New Mexico Decision-Makers Field Guide No. 1

Water, Watersheds, and Land Use in New Mexico

Impacts of Population Growth on Natural Resources

Santa Fe Region 2001

Peggy S. Johnson, Editor

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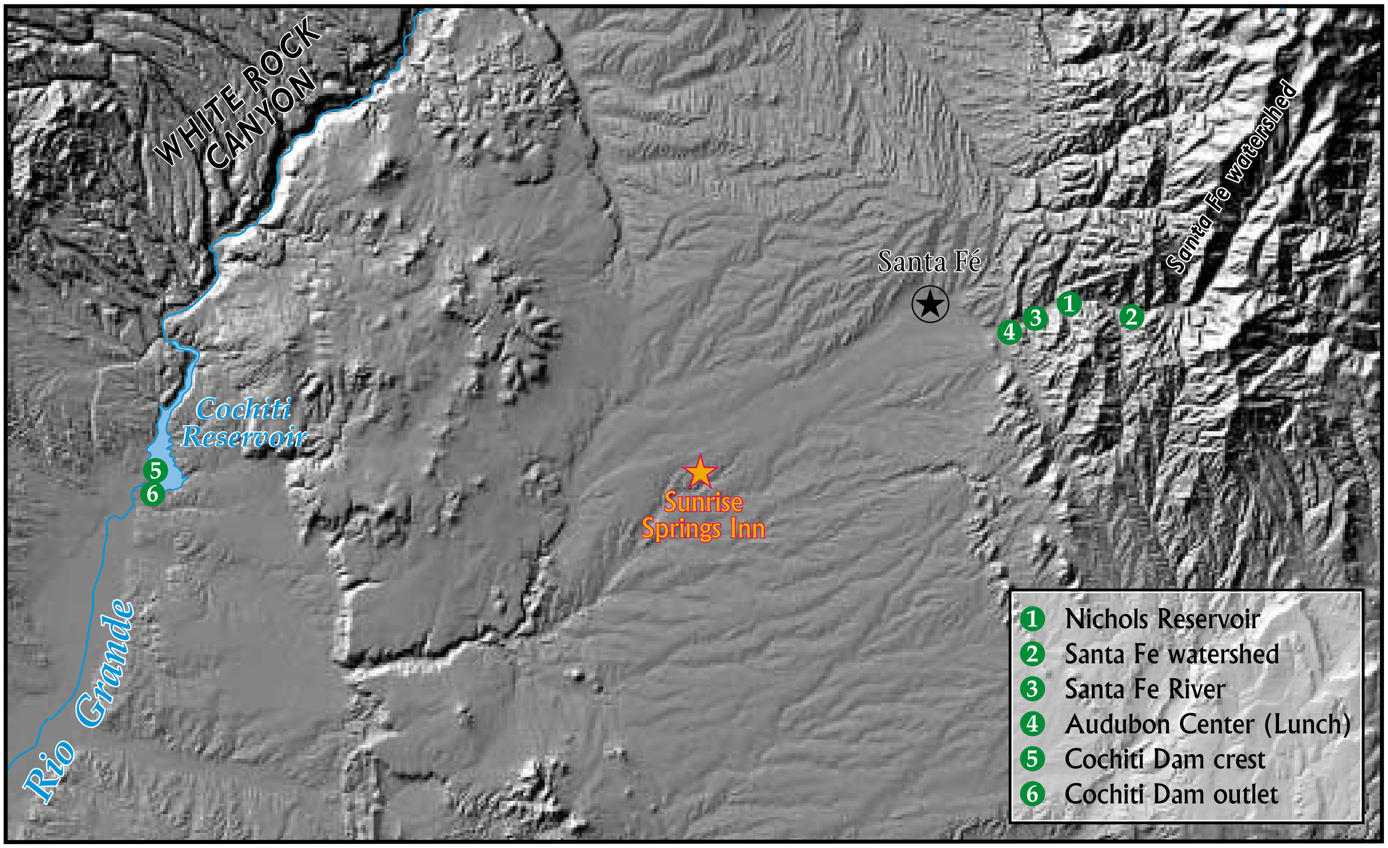
Day Two, May 10, 2001

The Santa Fe River—
Headwaters to the Rio Grande



Day Two

Thursday, May 10, 2001

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The Santa Fe Municipal Watershed—An Introduction

by *Amy C. Lewis*, Sangre de Cristo Water Division, City of Santa Fe

The forests of the Santa Fe watershed are in danger of a catastrophic fire similar to the Cerro Grande and Viveash fires in 2000. The 17,200 acres of the upper Santa Fe River watershed provide about 40% of the city of Santa Fe's annual water supply, stored in Nichols and McClure Reservoirs. The watershed is closed to the public pursuant to a 1932 order from the Secretary of Agriculture. A catastrophic fire in the watershed, followed by a summer monsoon as occurred after the Dome fire in 1996, would result in severe erosion, which would fill the storage reservoirs with dirt and ash, compromise the water treatment plant, and possibly flood downtown Santa Fe (McCord and Winchester, this volume).

The watershed's forests are threatened because they are not in a natural condition. Historically, fire was a common component of a healthy ponderosa pine forest, burning every 5–7 years (Cassidy, Fire and Vegetation Relationships on the Santa Fe National Forest, this volume). Before 1880, the Santa Fe National Forest was a typical natural forest. It was open, holding just 40–100 trees per acre, mostly ponderosa pine. Grass, sedges, forbs, and other ground cover held the soil in place and acted like a sponge, letting moisture gently seep into the streams. Open areas captured snow in the shade of the pines, acting as reservoirs. Low-intensity fires continuously renewed the forest, burning dead branches, needles, seedlings, fallen trees, and other accumulated fuel. Fire rarely got hot enough to kill larger trees.

Over the past 100 years, the forest has suffered a sequence of unfortunate management strategies, including overgrazing and aggressive fire suppression. Today, the average tree density is more than 900 trees per acre, with some areas up to 4,000 trees per acre. Dense trees crowd out ground vegetation and prevent the accumulation and storage of snowfall. Snow that cannot reach the ground through the tree canopy evaporates into the atmosphere. Consequently, Santa Fe's annual runoff yield from the watershed has declined 20% since 1913 (Cassidy, Fire and Vegetation Relationships on the Santa Fe National Forest, this volume).

Today the watershed is full of small trees, which are overcrowded, undernourished, and prone to disease and infestation. The accumulated, unburned fuel is very thick. The result is a significant threat of a catastrophic fire (Cassidy, The Potential for Crown Fires in the Santa Fe Watershed, this volume). The only way to reduce the fire risk and restore the watershed is to dramatically thin trees, remove the logs where feasible, and restore fire in a controlled manner as part of the ecosystem.

For 3 years, the city of Santa Fe and the U.S. Forest Service have been working together with the Santa Fe Watershed Association, Sierra Club, Audubon Society, Nature Conservancy, Forest Trust, and other groups seeking agreement on a watershed treatment plan. We have heard from a diverse group of experts, led tours into the watershed, and listened to public concerns. We have debated the right number of trees to leave in place and the optimum scale of tree diversity.

The main challenge currently facing the restoration project is removal of downed and thinned wood from the watershed. Several options exist, but none are without problems or controversy. The primary problem is access to the watershed, which is served by one road that offers limited access to steep and rugged slopes. Without new roads, access is limited to an area about 200 ft from the road, or about 600 acres. Timber removal would require rubber tire skidders during winter months when the ground is frozen. Cut trees could be piled and burned in areas farther from the road, but this carries the risk of damaging the ground and soil upon which the fire burns, and smoke would likely descend into Santa Fe. Another option of popular interest is to open the watershed to firewood gatherers or volunteers. But would they be willing to carry firewood over long distances and rugged slopes to their trucks, and would they exercise care with the fragile environment and our water supply reservoirs?

Other options considered include removal of wood by helicopter or a commercial logging operation. Helicopter removal produces the lowest impact, but would be extremely expensive. Contracting with a commercial operation is controversial and potentially impractical in that most timber in the watershed does not have a value sufficient to interest a large company with adequate resources. The trees could be used for latillas and vigas, but buyers may not be willing to move the logs a ½ mi over rough terrain for removal. Damage to the soil and forest floor from removal equipment or additional roads is a real concern associated with any of the available options.

The city of Santa Fe and the U.S. Forest Service have wrestled with these issues for over 3 years. In January 2000 the United States Forest Service issued a National Environmental Policy Act (NEPA) "scoping letter" seeking proposals for tree thinning and/or prescribed burn treatments in approximately 4,000 acres, the area most prone to a catastrophic fire and closest to the city's storage reservoirs. Because of the timetables in NEPA, implementation can not begin before fall 2001 and will take years to complete.

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Lewis has worked as a hydrologist in New Mexico for 17 years on both quantity and quality related water resource issues. She is presently the hydrologist for the Santa Fe Water Division and is coordinating the Jemez y Sangre Water Planning Council. She is interested in being a sound technical voice as the community struggles to make difficult decisions.

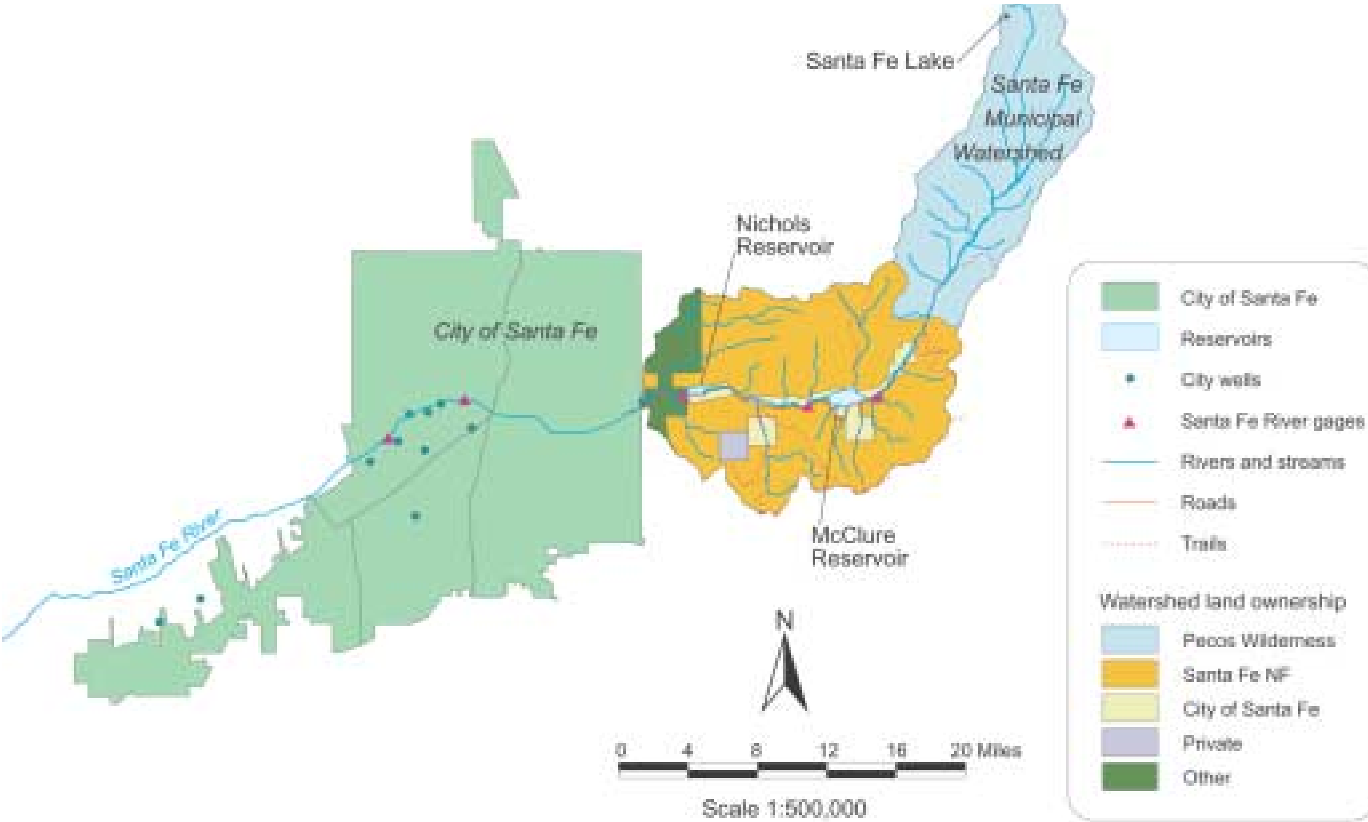

FIGURE 1—Santa Fe Municipal Watershed.

