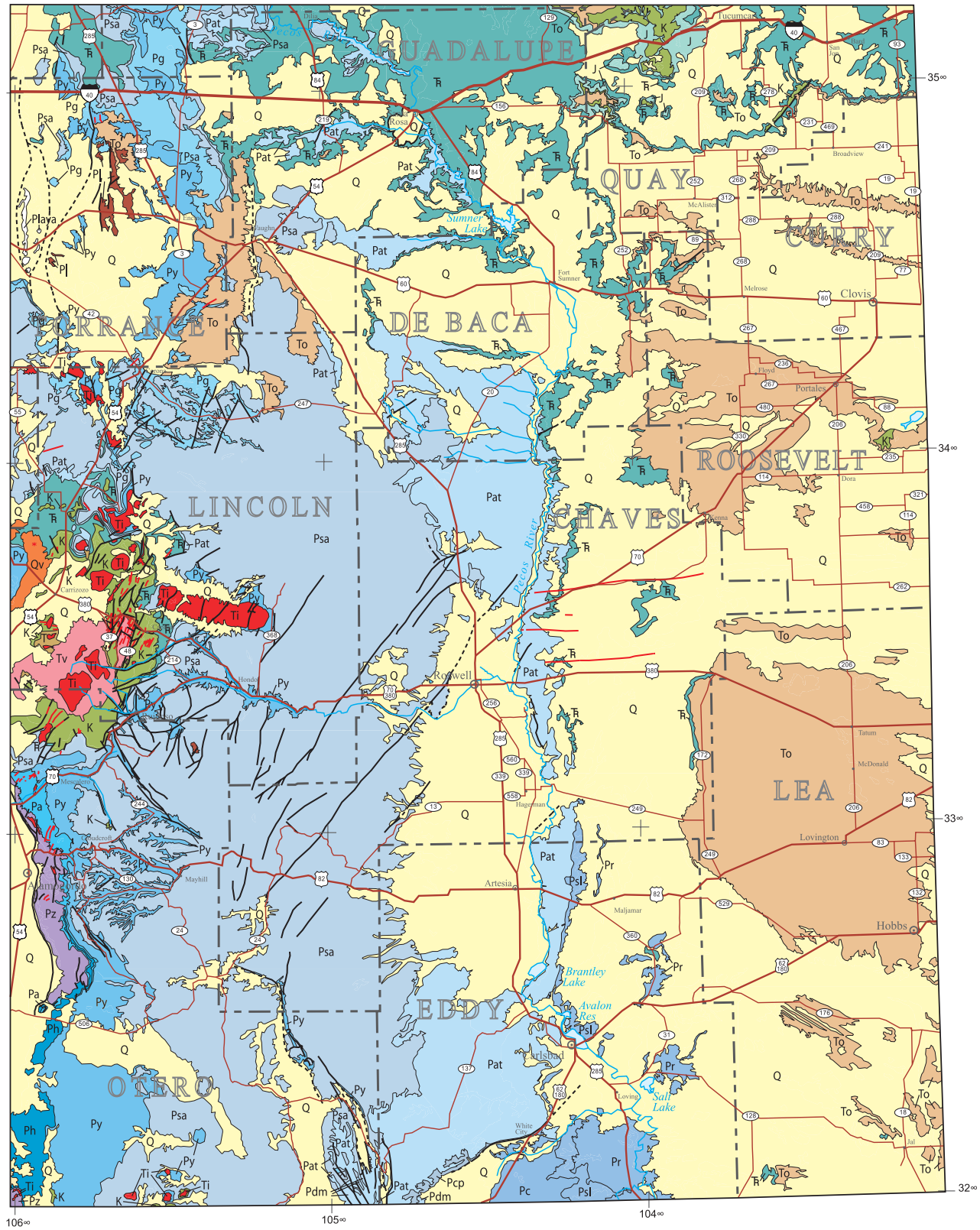
Acronyms

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
Qv
Quaternary volcanics (including basalts, tuffs, etc.)
Tertiary
Tv
Tertiary volcanics (including basalts and tuffs)
Ti
Tertiary intrusives
T
Tertiary sediments exclusive of the Ogallala Formation
To
Ogallala Formation
Major aquifer
65
Mesozoic
Cretaceous
K
Cretaceous
Jurassic
J
Jurassic
Triassic
Tr
Triassic
240
Paleozoic
Permian
Pr
Rustler Formation (including Culebra dolomite)
Minor aquifer; source of salt below Malaga Bend
Psl
Salado Formation (salt)
WIPP repository
Pc
Castile Formation (gypsum)
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
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
Py
Yeso Formation
Pa
Abo Formation
Ph
Hueco Formation
These formations are oil and gas producers in southeast New Mexico
Older Paleozoic
Pz
Older Paleozoic rocks
Oil producers
570
Precambrian
P-Є
Precambrian

(Not to scale)



Limestone

Siltstone

Salt

Sandstone

Igneous and metamorphic rocks

Gypsum

Alluvium

Dike

Fault

Water in New Mexico is a complex and important issue. Nowhere is that more true than on the Pecos River in eastern New Mexico. This anthology of 30 short articles is a timely look at water issues along the Pecos River, from Sumner Lake to the Texas state line. Topics include:

- Regional geology of the lower Pecos region
- An overview of water operations in the Pecos River basin
- Regional hydrology of the Roswell artesian basin and the Capitan aquifer
- Irrigation districts in southeast New Mexico
- Managing forests for increasing water yields
- Drought in New Mexico
- Salt cedar control and riparian habitat restoration

Produced in conjunction with the third annual Decision-Makers Field Conference in October 2003, this volume is an authoritative look at the historical framework and a summary of where we are—and where we're going—on the Pecos River in New Mexico.