Fire and Vegetation Relationships on the Santa Fe National Forest—Potential for Impact to the Santa Fe Municipal Watershed

by *Regis H. Cassidy,* Forest Silviculturist, Santa Fe National Forest

Stand-replacement wildfires (crown fires) in fire-dependent forest communities, such as ponderosa pine, are becoming larger and occurring more frequently than ever before. Historically, ponderosa pine and dry, mixed-conifer forests typically experienced low-intensity fires (ground fires) at relatively high frequency intervals of 5–25 years (Fig. 1). These low-intensity ground fires typically burned in surface fuels such as grass or litter and seldom interacted with the tree canopy (crowns).

On the other hand, crown fires burn through the tops of trees and spread at rapid rates, with flame heights sometimes reaching 200–300 ft (Fig. 2). The intensities and speed with which crown fires burn make control impossible. Historically, crown fires were relatively rare in ponderosa pine and dry, mixed-conifer stands (Covington and Moore, 1994), but the number and size of crown fires have been increasing in recent years throughout New Mexico and the intermountain west due to accumulations of surface fuels and increases in tree densities over historic levels.

In the past 5 years, New Mexico alone has experienced the Dome fire (16,000 acres) and the Hondo fire (5,000 acres) in 1996; the Oso fire (5,600 acres) in 1998; the Scott Abel fire (20,000 acres), Cerro Grande fire (48,000 acres), and Viveash fire (25,000 acres) in 2000.

The environmental factors influencing fire behavior are weather, topography, and fuels. Fuels include both dead-and-down material and live trees. Humans have limited influence over weather and topography but have had a major influence on both fuel loading and stand structure.

One descriptor of stand structure is stocking. Stocking refers to the number of trees per unit area and is usually expressed in terms of trees per acre. Stocking in most ponderosa pine and dry, mixed-conifer stands has dramatically increased over the past century. This is a problem throughout the intermountain west, not just New Mexico.

Stand data throughout the Santa Fe National Forest taken over the past 90 years show that stocking levels have increased dramatically. Table 1 compares stocking levels in some of the most productive ponderosa pine areas on the forest in 1911 with recent stand data collected since 1985. The post-1985 stand data were collected across the forest and represent approximately 1,550 ponderosa pine stands and 650 dry, mixed-conifer stands (ponderosa pine is still a dominant species) comprising 27,000 individual inventory plots from approximately 220,000 acres of national forest land.

Generalities that can be drawn from the data in Table 1 are:

(1) The total number of conifer trees/acre has increased by a factor of ~10–20 times between 1911 and the present in both the ponderosa pine and Douglas-fir habitat types. The increase is larger in trees 0–4 inches (~25–50 times). Trees currently in the 0–4 inch size class will move up into larger size classes over time;

(2) The number of conifers in the 4–12.9 inch diameter class has also increased by a factor of 25–50 times between 1911 and the present in the ponderosa pine habitat type. The increase is even larger in the Douglas-fir habitat type;

(3) The number of conifers in the 25+ inch category appears to have declined from approximately 10 trees/acre on the better pine sites in 1911 to 1–5 trees/acre as a district-wide average today; and

(4) The number of trees/acre today in the 16–18 inch diameter range appears to be similar to 1911 stocking levels.

The decline in large trees is in part a result of past harvest activities that tended to remove large overstory trees and retain smaller understory trees. However, it must be noted that comparing 1911 data from better pine sites with recent data on average stand conditions from all pine and dry, mixed-conifer stands in the forest is not a valid comparison when evaluating tree density in a size class that had few trees even under the best of conditions.

In size classes above the 16–18 inch diameter range, the number of trees per acre apparently has declined since 1911, but below this diameter range, the number of trees has increased. The influence of fire suppression may have a lot to do with the increase in the number of trees in the zero to 16-inch diameter classes over the past 80+ years.

Stand structure has also undergone change in the past 80+ years. Historically, ponderosa pine and dry, mixed-conifer stands were more even aged, especially in groups (0.5–2 acres). Mature trees typically dominated stand structure with small clumps (0.1–0.5 acres) of various aged trees scattered throughout the stands (Fig. 3).

Due to changes in land use and management practices in the late 1800s, low-intensity ground fires were dramatically reduced due to a lack of ground fuels to carry fire. The prac-

FIGURE 1—A low-intensity ground fire.

FIGURE 2—A high-intensity crown fire.

TABLE 1—Comparison of the number of trees/acre by diameter class between a 1911 inventory and post 1985 stand exam data.

Size (inches)	1911	Jemez	Cuba	Coyote	Española	Española/Pecos
0–4	~10–20	496–817	273–481	290–512	420–718	800–972
4–6	~2	121–125	94–99	76–120	106–150	147–178
7–9	~2	60–70	58–64	45–66	54–98	78–105
10–12	~2	24–39	10–33	26–36	26–48	36–51
13–15	~4	11–18	13–19	12–17	14–29	16–22
16–18	~6	6–10	6–9	7–10	8–13	6–10
19–21	~5	3–5	3–4	3–5	4–8	3–5
22–24	~6	2–3	1–3	2–3	2–4	2–3
25+	~10	2–3	1–2	1–2	1–5	1–2
Total	50–60	725–1,090	459–714	462–771	635–1,073	1,089–1,348

The inventory in 1911 did not include trees less than 4 inches. The number shown is a very liberal estimation of the number of trees less than 4 inches that were most likely present in 1911. We know that number was very small because of frequent, low-intensity fires and the fact that the 4–6 inch size class in 1911 had very few trees present.

The first number in the range is the average trees/acre in pine habitat types and the second number in the range is the trees/acre in wetter Douglas-fir habitat types. In both habitat types, the cover type is ponderosa pine.

tices affecting the amount of ground fuel included fire suppression, selective logging that cut large trees and left younger trees, and increases in cattle and sheep numbers. Accordingly, the numbers of seedlings increased dramatically, and stands became more two-storied or multistoried (Fig. 4).

The increase in multistoried stands has been most obvious in areas where fire suppression has allowed for an increase in fir regeneration beneath ponderosa pine canopies (Fig. 5). Firs can regenerate in shade, whereas ponderosa pine is more shade intolerant. Multistoried stand structures in mixed-conifer areas create well-developed, fuel-ladder conditions that allow ground fires to quickly become crown fires under most burning conditions.

Fuel loading has increased since the decline in low-intensity ground fires. Low-intensity ground fires typically occurred in the dry months of May, June, and early July. During this period, dead-fuel moisture levels often reached 4–5% (kiln dried wood is dried to 12%). Down logs would often be completely consumed in these ground fires that occurred on a 5–25-year cycle. Accordingly, ground fuels never accumulated to the levels that currently exist.

Current fuel loading in the Santa Fe watershed and elsewhere on the forest can reach 40–60 tons/acre or more. Fuel loading values in ponderosa pine before fire exclusion were typically 5 tons/acre or less. These high fuel loadings are the result of overstocked stands beginning to break up through natural mortality (tree-to-tree competition), increases in insect activity resulting in tree mortality, and increased mortality in fir understories during periods of drought.

FIGURE 3—An open mature stand of ponderosa pine in the Jemez Mountains canopy.

Existing Conditions within the Santa Fe Municipal Watershed

Figures 6, 7, 8, and 9 depict existing conditions within the Santa Fe Municipal Watershed. These conditions are the result of fire exclusion over the past 70–80 years.

Most ponderosa pine stands on pine habitat types are two storied consisting of 10–20 mature trees in the overstory and 600–1,000 trees/acre in the understory. Fuel loading generally exceeds 20–30 tons/acre.

Ponderosa pine stands on fir habitat types most often are multistoried and consist of a pine overstory, a dense mid-story of pine, and an extremely dense understory of mostly fir. Total stem count can easily approach several thousand trees per acre. Fuel ladders are usually very well developed. Fuel loading often exceeds 40 tons/acre.

Conditions are such that a stand-replacement fire is highly likely rather than the low-intensity ground fires more typical in ponderosa pine and dry, mixed-conifer areas.

FIGURE 4—A two-storied ponderosa pine stand.

FIGURE 5—A multistory stand with fir regeneration in the lower canopy.

Desired Future Conditions in the Santa Fe Municipal Watershed

Several management alternatives are under consideration to improve future conditions in the Santa Fe Municipal Watershed. Proposed treatments include thinning from below followed with broadcast burning and/or pile burning of the created slash and broadcast burning without thinning pre-treatment (Fig. 10).

Thinning is aimed at removing the majority of small, under-story trees. Slash and thinned materials are either piled for later burning when an adequate snow cover exists that will reduce the chance of an escape fire, or slash is lopped to several feet and then burned under wet weather conditions. These treatments open the tree canopy by reducing stand density (number of tree per acre) and crown bulk density (spacing between tree crowns). The treatments also reduce ladder fuels

FIGURE 6—Dead-and-down fuel loading with well-developed ladder fuels in the background.

FIGURE 7—A two-storied ponderosa pine stand common within the Santa Fe Municipal Watershed.

FIGURE 8—A multistoried, dry, mixed-conifer stand with a pine overstory/mid-story and a fir understory.

FIGURE 9—Pockets of insect-killed trees in the watershed continue to add to the overall dead fuel loading.

FIGURE 10—A test plot in Santa Fe watershed showing thinning from below followed by slash piling of the smaller material for later burning.

FIGURE 11—A treated area in the Jemez Mountains—ladder fuels, dead-and-down fuel loading, and crown bulk density have been reduced below critical threshold levels by a combination of thinning and burning.

by raising the height-to-crown base, and allow establishment of a ground vegetation cover that is more effective than tree roots at stabilizing soils (Fig. 11). Once a substantial proportion of the watershed has been thinned and burned, isolated areas too steep for thinning will be broadcast burned without thinning pre-treatment. These treatments will dramatically reduce the probability of a stand-replacement crown fire occurring within the watershed.

Concluding Remarks

A combination of thinning and burning is needed within ponderosa pine and mixed conifer associations to bring these forest communities back within their "normal range of variability." Maintenance burning on regular intervals will be necessary following initial thinning and burning to sustain desired conditions. Failure to maintain treated areas with fire will have us back in similar undesirable conditions within a few short decades.

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View downstream of McClure Reservoir on the Santa Fe River during the dry summer of 2000. The reservoir level is low enough to reveal the sediment delta (dark-colored flat area in lower half of photo) that the river built up during wetter years. Over time, the accumulation of such sediment decreases the storage capacity of the reservoir. Note that the Santa Fe River is reduced to a trickle (lower right), and it has eroded a channel into the sediment delta. Photograph by Paul Bauer, August 2000.

The Potential for Crown Fire in the Santa Fe Watershed

by *Regis H. Cassidy*, Forest Silviculturist, Santa Fe National Forest

There are two classes of crown fire, wind driven and plume dominated. A wind-driven crown fire is one in which the power of the fire is dominated by the power of the wind. Three New Mexico crown fires that occurred within the past three decades that were primarily wind driven are the La Mesa fire in 1977, the Hondo fire in 1996, and the Cerro Grande fire in 2000 (Fig. 1).

Wind-driven crown fires generally exhibit an elliptical shape with the rate and direction of spread directly related to wind speed and direction. The convection column produced by the fire's heat is bent over by the wind. Heat from this column preheats fuel ahead of the fire making this fuel more readily available to burn. Burning embers are thrown for long distances in front of the main fire igniting more fires and contributing to increased rates of spread.

A wind-driven fire can be safely attacked from the rear and along the flanks, even if it is too dangerous at the head. Rates of spread, direction, intensity, and size of wind-driven fires can be predicted by models.

A plume-dominated crown fire occurs when the power of the fire overcomes the power of the wind. Plume-dominated fires are associated with relatively low-wind speeds and the development of high convection columns. The term fire storm has been used to describe plume-dominated fires. The Dome fire in 1996 and the Viveash fire in 2000 exhibited plume dominance (Fig. 2).

The development of plume dominance can be compared to the development of a thunderhead. A plume-dominated fire develops its own weather. As the fire intensity builds, the air above is heated and rises rapidly creating low pressure into which surrounding air flows. This inflow adds more oxygen to the fire, increasing intensity, which increases heat. The fire feeds itself and spreads in all directions including downslope. Burning embers are not thrown for great distances (generally ¼ mi or less) but are profuse and are thrown in all directions. The convection column is well developed and typically resembles a cumulonimbus or thunderhead. Whirlwinds (fire tornadoes) are typical around the perimeter.

Plume-dominated fires generally start out as wind-driven fires. Fires can alternate between wind driven and plume dominated. Direction and rates of spread of plume-dominated fires cannot be predicted. Oftentimes, these fires increase dramatically in rate of spread and intensity with little warning. They are extremely dangerous from a suppression standpoint, and pose a serious safety threat to fire-fighting personnel.

There are three stages of crown fire:

(1) The passive-crown fire stage, called torching, is small in scale, consuming single or small groups of trees. This stage of a crown fire reinforces the spread of the fire, but the main fire spread is still dependent upon surface fire behavior;

(2) The active-crown fire stage is associated with pulsing spread. The surface fire ignites crowns, and the fire spreads in the crowns faster than on the surface. After a distance the crown fire weakens, due to a lack of reinforcing surface fire heat. When the surface fire catches up to where the crown fire died, the surface fire intensity again initiates a crown fire pulse; and

(3) The independent crown fire stage occurs when conditions are such that fire will run through the crowns without support from an intense surface fire. The crown fire may race far ahead of surface fire spread.

Crown fires may transition rapidly from passive to active to independent, or remain in the passive or active stages without ever reaching the independent stage.

Favorable conditions for a wind-driven crown fire include steep slopes, strong winds, continuous forest of conifer trees, low humidity, unstable atmosphere, heavy surface fuel accumulations, ladder fuels, and low live-fuel moistures

Steep Slopes

Steepness of slope has a direct relationship with fire spread and intensity. Fire burns faster uphill than on level ground or downhill. Slopes average 40–70% in the Santa Fe watershed. A fire starting anywhere within the Santa Fe watershed would have a high probability of becoming a crown fire as a result of the steep topography.

Strong Winds

During fire season the winds are predominately out of the southwest. Wind speed increases as wind is funneled through canyons. High-wind speeds fan the flames and make fires burn hotter and spread faster. On-site weather observations show that it is not uncommon to have 10–15 mph winds at eye level in the spring and early summer. The Santa Fe watershed is oriented NE–SW and funnels the prevailing winds.

Continuous Forest Canopy

Crowns in close proximity are more susceptible to spreading crown fires than where widely spaced. Twenty feet or less

FIGURE 1—The wind-driven Cerro Grande fire, 2000.

FIGURE 2—The plume-dominated Viveash fire, 2000.

between crowns seems to be a good indicator of crowning potential. The crowns are then close enough together to allow fire to jump from tree to tree. The fuel mass of the crowns, a measure of how much fuel is in the crowns, is called crown bulk density. Greater numbers and sizes of trees per unit area mean more crown fuel in the form of needles and branches. Research has determined that a threshold value for crown bulk density of 0.125 kg/m^3 is needed to sustain crown fire spread. Densities below .02–0.05 kg/m^3 have been shown to result in no crowning (Agee, 1996) and will not permit sustained spread of crown fires.

Currently, crown bulk densities in many pine stands in the Santa Fe watershed are approximately 0.3–0.4 kg/m^3, significantly greater than the threshold value needed to sustain a crown fire.

Fire Weather

Fire season in New Mexico is characterized by low humidity, strong winds, and unstable atmosphere, which are also characteristics of worst fire conditions. An analysis done for the Santa Fe watershed shows that there is a 37% chance of having a weather day within the fire season (between April 1st and July 20th) that would exhibit worst fire conditions. The probability of having an ignition on one of those days is 20% for any given year. If an ignition was to occur on a worst fire condition day, the fire would be difficult to control and would produce undesirable fire effects, such as a wind-driven or plume-dominated crown fire.

Heavy Fuel Accumulations

In the Santa Fe watershed, heavy surface-fuel accumulations, or fuel loadings, range from 14 tons/acre in the low elevations to 55 tons/acre or more in the high elevations. Fuel loadings of around 5–7 tons/acre were more common in the ponderosa pine type. The heavy fuel loadings present in the watershed make the probability of crown fire more likely. However, what kind of fuel, the arrangement of the fuel, and other characteristics are as important as fuel quantity in determining how hot and fast a fire burns.

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There are 13 standard fuel models formulated to define the many fuel characteristics that affect how fuels influence fire behavior. These are called the Fire Behavior Prediction System models and they are used in conjunction with the computer model BEHAVE. Together these models predict the height of the flames generated and the rate of spread of a fire under chosen environmental inputs.

Four fuel models, known as timber litter models, are relevant to the Santa Fe watershed and simulate fire behavior under the various fuel conditions observed in the watershed. Model results indicate that the potentially hottest and fastest fires may occur in the lower elevations of the west and south slopes of the Santa Fe watershed where long needles from ponderosa pine provide the principal fuel. However, current inventory data and field reconnaissance show that large numbers (up to 300/acre) of standing dead trees of mixed conifer, killed by spruce budworm and drought, exist at lower and middle elevations on the north and east slopes of the watershed. As these trees fall they create especially heavy fuel accumulations. Fuel models predict that these heavy fuel accumulations will result in potentially hotter fires than expected in healthy stands of ponderosa pine.

Ladder Fuels

Ladder fuels, critical in initiating crown fire (van Wagner, 1977), are abundant throughout the Santa Fe watershed. Ladder fuels are the small trees growing beneath the larger trees in the overstory, and the low hanging limbs and foliage of larger trees. (See R. Cassidy, 2000, Fire and Vegetation Relationships on the Santa Fe National Forest, this volume.) Where there are small trees with foliage or large trees with limbs close to the ground a fire that is burning on the forest floor can quickly climb these ladders into the canopy and transition into a crown fire. Ladder fuels in the Santa Fe watershed begin at an average of 2–4 ft above the ground, a condition that will facilitate initiation of a crown fire.

Low Live-fuel Moistures

Low live-fuel moistures are also critical to crown fire initiation and spread. Crown fire potential increases when foliar moisture content drops below 100–120%, a condition that typically occurs in May or June and under drought conditions in the Southwest.

Live-fuel moistures during a wet growing season can be as high as 200%. In contrast, live-fuel moistures in the Santa Fe National Forest before the Cerro Grande fire (May 2000) were 80% in the pine and mixed conifer and had dropped to nearly 50% during the Viveash fire less than a month later. When foliar moisture content is below 120% and crown-to-base heights (ladder fuels) are 5 ft or less, it takes a flame height of only 4 ft to initiate crown fire (Agee, 1996).

Predicted Crown Fire Behavior in the Santa Fe Municipal Watershed

Fire models that predict crown fire characteristics have been developed for crown fires in the northern Rockies and have been validated on fires in northern New Mexico where similar tree types exist in mountainous terrain. An analysis done by the Santa Fe Forest in 1998 on the risk of crown fire initiation and spread west of Los Alamos, New Mexico, accurately predicted the size, shape, and direction of the Cerro Grande fire that occurred in May of 2000. These fire models predict that under drought spring and summer conditions, a crown fire starting just outside of the watershed could grow to nearly 11,000 acres in the first 5 hr burning period. A Wildland Fire Situation Analysis that has been completed for the watershed indicates that a fire starting within the watershed could easily grow to a fire 50,000–100,000 acres before containment at an estimated suppression cost of between $37,000,000–43,000,000.

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Analysis of Management Alternatives for the Santa Fe Municipal Watershed

by *James T. McCord* and *John Winchester*, Hydrosphere Resource Consultants

What effect would a catastrophic, stand-replacement fire have on the health of the Santa Fe Municipal Watershed? Which management alternative will best protect the watershed and its sustainable water supply? The search for answers to these questions has been the focus of hydrology and soils studies in the Santa Fe watershed. These studies (Hydrosphere, 2000) were undertaken as part of an Environmental Impact Statement (EIS) that assesses management alternatives (or "proposed actions") for the watershed, the objective of which is to reduce the risk of a catastrophic fire. The alternatives range from a "no-action" alternative to an aggressive alternative of mechanical thinning with prescribed low intensity burning. Because of the high probability of a catastrophic fire in the near future[1] the consequences of a catastrophic, stand-replacement fire were considered as part of the "no-action" alternative.

For each management alternative, we predict erosion and sediment yield, in acre-ft (including potential for movement of sediments into water supply reservoirs), peak flood flows on the Santa Fe River, in cubic feet per second or cfs (including peak discharges in the river near the downtown plaza), and watershed water yield, in acre-ft. Predictions are based on results of field experiments; observations in watersheds comparable to the upper Santa Fe River watershed on the basis of slope, canopy density, and other relevant parameters (analogue watershed data); and mathematical models. We selected analogue watersheds that experienced fires of various severities before and/or during observational monitoring. By combining analogue watershed results with predictive mathematical models we can better constrain model uncertainties, and create a defensible basis for predicting the hydrologic effects of various management alternatives. A description of the management alternatives and watershed response in terms of sediment yield, flood flows, and water yield are summarized in Table 1 and the following paragraphs.

Erosion and Sediment Yield

Our analysis of erosion and sediment yield focuses on estimating the volume of sediments that would be eroded from the watershed and deposited in the riparian (streamside) zone and the city's water supply reservoirs under different management alternatives. Significant sedimentation in the riparian zone could adversely affect the fish and wildlife, and large volumes of sediment moving into the reservoirs would be trouble for the city's water supply.

We employed a standard engineering erosion model (the Revised Uniform Soil Loss Equation, or RUSLE) and analogue watershed data to predict watershed erosion. The RUSLE analysis was greatly facilitated by application of the Terrestrial Ecosystem Survey (USDA Forest Service, 1993) results for the Santa Fe National Forest. The Terrestrial Ecosystem Survey provides a detailed description of the physical and biotic surface conditions for the entire national forest. The forest was categorized into 209 Terrestrial Ecosystem Survey units that describe areas with similar biological and physical characteristics. Our RUSLE analysis used the Terrestrial Ecosystem Survey results to assess erosion under current conditions and under the proposed watershed treatments. For erosion following fire, we also accounted for the likelihood of magnified erosion due to soil hydrophobicity (or decreased wettability) that typically occurs following a catastrophic fire. To account for hydrophobicity, we incorporated the hydrophobicity multiplier developed by the Forest Service for its analysis of erosion following the Viveash fire (USDA Forest Service, 2000). For the analogue watershed analyses, we identified seven watersheds in the western United States with similar vegetation and physical characteristics that had experienced a high severity fire followed by monitoring and quantitative analysis of erosion. In these cases, post-fire erosion rates increased by 25–448 times over pre-fire erosion, with an average 216.5-fold increase. This average post-fire to pre-fire ratio was multiplied by the RUSLE "current conditions" erosion rate to obtain an analogue watershed prediction of sediment yield for the Santa Fe watershed following a catastrophic fire.

Figure 1 presents a summary of our erosion analysis, showing sediment yield in the Santa Fe River riparian area and reservoirs under current conditions, for the proposed treatment alternatives, and under a no-action alternative (following a catastrophic fire). One can see that a catastrophic fire associated with the no-action alternative leads to by far the worst effects for erosion and sediment yield.

Runoff and Peak Flow

Following a catastrophic fire, peak flood flows from the Santa Fe watershed are expected to increase dramatically for several years, until vegetation re-establishes itself. This would increase the risk of flooding in the Santa Fe River floodplain where the river passes through town, including in the downtown plaza district.

Our analysis of runoff and peak flow utilized an engineering method known as the SCS curve number approach, and analogue watershed data. In addition, gaging records from the watershed and published rainfall-runoff analyses (FEMA, 1993; Woodward Clyde, 1994) for the watershed were used to assess current conditions and compare with our predictions. The runoff curve number method is widely applied to southwestern U.S. watersheds less than 10 mi^2 in area to estimate peak discharges (SCS, 1973; Dunne and Leopold, 1978; Viessman et al., 1989). We adapted the curve number approach and results from the Burned Area Emergency Response

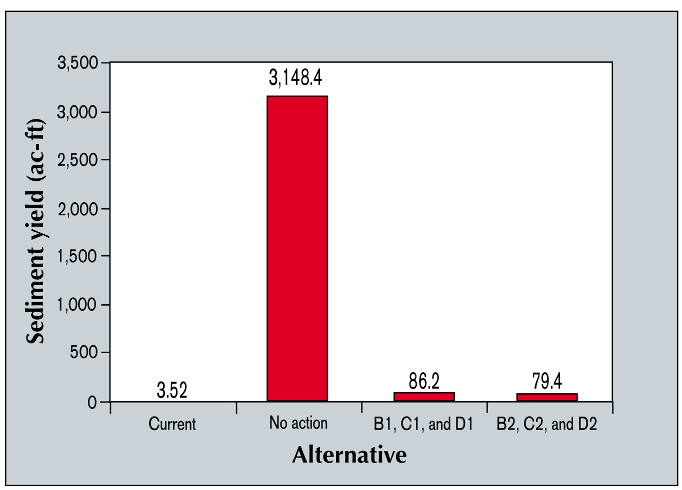

FIGURE 1—Erosion analysis showing sediment yield in the Santa Fe River area and reservoirs under current conditions.

[1]Based on existing fuel loading, climatic conditions, and ignition sources, it has been extimated there is a 20% chance of a stand replacement fire in the watershed in any given year (Armstrong, 2000); which suggests a 90% probability of a catastrophic fire within the next 10 years.

Day Two

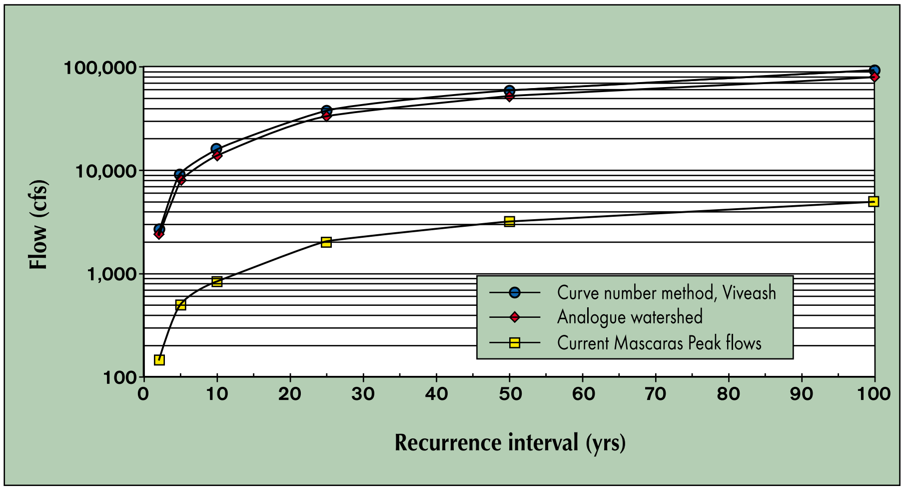

FIGURE 2—Peak flow (flood) frequency curves under current conditions.

(BAER) team analysis of the Viveash fire (USDA Forest Service, 2000) to develop a post-fire to pre-fire peak flow ratio.

We also used analogue watershed observations to predict a possible range of post-fire peak flows. The post-fire peak flows for analogue watersheds range from 2.9 to 386 times pre-fire peak flows, depending on fire severity. DeBano et al. (1998) show that whereas high severity fires generally lead to large increases in peak flows that can continue for up to a decade following the fire, low to moderate severity fires generally lead to only small increases in peak flow for the first few years following the fire. Utilizing both the curve number method and analogue watershed peak flow ratios, we predicted post-fire peak flows in the Santa Fe watershed by multiplying the watershed's estimated unregulated peak flows by the peak flow ratio.

Given that the gravest threat from peak flows is their impact in the downtown area of Santa Fe, we projected Santa Fe River peak flows at its confluence with Arroyo Mascaras. Arroyo Mascaras was selected as the location for predicting peak flows because it is immediately downstream of the downtown commercial district, and the FEMA flood insurance study for the city of Santa Fe (FEMA, 1993) projects Santa Fe River flows at this location.

Figure 2 presents peak flow (or flood) frequency curves under current conditions for various return intervals, together with the predicted peak flows following a catastrophic fire. In a flood frequency curve, the recurrence interval refers to the average amount of time between floods of that magnitude. For instance, referring to Figure 2 we can see that under current conditions (bottom curve) a peak flow of approximately 1,000 cubic ft per second (cfs) occurs on average once every 10 years; this is referred to as the "10-year storm." It is interesting to note that the 5-year storm flow following a catastrophic fire is nearly double the 100-year storm flow under current conditions. Peak flows following prescriptive treatments in the watershed will not significantly differ from current conditions.

Water Yield

Water yield refers to the annual total runoff from a watershed. Water yield from the Santa Fe watershed has declined approximately 20% over the past 70 years (Hydrosphere, 2000), which is adversely affecting Santa Fe's water supply. In other words, there is approximately 20% less runoff each year that flows into the Santa Fe River, fills the reservoirs, and recharges the aquifers. This is likely a result of dramatically increased tree density due to management practices over the past 70 years.

Based on observed impacts in other watersheds following catastrophic stand replacement fires (Helvey, 1980; Campbell et al., 1977; DeBano et al., 1998), we expect that water yield will increase significantly (as much as double) in the first year following a fire. The increased annual water yield is expected to continue for several years following the fire, returning to pre-fire yields only after a decade or more. Increased yields occur as a result of the combined effects of loss of vegetative cover (and consequent reductions in evapotranspiration, interception, and sublimation of intercepted snowfall) and decreased litter accumulations. In the first year following the fire, water repellent (hydrophobic) soils present a compounding factor.

Considering these observations, we expect that annual water yields from the watershed would increase up to 100% following a catastrophic fire (Table 1), and would be expected to return to pre-fire levels over a 10 to 20 year period as vegetation re-establishes itself. Under the proposed treatments, we would expect a much milder yield increase, on the order of 5 to 10%.

Summary and Conclusions

A no-action management alternative, which includes a catastrophic stand-replacement fire, would have devastating impacts on the Santa Fe watershed and the downstream area. The most severe effects will occur to the sediment yield and Santa Fe River peak flow, which are both expected to increase by orders of magnitude. Annual water yield is expected to undergo only minor increases, on the order of 5–50%. Predictions of accumulated sediment yields in the first 8 years following a fire range between 500 and 3,100 acre-ft. Considering that the total surface-water storage capacity in the reservoirs in the watershed is roughly 4,000 acre-ft, it appears

TABLE 1—Summary of soil and water effects for each management alternative.

		Key soil and water issues		
Alternative	Description (acreage treated)	Sediment yield (acre-ft) (Maximum over 8 yrs)	10-yr peak flow at Arroyo Mascaras (cfs)	Water yield (% change after treatment)
A	No action, following catastrophic wildfire	3,148	>15,000	>+100%
B1	Limited manual thinning with broadcast burning (2,900 acres)	86	<1,000	<+20%
B2	Limited manual thinning with no broadcast burning (7,270 acres)	79	<1,000	<+20%
C1	Manual thinning with broadcast burning (4,900 acres)	86	<1,000	<+20%
C2	Manual thinning with no broadcast burning (7,270 acres)	79	<1,000	<+20%
D1	Machine thinning with broadcast burning (4,900 acres)	86	<1,000	<+20%
D2	Machine thinning with no broadcast burning (7,270 acres)	79	<1,000	<+20%

that a catastrophic fire would seriously threaten the city of Santa Fe's surface-water supplies. Peak flow increases in the first years following a catastrophic fire are expected to greatly increase the likelihood of flooding in the city's downtown area. For instance, Figure 2 shows that 5-year peak flows after a severe fire exceed the 100-year peak flow under current conditions.

The proposed treatment alternatives, on the other hand, will impart negligibly adverse to obviously favorable effects on the key soil and water issues, including very minor increases in sediment yield and peak flow, and slight increases in water yield. From a hydrologic perspective, the primary differences between the proposed treatments relate to differences in acreages treated. Whether it be mechanical thinning or prescribed low intensity burning, the hydrologic effects are quite minor with respect to all of the key soil and water issues (Table 1). In general, the treatments are designed to reduce the risk of fire, and the alternatives which treat the greatest acreage lead to the greatest risk reduction.

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John and his wife Janet live in the foothills west of Boulder, Colorado, with their three children. The Winchesters are active members of the Sugar Loaf Volunteer Fire Department, and are foster parents for Boulder County Social Services Departments.

What Decision Makers Should Know About Arroyos in New Mexico

by *David W. Love*, New Mexico Bureau of Mines and Mineral Resources; and
Allen Gellis, U.S. Geological Survey

Arroyo is a Spanish term for stream, but in the Southwest the term is commonly applied to streambeds that are dry most of the time. Some geographers have tried to restrict arroyo to streambed shapes that are eroded narrow and deep as opposed to washes that are wide and shallow, but some streambeds alternate between the two shapes either from year to year or along their courses downstream. Streambeds with eroded vertical banks evoke negative reactions from most viewers, and arroyos are commonly seen as a symptom that something is wrong and that someone or something is to blame. The natural function of arroyos is complicated and depends on several independent and linked variables of landscape, climate, vegetation, and land use.

The primary reason streambeds exist is that water passes from higher in the drainage basin to the mouth of the drainage basin. Water moving downhill has energy to transport loose soil particles (sediment) and does work to do so. The size and shape of the streambed is a direct reflection of the amount of water (both quantity and duration of flow), the energy gradient, and the characteristics of the sediment along the stream channel as well as resistant features along the path, such as bedrock and vegetation. Arroyos tend to respond quickly to precipitation and have flashy flow—streamflow that rises to floodstage and wanes quickly.

Each one of these variables (such as runoff-water from rainfall) is complicated in its own natural behavior, and alterations in any one of the variables affect others in more than one way. For example, the amount of water a drainage basin processes during the year is related to the amount of precipitation and its fate across the landscape. Precipitation in New Mexico is extremely variable. It is measured in amount and duration (e.g. rainfall intensity). Intense thunderstorm rainfall may do more landscape work than melting snow, but may not aid the growth of vegetation. Vegetation depends on the amount, frequency, and sequence of precipitation as well as other landscape variables (bedrock, soils, and orientation of slopes). If vegetation is dense enough to slow overland flow downslope to the streambed, much flow may be trapped by the vegetation and seep into the ground, nurturing the vegetation. Soil is held in place. If vegetation is less dense, some flow reaches the channel and affects flow downstream. With less vegetation, runoff may increase and flow may increase downstream. If climate shifts to less precipitation, vegetation may die, affecting overland flow and flow within the channel. If soil is eroded from the hillslopes and overwhelms the ability of the channel to transport it, the channel becomes choked with sediment, and the slope in the channel may decrease, affecting the energy to transport sediment. Unsaturated loose sediment may absorb more water, reducing flow until a threshold is met, after which both water and sediment continue to move down gradient. Excess runoff leads to erosion and transport of sediment within the channels. That sediment may be redeposited downstream (such as in man-made reservoirs).

As a result of considering all these factors, one may construct a generalized pathway diagram (Fig 1) to show how adjusting different variables may result in forming the same type of arroyo channel. For example, if land use changes rainfall runoff and vegetation, increased water flow may increase sediment transport, causing erosion of the channel base and resulting in a deep, narrow channel or arroyo. A similar diagram could be used to show how arroyos could be filled in.

One drainage basin near Santa Fe, the Frijoles Basin, has been the subject of scientific scrutiny off and on for nearly 50 years to see how arroyos behave through time. The initial study applied simple monitoring techniques that have withstood the test of time. The locations of the monitors were marked with steel rebar and big nails with washers driven into the ground. Where the soil eroded, the washers followed the ground surface down. Where the ground surface aggraded, the nails and washers were buried. In the channels, 4-ft-deep (1.22 m) post-like holes were dug and loose chains were lowered into the holes to the level of the sediment surface. When streams scoured, the chains fell over to the level of scour and oriented their links downstream. Where streams aggraded, the chains were buried. The size and shape of the channels were measured in the 1950s and 1960s and have been remeasured since then more than once. In general the channels have eroded a little bit [entrenched approximately 1.2 inches (about 3 cm) on average] and gotten about 4% bigger in width and depth. The biggest changes were noted where new roads had disrupted the channels—causing deposition upstream from culverts and erosion as much as 5 ft (1.53 m) below culverts.

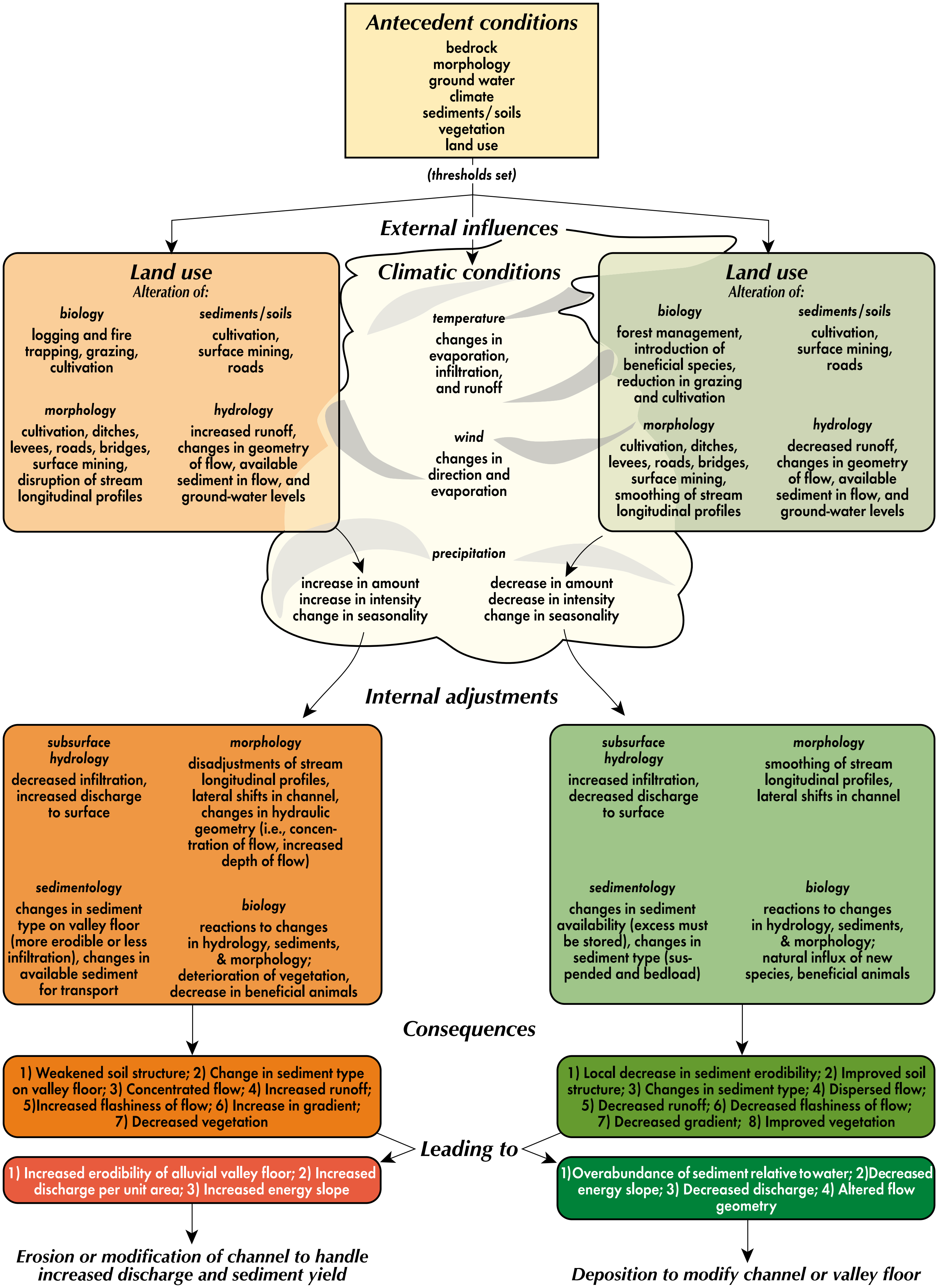
The banks of arroyos commonly preserve evidence to show that drainages have a history of aggrading and eroding. In the Santa Fe area, it is common to find artifacts of various ages within the sediments cut by arroyos. Some low stream banks along arroyos such as Tesuque Arroyo have developed during the 20th century and have metal cans and glass in them. Older banks contain prehistoric potsherds and fire hearths used by early Native Americans. Some stream banks show that prehistoric arroyos were eroded and later filled in before the extensive human land use changes associated with arroyo erosion of the late 19th and early 20th centuries. Some drainages have multiple episodes of arroyo cutting and filling; others have none. Clearly some drainages are more responsive to changes in climate, vegetation, and land use than others.

What Can Property Owners Do?

Management of the natural or human-influenced landscape depends on the many variables involved in shaping that landscape. The location of the land within the drainage basin, the slope of the land, the microclimate and vegetation, soils, and bedrock all play a role in determining what the "best" management practice may be. The projected future use of the land also may determine what the best current management should be. In this semiarid climate with intense summer rains, property owners may want to keep as much precipitation and vegetation on the land as possible and to slow the erosion and movement of sediments off the land. Disturbances such as roads and overgrazing lead to more runoff and more erosion. Commonly it is prudent not to alter the gradient of slopes and stream channels with soil removal or berms. Check dams may temporarily trap sediment and decrease erosion, but after the small dams fill, the problem may be worsened by entrenchment of the dams and sediments behind the dams.

What Can Geologists, Engineers, and Soil Scientists Do?

Hydrologic engineers are developing increasingly sophisticated modeling techniques to predict runoff, stream flow, and sediment transport within drainage basins. The modelers require detailed quantitative knowledge of the landscape variables of topography, rocks, soils, vegetation, and climatic variability outlined above. Geologists, soil scientists, hydrologists, and biologists all can contribute by documenting the details of the landscape variables and gathering them into geographic information systems (GIS). Geologists and soil scientists may


Antecedent conditions
bedrock
morphology
ground water
climate
sediments/soils
vegetation
land use
(thresholds set)
External influences
Land use
Alteration of:
biology
logging and fire trapping, grazing, cultivation
sediments/soils
cultivation, surface mining, roads
morphology
cultivation, ditches, levees, roads, bridges, surface mining, disruption of stream longitudinal profiles
hydrology
increased runoff, changes in geometry of flow, available sediment in flow, and ground-water levels
Climatic conditions
temperature
changes in evaporation, infiltration, and runoff
wind
changes in direction and evaporation
precipitation
increase in amount
increase in intensity
change in seasonality
decrease in amount
decrease in intensity
change in seasonality
Land use
Alteration of:
biology
forest management, introduction of beneficial species, reduction in grazing and cultivation
sediments/soils
cultivation, surface mining, roads
morphology
cultivation, ditches, levees, roads, bridges, surface mining, smoothing of stream longitudinal profiles
hydrology
decreased runoff, changes in geometry of flow, available sediment in flow, and ground-water levels
Internal adjustments
subsurface hydrology
decreased infiltration, increased discharge to surface
morphology
disadjustments of stream longitudinal profiles, lateral shifts in channel, changes in hydraulic geometry (i.e., concentration of flow, increased depth of flow)
sedimentology
changes in sediment type on valley floor (more erodible or less infiltration), changes in available sediment for transport
biology
reactions to changes in hydrology, sediments, & morphology; deterioration of vegetation, decrease in beneficial animals
subsurface hydrology
increased infiltration, decreased discharge to surface
morphology
smoothing of stream longitudinal profiles, lateral shifts in channel
sedimentology
changes in sediment availability (excess must be stored), changes in sediment type (suspended and bedload)
biology
reactions to changes in hydrology, sediments, & morphology; natural influx of new species, beneficial animals
Consequences
1) Weakened soil structure; 2) Change in sediment type on valley floor; 3) Concentrated flow; 4) Increased runoff; 5)Increased flashiness of flow; 6) Increase in gradient; 7) Decreased vegetation
1) Local decrease in sediment erodibility; 2) Improved soil structure; 3) Changes in sediment type; 4) Dispersed flow; 5) Decreased runoff; 6) Decreased flashiness of flow; 7) Decreased gradient; 8) Improved vegetation
Leading to
1) Increased erodibility of alluvial valley floor; 2) Increased discharge per unit area; 3) Increased energy slope
1)Overabundance of sediment relative to water; 2)Decreased energy slope; 3) Decreased discharge; 4) Altered flow geometry
Erosion or modification of channel to handle increased discharge and sediment yield
Deposition to modify channel or valley floor

Day Two

FIGURE 1—Flow-chart summarizing possible antecedent conditions, climate and land-use factors, and adjustments by streams leading to increased erosion or deposition along stream valley.

also help by testing the results of the models by monitoring landscape changes in relation to weather-related events, longer-term climate fluctuations, vegetation changes, land-use changes, etc. Finally, geologists and paleobiologists can determine the longer-term record of changes by studying the sediments stored in arroyo banks and other deposits. New, more sophisticated techniques may be developed to extract the flood, vegetative, and climatic record from these deposits. More publicity about the complicated behavior of stream channels and banks may alter the present perception that all arroyos are caused by overgrazing or mining of streambeds. Greater public awareness of stream behavior may make both property sellers and buyers more apt to consider the consequences of property use in potentially erosive or flood-prone areas.

What Can Decision Makers Do?

Be aware of the complexity of drainage basins and their response to change. One can never do just one thing—there are always consequences both upstream and downstream. Once the work of a drainage basin is disrupted, humans will have to take on a workload to make up for what the stream used to do naturally. The dilemma for decision makers is how to balance the protection of would-be buyers and users of property at risk from arroyo erosion versus the undue burden of expensive engineering measures to curb runoff and erosion, regardless of the property's location. Impacts of erosion or sedimentation upstream or downstream from particular property are difficult to assess, but may lead to legal complications. Some municipalities and counties have zoning restrictions that may aid in limiting inappropriate uses of some property. All construction of public facilities should have proper evaluation before bidding takes place and should have supervision of the site during the building phase.

Where Can I Get More Information?

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David Love has been with New Mexico Bureau of Mines and Mineral Resources as an environmental geologist since 1980. He is working on impacts of surface and subsurface mining; shrinking, swelling, collapsing, and corrosive soils; behavior of arroyos; geology of archaeological sites; movement of contaminants in the shallow subsurface; faulting, earthquakes, and earthquake education; geology outreach for teachers and students. He has taught geology for the Southwest Institute and as a sabbatical replacement at Washington State University (1976–1978), and he has worked as a seasonal interpreter for the National Park Service.

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Gellis' research has been examining reservoir sedimentation in Puerto Rico, sources of sediment, and causes for sediment concentration changes during storm events. He has also studied 20th century arroyo changes in the southwestern United States and sediment budgets in semi-arid watersheds.

Decision makers should be asking for quantitative information on the effects of grazing on channel systems and erosion. Studies on sediment sources and the effectiveness of their control need to be accomplished.

The TMDL Program in New Mexico— An Example from the Santa Fe River

by *James H. Davis*, Bureau Chief, Surface Water Quality Bureau, New Mexico Environment Department

The Total Maximum Daily Load (TMDL) Program is not new, but has been a part of the Clean Water Act since 1977. Section 303(d) of the Clean Water Act requires states to determine whether water bodies meet water quality standards and protect beneficial uses. For water bodies that do not meet a particular quality standard, states must identify the water body as impaired and determine the TMDL of the pollutant that the water body can receive and still meet water quality standards. The state then allocates that TMDL among those sources, including both point and non-point sources, discharging to the water body with the objective of reducing pollutants and improving water quality. However, because states lacked data and resources to accomplish this objective, neither the U.S. Environmental Protection Agency (U.S. EPA) nor states historically used the TMDL program to address water quality problems—that is until the U.S. EPA was barraged by citizen lawsuits.

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

$$\text{TMDL} = \sum (\text{Waste Load Allocation} + \text{Load Allocation} + \text{Margin of Safety})$$

A TMDL is not a regulatory document, it is a planning document that contains recommended actions intended to protect or restore the health of the water body.

In 1999, the New Mexico Environment Department, Surface Water Quality Bureau developed 26 TMDLs on 11 different reaches in four watersheds throughout the state. These TMDLs were determined for a variety of pollutants such as stream bottom deposits, turbidity, total phosphorous, total ammonia, fecal coliform, and temperature. After TMDLs are developed, there is a legitimate expectation that they will be implemented. The Surface Water Quality Bureau has started implementing TMDLs in several watersheds.

A Program Example: The Santa Fe River TMDL

The Santa Fe River study area is a sub-basin of the upper Rio Grande basin, located in north-central New Mexico. The study area is located on land managed by the United States Department of Agriculture Forest Service (FS) and flows in a generally southwest direction toward the city of Santa Fe. Upstream of the city of Santa Fe wastewater treatment plant, the Santa Fe River is generally a dry arroyo that flows during some snowmelt periods in the spring and after some storm events (Fig. 1). Thus, the critical point for application of many numeric water quality standards is at the wastewater treatment plant's point of discharge into the Santa Fe River.

Before January 1998, several water quality surveys were conducted along the Santa Fe River. Data collected during these surveys identified chlorine, pH, metals, stream bottom deposits (siltation), total ammonia (as a toxic), and gross alpha (radioactivity) as pollutants causing "impairment" of the river for its designated beneficial uses.

Many recent changes in the watershed, including restoration work at the La Bajada mine, upgrades at the city of Santa Fe wastewater treatment plant, and additional water-quality-data collections, have led to some parameters being removed from this list. For example, the fieldwork associated with the La Bajada mine restoration was completed in 1996. Based on monitoring since completion of restoration activities at the La Bajada mine it has been determined that the Santa Fe River currently meets the numeric water quality standards for gross alpha. In 1998, the Santa Fe wastewater treatment plant completed treatment upgrades to eliminate the use of chlorine and to significantly lower ammonia, biochemical oxygen demand, and total suspended solids discharges from the plant. Based on sampling data from 1998–1999, metals were no longer found to impair the Santa Fe River. Recent monitoring from fall 1998 through summer 1999 has also demonstrated that the Santa Fe River now meets water quality standards for total ammonia. Therefore, TMDLs were not developed for gross alpha, total ammonia, or metals. TMDLs were completed and approved for chlorine and stream bottom deposits in December 1999. Sampling efforts during 1998–2000 continued to support the 303(d) listings for dissolved oxygen and pH and the need to develop TMDLs for these parameters. The 303(d) listing for dissolved oxygen and pH is the result of algal growth in response to plant nutrients available from the stream bottom.

TMDLs have been developed to address the dissolved oxygen and pH water quality criteria adopted by the New Mexico Water Quality Control Commission (August 8, 2000). Water quality sampling of wastewater treatment plant discharge and the Santa Fe River by the Surface Water Quality Bureau (1998–2000) provided sufficient evidence to link water quality to the Santa Fe wastewater treatment plant discharge, since the wastewater treatment plant is the only source of water in this reach of the Santa Fe River. The combination of the wastewater treatment plant effluent, no upstream flow, and less than ideal downstream riparian and geomorphic conditions contribute to excessive algal growth and violations of water quality standards.

There are two potential contributors to nutrient enrichment, excessive nitrogen and excessive phosphorous. To determine which of these two nutrients is limiting, an algal growth test was performed. Laboratory analysis of ambient waters showed that the limiting nutrient to the Santa Fe River system was nitrogen. This means that the level of nitrogen in the river is driving the productivity of the algae. Therefore, nitrogen needs to be controlled to limit the excessive algal growth. The water quality model used in the development of this TMDL predicts the algal growth response to reduced levels of nitrogen. Since dissolved oxygen and pH are dependent on the algal biomass, reductions in algal biomass are expected to maintain dissolved oxygen and pH criterion.

In addition to nutrient loads, the in-stream oxygen level is impacted by the introduction of other oxygen demanding substances. This is expressed as the carbonaceous oxygen demand (5-day-$CBOD_5$ or ultimate-CBODu). These components, $CBOD_5$, CBODu, NH_3-N (ammonia), and nitrite (NO_2) plus nitrate (NO_3) must be controlled to maintain water quality standards for dissolved oxygen. The TMDL was calculated for the Santa Fe River using the point source design flow and effluent concentrations for wastewater treatment plant discharge that will maintain the current dissolved oxygen and pH standards. The TMDL is equal to the waste load allocation for

TABLE 1—TMDL results for the Santa Fe River study area.

Parameter	Waste Load Allocations (lbs/day)	Load Allocations (lbs/day)	Margin of Safety (lbs/day)	TMDL (lbs/day)
$CBOD_5$	708.9	0.00	Implicit	708.9
CBODu	1,985.0	0.00	Implicit	1,985.0
NH_3-N	141.78	0.00	Implicit	141.78
Nitrate + Nitrite	212.67	0.00	Implicit	212.67

the city of Santa Fe wastewater treatment plant because the load allocation has been set to zero (no identified non-point sources were quantified in the Santa Fe River study area), and the margin of safety is implicit in the conservative model assumptions. Results are presented in Table 1.

TMDL Implementation

Several Clean Water Act Section 319(h) projects indirectly address dissolved oxygen and pH problems in the Santa Fe River. The project which most directly addresses this TMDL is the Santa Fe River Restoration Project being conducted on city of Santa Fe land along the Santa Fe River. The purpose of this project is to enhance the riparian zone vegetation (partly to reduce temperatures), remove nutrients from the water, and decrease sediment discharge. The best management practices being implemented include temporary cattle exclusion, revegetating stream banks (e.g., planting of willows and cottonwoods), and removal of a levee to allow of high flows access to the floodplain. These practices are expected to create wetlands that will directly address pH and dissolved oxygen problems in the river by removing a portion of the nutrient load. This project will also indirectly contribute to stabilized dissolved oxygen concentrations and pH in the Santa Fe River by inhibiting algal growth through decreased solarization.

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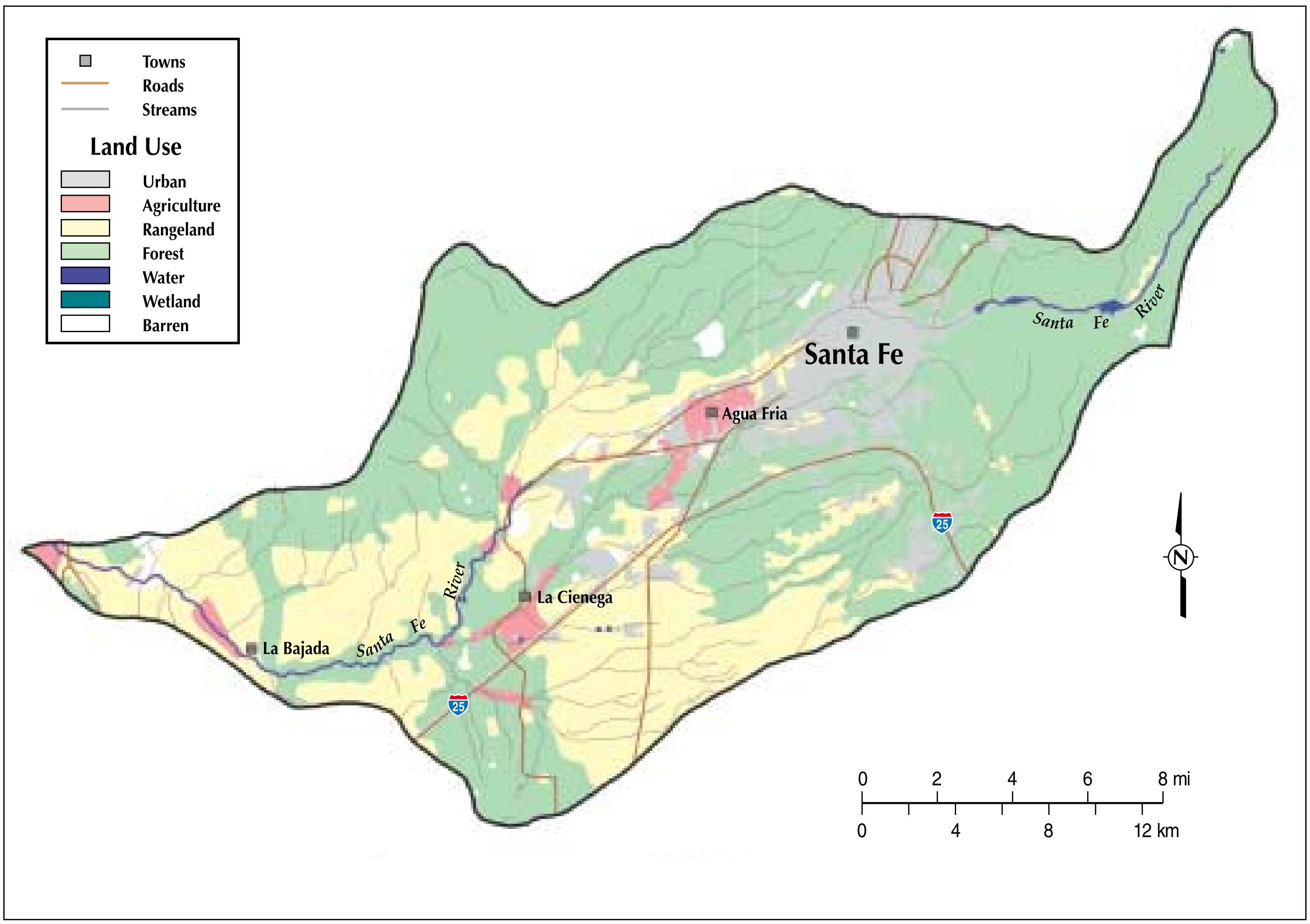

FIGURE 1—Watershed map of the Santa Fe River study area.

A Brief History of Water Planning in New Mexico

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

New Mexicans know that we face a bewildering array of water issues, but it is not always clear how to deal with them. Our water situation can be summarized simply:

(1) In most of New Mexico the renewable-water supply, provided by the rivers, varies a lot from year to year. We must deliver part to Texas and Arizona, and we already use nearly all the rest. "Varies a lot" is more serious than it sounds; there will be good and bad years, but we will also confront some profound droughts (see, for example, Ackerly, 2000);

(2) We have a lot of ground water, but it is not really a renewable supply. We can use it up in a short time, or extend its use over a long time, but not forever. New ground-water production also leads to new depletion of river flow, and all of it is already committed;

(3) There is growing pressure to preserve the quality of both surface water and ground water; and

(4) New needs continue to arise: water for endangered species, for aesthetic and other environmental purposes, for growth in New Mexico, and for growth outside the state that would depend on water we deliver.

There are several ways to deal with our water issues: we can decide, as a state or region, what actions to take; let some needs go unmet while we litigate among ourselves; or allow outside forces to decide for us. The primary water issue to resolve is this choice itself.

New Mexico is engaged in comprehensive water planning, but we have come to it by a rather indirect route. Our fundamental water law, enacted in 1907 for surface water and extended to ground water in 1931, declares that the waters "belong to the public." The right to use water, on the other hand, is a property right, established by appropriation of water before 1907 or 1931 as the case may be, or by putting water to beneficial use under a permit from the State Engineer.

Day Two

As conceived by the legislature in 1907 and 1931, appropriation and transfer of water would be governed by strict prior-appropriation doctrine: the oldest water right on a stream is fully served first, and so on down to the most junior right, which might never receive water except in the wettest years. Streamflow depletion due to ground-water pumping is treated as any other surface-water appropriation. Transfers of water, which are needed for new or higher-value uses, would be governed by the market, all beneficial uses having equal status. The State Engineer would administer the process as the referee administers a game, ensuring that the parties play by the rules, but not managing the water. Planning would not be needed.

If New Mexico had a water plan, it was simply to prevent water from crossing the state line. A statute prohibited export. In 1980, El Paso, having applied for permits to appropriate ground water in New Mexico, challenged the constitutionality of our no-export law. El Paso's commerce-clause argument prevailed. Of course, we wanted to salvage our export prohibition, and a strategy appeared in the U.S. Supreme Court's decision in *Sporhase vs. Nebraska* (458 U.S. 941, 1982), over a transfer of water from Nebraska into Colorado.

For a state to reserve water to itself it must show, among other things, that the water would be needed for the "public welfare." Thus did New Mexico develop an enthusiasm for regional water planning. Each planning region could prepare an inventory of supplies and a projection of demands, and then reconcile them, establishing the amounts of water needed for the public welfare.

Now that we're doing water planning, we find that we must have it anyway, for other reasons. Pure market control of water allocation hasn't been working well. Federal environmental law has led to water requirements not represented in the market. The transfer process is slow and cumbersome, especially where court confirmation, or adjudication, of rights has not been completed (as in most of the state, even though it was mandated in 1907). In-stream-flow and aesthetic considerations are difficult to reconcile with market-governed allocation, and demand seems to be catching up with supply.

It looks as if planning may actually evolve further, into negotiated water allocation, which will include drought-contingency plans, much attention to conservation and to conjunctive use of ground water and surface water, and creative exchanges that involve money and the forbearance of certain rights. The endless process of adjudication may be bypassed. Our water law may change significantly.

Water planning was authorized in 1987. Plans at some level have been prepared by most of the 16 planning regions and by many municipalities and counties as well, but as of late 2000 only one regional plan had been accepted by the Interstate Stream Commission. That was for the Estancia Basin—an interior basin with no river, no Indian claims, and only 1.6% of New Mexico's land area. Mary Helen Follingstad's paper in this guidebook describes the current status of planning in the regions.

The legislature has been unhappy about the cost of water planning and with the fact that plans are coming along slowly. Why are they so difficult to complete? It may just be our collective nature—Norman Gaume, our Interstate Stream Engineer, has said "you may be from New Mexico if you believe passionately that 'water is priceless,' but you aren't willing to pay any money for it."

Some other reasons: people have concentrated on data-collection, which costs some money but is easy and non-controversial, rather than the decision-making aspect of planning—the reconciling of supply with demand, and the enforcement which can be extremely difficult because it involves unpleasant choices. They commonly assumed that water would be imported into their region if shortages began while the potential source regions were assuming the same thing.

Tough decisions must be made, but as yet there is no settled institutional structure for making them. For example, if renewable water supply is already at the break-even point, as it appears to be in the middle Rio Grande basin (MRGWA, 1999), and we still expect growth, what will we give up, and how does the public decide what to give up and what to keep?

Will we choose riparian vegetation and habitat? or a concrete-lined river channel (as in El Paso) to save water? Will we emphasize municipal supply? or agriculture, to preserve the ambiance of the valley? Water rights are private property in New Mexico. How can we collectively plan the owners' use of their water? Much water-use is mandated by federal law—the Endangered Species Act in particular. Tribes and Pueblos typically have preferred not to join in the water-planning process, for fear of inadvertent adjudication of their rights, but they represent a large, largely unquantified, part of the state's water. The planning process must resolve all these issues.

The Interstate Stream Commission is preparing a new statewide water assessment, which will summarize ground- and surface-water resources and the costs and consequences associated with making them available for use. The new assessment is intended to support the regional planning process and represents an update of previous statewide water assessments.

A progress report (January 2001) touches on most of the subject matter that will be included in the final assessment, due in September, except that quantitative information is given for only the Rio Grande basin, from the Colorado line to Elephant Butte. The assessment is intended to support, and not infringe upon, regional planning by offering a statewide context, a uniform and consistent overview of water resources in all parts of the state, the results of research on management options, and descriptions of existing and suggested water-supply projects.

Managing New Mexico's water is not a matter of setting administrative rules and watching from a distance as they play out, nor of making once-and-for-all choices to allocate a fixed supply of water. We must recognize the constant, competitive interplay between actual supply, water needs, and the costs and consequences of each allocation. Planning is essential, on a regional and even local level, and it must be a continuing enterprise.

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Shomaker is particularly interested in the water-planning process in New Mexico. There is heavy competition for the resource, and we are better off to plan cooperatively, basing our planning on sound science and engineering, than to relinquish the allocation of water to litigation.

Statewide Water Planning—A Progress Report

by *Mary Helen Follingstad*, AICP, Manager, Regional Water Planning Program, New Mexico Interstate Stream Commission

Statewide water planning fits within a larger context of initiatives recently unveiled by the New Mexico State Engineer. The Office of the State Engineer (OSE) Strategic Plan includes programs to achieve "active management" of the state's surface- and ground-water resources. The first steps include investigations into the state's water resources data (hydrology, water use, hydrographic surveys, and water rights), measurement of the resources via well monitoring and surface-water gaging, management of the resources via adjudications (quantification of water rights), water planning, appropriate responses to federal issues relating to the Clean Water Act and the Endangered Species Act (ESA), and implementation and execution of various water development projects.

New Mexico State Water Plan

A New Mexico State water plan will be developed via an assessment of surface water systems in New Mexico for management purposes and various components of the Framework State Water Plan program. To expedite these evaluations, a procurement was initiated in January 2000 by the New Mexico Interstate Stream Commission (ISC) and OSE for the purpose of obtaining a detailed evaluation of the hydrology, geohydrology, and ecology of the state's river systems. The evaluation will provide the agency with an understanding of the river systems and the potential consequences resulting from the design and installation of surface water works for the conservation of endangered species.

Contracts in place include litigation support related to assessment of biological and ecological requirements and impacts of conservation of endangered species, an evaluation of surface water gaging and monitoring needs, ground-water level measurement projects, and tasks associated with the Framework State Water Plan.

The Framework State Water Plan

The Framework State Water Plan will establish the required data and technical evaluations of the state's water resources for planning purposes. Phase One of the Framework State Water Plan is funded with $600,000 from severance tax bond funds appropriated to the OSE in 1998 (Table 1).

The scope of work for the Framework State Water Plan includes the following tasks, some of which are currently under contract:

(1) An update of the 1976 New Mexico Water Resources Assessment for Planning Purposes—preparation of a statewide water budget, and future water demand scenarios for each river basin and major ground-water aquifer or basin;
(2) An investigation of the adequacy of data available for water planning purposes including an estimate of costs required to develop and prioritize data needs and development of a map atlas of the state's water resources in electronic format for input to a Geographic Information System (GIS);
(3) A statewide evaluation of evidence of decreasing watershed yields;
(4) A statewide evaluation of the adequacy of water resources measurement and monitoring systems (location, frequency, and technology);
(5) Establishment of a public involvement program for water planning on a statewide basis;
(6) An evaluation of regional water plans; and
(7) Estimated costs and budget to implement recommendations.

Contracts have been executed for the first four work tasks. The first *Framework State Water Plan* reports are expected to be submitted to the ISC in the fall of 2001.

TABLE 1—Framework State Water Plan budget.

Update statewide water resources assessment and develop water budgets	$250,000
Evaluate watershed yield	$75,000
Evaluate statewide stream gaging program	
Evaluate statewide ground-water monitoring program	$225,000
Statewide meetings to identify issues for the state water plan	$10,000
Review and evaluate regional water plans	$40,000
Total	$600,000

Regional Water Planning

In 1987, the New Mexico Legislature recognized the state's need for water planning and created and funded New Mexico's Regional Water Planning Program. The objective of the legislation was to address the reservation of any unappropriated water for a region's future. The legislature gave the (ISC) the responsibility of overseeing a grant program and the planning process.

The legislative criteria [NMSA 1978 §72-14-43 and §72-14-44 (1997 Repl.)] stipulated that planning regions could be self-defined on the basis of common hydrologic, political, and economic interests. Sixteen water-planning regions have been recognized by the New Mexico Interstate Stream Commission (Fig. 1).

Other important legislative requirements include:

(1) Public involvement in the planning process;
(2) Opportunities for participation by tribes;
(3) Reasonable costs and schedules for planning;
(4) Review for conflicts with laws protecting existing water rights;
(5) Provisions for evaluation of conservation and public welfare; and
(6) Sources of funding to supplement state funds.

In late 1994, the ISC developed the *Regional Water Planning Handbook* to provide guidance for water plans. The ISC adopted regional water plan acceptance criteria in April 1999. These criteria mandate conformance to the handbook and inclusion

TABLE 2—Regional water planning awards, November 2000.

Regions awarded funds	
3 Jemez y Sangre	$240,000
5 Tularosa, Sacramento, Salt	$45,000
9 Colfax	$207,000
11 Lower Rio Grande	$165,000
12 Middle Rio Grande	$150,000
14 Rio Arriba	$71,000
15 Socorro-Sierra	$105,000
Total	$983,000
Miscellaneous plan-related awards	
Award to WRRI for GIS maps for regions	$20,000
Award to NMSU to develop climate data*	$6,000
Award to Lea County*	$41,000
Total	$67,000
Awards to tribes or pueblos*	
2 Navajo Nation*	$50,000
12 Six Southern Pueblos Coalition*	$50,000
Total	$100,000
Grand total	$1,150,000

* Funding awarded, no contract executed

of local governments in implementing provisions of regional water plans.

The benefits of regional water planning include:

(1) An increased public awareness of New Mexico's water supply issues and tradeoffs;
(2) Strategies to deal with water supply limits and droughts;
(3) Assurance of economic vitality and environmental quality;
(4) Strategies for coping with and making use of flood waters;
(5) Conservation of water;
(6) Enhancement of the public welfare; and
(7) General quality of life.

Regional Water Planning Program Funding Status

The limited yearly appropriation ($200,000) funding the planning program shifted in 1998 because only one regional water plan had been completed (Estancia Basin, 1998) during the 12 years the program had been in place. The New Mexico legislature recognized that completion of regional water plans could be accelerated by a higher funding level coupled with increased accountability for funds and responsibility for plan products via use of professional service contracts as opposed to grants. To accomplish this $1,750,000 of severance tax bond funds was appropriated to the State Engineer for statewide water planning. One million dollars from these funds was set aside for regional water planning. Seven of the 14 regions participating in the 1998 Request For Proposals were successful in competitive bidding, and $1,051,341 is currently encumbered and/or under contract for regional water planning (Table 2). An additional appropriation will be requested in the 2001 legislative session to assist in completing water plans for FY 2002.

As of January 2001, two regional water plans have been finalized and accepted by the ISC, with a third soon to follow. Three additional plans have target completion dates of this year. Fourteen of the 16 regions are expected to have completed water plans by 2003. Program progress is depicted in Table 3.

Status of Regional Water Planning on the Upper Rio Grande

For administrative and interstate compact accounting purposes, the upper Rio Grande is defined by those reaches of the Rio Grande and its tributaries above the Otowi gage. Three of the 16 water-planning regions designated by the New Mexico Interstate Stream Commission are in the upper Rio Grande. These regions include portions of Rio Arriba County (Region 14), Taos County (Region 7), and Los Alamos County, portions of Santa Fe, Taos, and Rio Arriba Counties (Region 3). These water-planning regions and their planning programs are described below.

Region 14—Rio Arriba County. The Rio Arriba water-planning region encompasses the portion of Rio Arriba County east of the continental divide in the Chama River basin. Rio Arriba County has participated in the ISC water-planning program since 1990. Previous grants total $180,319. The current funding is $75,500. Water-planning documents produced to date are the *Northern Rio Arriba County Regional Water Plan (1993)* and the *Draft Rio de Chama Regional Water Plan, Vol. 1 (1997)*. Current funding is being used to complete the surface-water assessment, document the location and extent of ground-water resources, develop a water budget, and augment public participation. The target date for completion of the water plan is December 2002.

Water-planning issues faced by the region include managing a limited supply of ground water, balancing the supply and demand for acequias and mutual domestic water system with "native" water as opposed to San Juan–Chama contract water, and characterizing unknown ground-water supplies that are not stream connected to the Chama River and its tributaries.

TABLE 3—Completion status of regional water plans.

Region	Water Supply Study	Water Demand Study	Legal Analysis	Alternatives Listed	Alternatives Evaluated	Target Completion Date	Plan Finalized	Accepted by ISC
1 Northeast New Mexico[c]	1989[d]	1989[d]	1989[d]	1997[d]	1997[d]	2000[d]	2000[d]	
2 San Juan[b]	1994[e]	1994[e]	1994[e]			2002		
2 Navajo Nation[a]	2001	2001	2001			2003		
3 Jemez y Sangre[a]	2000[d]	2000[d]	2000[d]	2001	2002	2002		
4 Southwest New Mexico[c]	1991[e]	1991[e]				2003		
5 Tularosa, Sacramento, Salt[a]	2000[d]	2000[d]		2000		2001		
6 Northwest New Mexico[c]	1997[d]	1997[d]	1998[d]	1999[d]	pending[d]	2001		
7 Taos[b]	1999[d]	1995[e]	1995[e]			–		
8 Mora-San Miguel[b]	1994[e]	1994[e]				–		
9 Colfax[a]	2001	2001				2002		
10 Lower Pecos Valley[c]	1999[d]	1999[d]	1999[d]	1999[d]	pending[d]	2001		
11 Lower Rio Grande[a]	2001	2001				2002		
12 Middle Rio Grande[a]	2000[d]	2000[d]				2003		
13 Estancia Basin[b]	1996[d]	1996[d]	1996[d]	1999[d]	1999[d]		1999[d]	1999[d]
14 Rio Arriba[a]	2000[d]	2001				2002		
15 Socorro–Sierra[a]	2000[d]	2000[d]	2001			2002		
16 Lea County[c]	2000[d]	2000[d]	2000[d]	2000[d]	2000[d]		2000[d]	2000[d]

[a]Funded by the 1998 appropriation
[b]Not funded by the 1998 $1.0 million appropriation for regional water planning
[c]Funded from other sources: previous regional water planning appropriations, local funds, ISC operating funds, etc.
[d]Portion of regional water plan completed
[e]Updates of studies needed

Region 7—Taos County. The Taos County water-planning region encompasses most of Taos County, or that portion north of the Rio Embudo gage on the Rio Grande. Taos County has participated in the ISC regional water-planning program since 1988. Previous water-planning funds total $104,250. Funds provided by the Office of the State Engineer have contributed to technical reports for planning and administrative purposes. There is no current funding. Documents developed in support of water planning in the Taos region include: *Rio Grande joint investigation in the upper Rio Grande basin, 1937* (New Mexico ISC and the U.S. Bureau of Reclamation), *Taos County regional water plan, Volumes I and II, 1991* (Lee Wilson & Assoc.), a 1995 review of legal and institutional constraints to water in the Taos region by the New Mexico ISC (unpublished), and *Surface water assessment for Taos Valley, 1998* (New Mexico Bureau of Mines and Mineral Resources for the ISC).

Considerable public involvement has already occurred in over 60 community meetings held throughout the region between 1995 and 1997. Planning activities required to complete a water plan for Taos County include: completion and compilation of a water resources assessment, including documentation of water resources in parts of Taos County outside of the Taos Valley and the Rio Grande corridor; development of a water budget; and formation of a stakeholder steering group to oversee the process and to develop and analyze water management alternatives. The estimated time to complete a water plan is 3 years.

Issues facing the water-planning region include settlement of the ongoing water rights adjudication with Taos Pueblo and sustaining public involvement.

Region 3—Jemez y Sangre. The Jemez y Sangre water-planning region encompasses Los Alamos County and portions of Santa Fe, Taos, and Rio Arriba Counties. The principal river basin is the Rio Grande and the following tributaries: the Santa Cruz River, the Nambe, Pojoaque, and Tesuque Rivers (above the Otowi gage), and the Santa Fe and Galisteo Rivers (below the Otowi gage). Pertinent facts about the Jemez y Sangre regional water-planning effort are described in detail in Lewis, Water Planning in the Jemez y Sangre Water Planning Region, this volume.

The water-planning entity is the Jemez y Sangre Water Planning Council, formed in 1998 under an ISC grant. The council is comprised of water resources stakeholders via a co-operative agreement. Previous ISC grants total $141,315. Current funding is $240,000 in ISC funds and $240,000 in local matching funds. The Bureau of Reclamation has also provided funds. Documents produced to date with ISC funds in support of the water planning effort are: *Long range planning study for the Santa Fe area*, 1988-89 *(Harza report)*, *South Santa Fe County report*, 1992 (BBC), *Conservation in Santa Fe*, 1995, and a *Water rights letter report*, 1995. The target date for completion of the water plan is June 2002.

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Before joining the New Mexico Interstate Stream Commission staff to manage the state's Regional Water Planning program in May of 1997, Follingstad worked as a community planner for Santa Fe County for fourteen years (1983-1997). Her principal professional interests are economic development, "smart" growth and public involvement.

She is a native of Santa Fe, New Mexico. She is an active member of the New Mexico Chapter of the American Planning Association and the American Institute of Certified Planners (AICP). She completed the Leadership Santa Fe course in 1996 and has been active with New Mexico First since 1997. She is also an active member of the Museum of New Mexico Women's Board. She has been a member of the Santa Fe Historic Design Review Board (1976-80), the Santa Fe Urban Policy Board (1978–1982), and the Board of Directors for the Old Santa Fe Association (1975–1980).

Water Planning in the Jemez y Sangre Water Planning Region

by *Amy C. Lewis*, Water Resource Planning Coordinator, Sangre de Cristo Water Division, City of Santa Fe

Water stakeholders from the northern two-thirds of Santa Fe County, Los Alamos County, and the southeastern part of Rio Arriba County formed the Jemez y Sangre Water Planning Council in 1998. The planning region, shown in Figure 1, encompasses the Española geologic basin and the geographic area between the Jemez and Sangre de Cristo Mountains. Although members of the council signed a cooperative agreement addressing the need for water planning, the agreement does not commit parties to any implementation of a plan. It was viewed as important for all members to retain their power, their water rights, and their positions. The objective of the water planning council is to gather data on available water

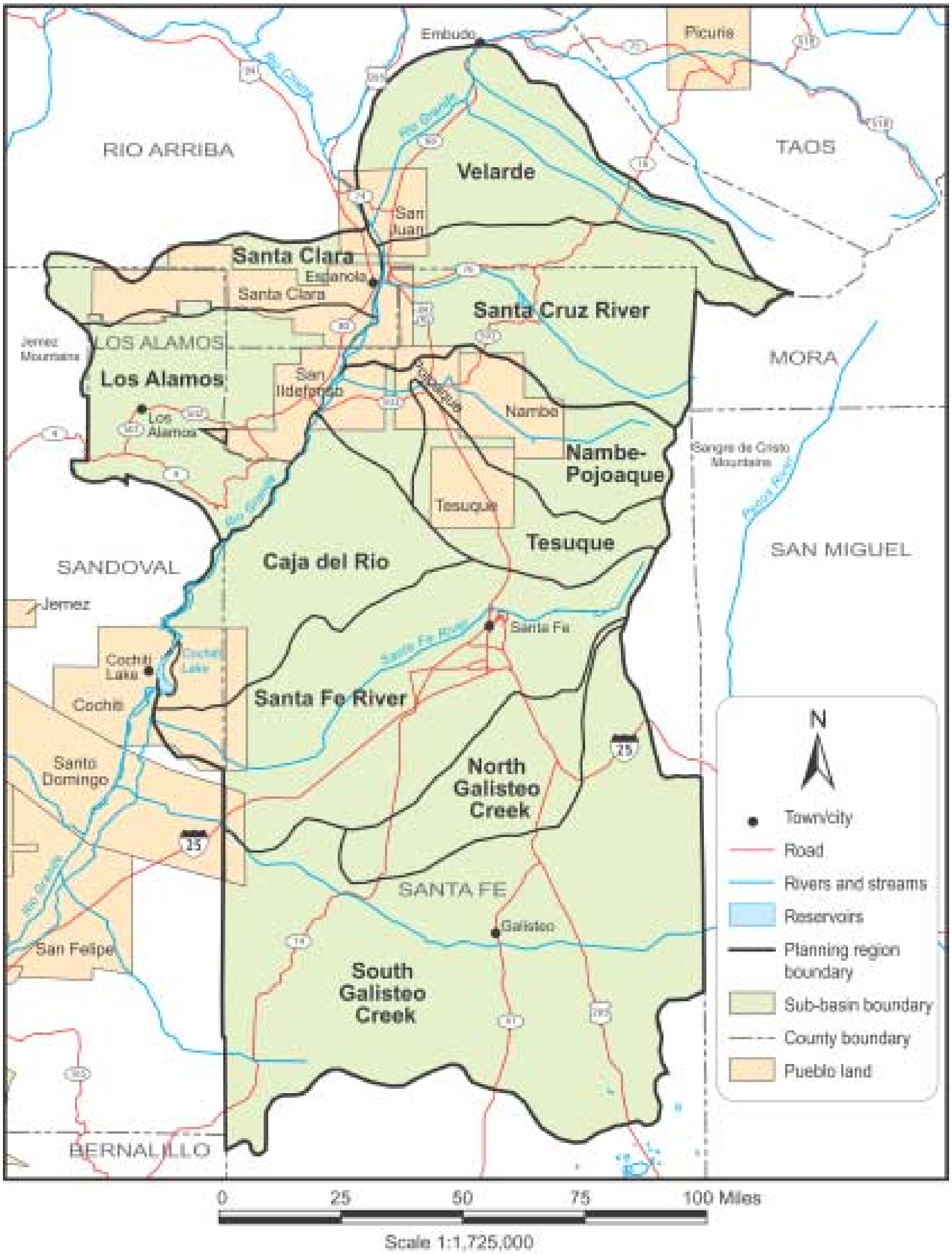

FIGURE 1—Jemez y Sangre Water Planning Region and sub-basins.

supply and projected demands, agree on the data (or on its deficiencies), and examine options for meeting projected demands. Critical to the planning process is the understanding that water use by any stakeholder impacts other stakeholders, and only by working together can we attain a water management strategy that effectively addresses everyone's needs.

Members of the council include Acequia Madre, Bureau of Indian Affairs, Bureau of Reclamation, city of Española, city of Santa Fe, Eldorado Area Water & Sanitation District, Garcia Ditch, La Acequia De La Cañada Ancha, Las Acequias de Chupadero, League of Women Voters, Los Alamos National Lab/DOE, Los Alamos County Public Utilities Department, New Mexico Rural Water Users Association, North Central New Mexico Economic Development District, Pojoaque Valley Irrigation District, Rio Arriba County, Rio Grande Restoration, Santa Fe County, Santa Fe Area Home Builders Association, Santa Fe Land Use Resource Center, Santa Fe–Pojoaque Soil Water Conservation District, State Land Office, and 1000 Friends of NM Rio Grande.

Status of the Planning Effort

The council, through funding from the New Mexico Interstate Stream Commission and the U.S. Bureau of Reclamation, contracted for completion of technical studies on population projections (Alcantara et al., 2000) and water supply (Duke, 2001). Using data produced from these two studies, the council can show the projected water demand and the available water supply. The projected water demands for the year 2060 show an increased domestic/commercial need of over 31,000 acre-ft/yr, above the existing uses. The only new source of water is from the San Juan–Chama Project, which could meet about 17,000 acre-ft of this need if return flow credits are secured. The remaining gap in meeting demand must be met by either reducing demand, transferring water from other uses, or allowing continued mining through domestic wells with no certainty for the future.

Assessments of projected water demand and supply for the Santa Fe sub-basin are shown in Figure 2. This figure illustrates that the total water supply available to the sub-basin from all sources, including the municipal surface water stored in Santa Fe watershed reservoirs, city ground-water wells, individual domestic wells, the Buckman well field, and other metered sources, is barely sufficient to meet current demands in the Santa Fe area (as of 2000). Before 2010 projected demands will actually exceed supply unless additional resources, such as San Juan–Chama Project water, are developed. Future water needs can be met with San Juan–Chama water until about 2040.

The council will develop alternatives for meeting or reducing future water demand, particularly in the Nambe–Pojoaque, Tesuque, Santa Fe, North Galisteo, and South Galisteo sub-basins, which show a projected supply deficit. In the northern sub-basins and South Galisteo Creek, water quality may be a critical constraint on the available supply, and future alternatives will need to address the natural and man-made contamination issues in those areas. We will evaluate each alternative to assess legal, environmental, technical, political, and financial feasibility; public welfare; implementation schedule; and physical, hydrologic, and environmental impacts.

Challenges for the Planning Region

Numerous challenges face the Jemez y Sangre water planning region in a variety of jurisdictional, regulatory, environmental, and legal arenas. The following summarizes some of the major water resource planning issues for the region:

(1) Jurisdictional issues. Multiple jurisdictions present a significant resource management challenge to the region. The planning region incorporates significant parts of three counties, two cities, seven pueblos, numerous villages, mutual domestic water associations and acequias, as well as several state and federal agencies. The conflict between the State of New Mexico Office of the State Engineer administrative policy and the basis for development under the Santa Fe County Land Use Code is a good example of one such conflict. Development in Santa Fe County is based primarily on a demonstration that the volume of water in storage beneath the proposed development will last 100 years (40 years in the metropolitan area). This may present a serious conflict with the state's compact obligations, which require that the aquifer continue to discharge to the Rio Grande. If land development could only occur through water right transfers, this would not present a problem. The county regulations could simply require demonstration of physical water associated with paper water. Applications for new appropriations or transfers of water in the Santa Fe area to the Office of the State Engineer are required to offset depletions on the Rio Grande (pumping a well ultimately impacts flow in the river). An added problem is presented by the fact that diversion of water is available through individual domestic wells (wells allowed under article 72-12-1 of the N.M. Statute, 1978), which are automatically approved by the Office of the State Engineer.

(2) Lack of adjudication. Increased and/or changing demand for limited water resources in the region has created tension between diverse water stakeholders and interests, and on-going water rights adjudications and litigation between the various stakeholders are an impediment to planning. The lack of adjudication means that water rights in the region are unquantified. A serious water management problem arises when it is unknown whether a water right

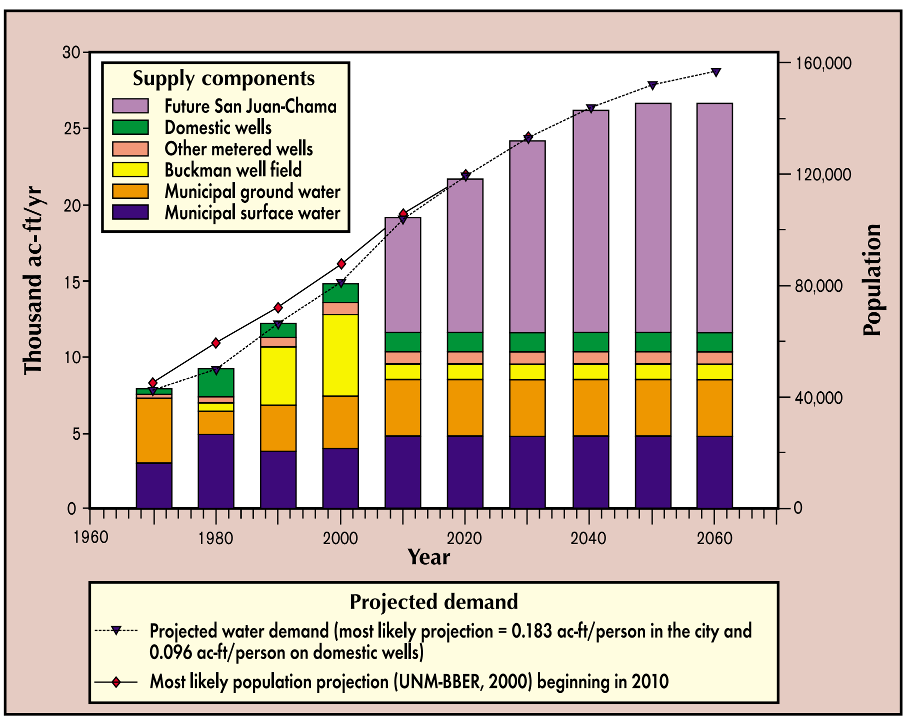

FIGURE 2—Water availability and future water demand in the Santa Fe sub-basin.

will be available to a planning entity in the future. Furthermore, litigious relationships between the stakeholders have created an atmosphere of mistrust that must be overcome if we are to develop and successfully implement a water plan.

(3) Water quality. Ground-water and surface-water contamination throughout the region impacts the availability and cost of water. For example, several city of Santa Fe and Española wells have been taken out of production or undergone expensive treatment due to anthropogenic or natural contamination. Domestic wells near Pojoaque are contaminated with nitrate from local septic tank effluent. Water quality data near Los Alamos indicate the occurrence of tritium, chloride, nitrate, strontium, plutonium, and other contaminants in either surface or ground water associated with the canyon systems. Tesuque Creek, Rio Frijoles, Rio Chupadero, Little Tesuque Creek, Pojoaque River, Rio en Medio, Santa Cruz River, and the Santa Fe River are affected by some or all of the following: siltation, turbidity, heavy metals, chlorine, pathogens, stream bank destabilization, and reduction of riparian vegetation.

(4) Surface-water availability. The city of Santa Fe, the pueblos, and the acequias depend at least in part on surface water to meet their water demands, yet the surface-water supply in our semi-arid region is highly variable. The council may examine conjunctive use strategies to maximize surface water use in wet years and rest our aquifers so that ground water in storage will be available during times of drought.

(5) Access to San Juan–Chama water. The ability for the region to meet future demand will be dependent on accessing San Juan–Chama Project water. The council will examine the frequency for which the San Juan–Chama water may be required for other needs and work toward solutions that result in the greatest gain for all. If the silvery minnow requires water a few weeks each year or every few years, we need to be prepared to utilize ground water during those and other shortages.

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Regional Water and Wastewater Services

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

Thinking of Water Regionally

More and more we are seeing the regionalization of water in New Mexico. This is occurring not only in the form of regional water planning but in the actual development of regional water and wastewater utilities that provide services on a larger scale.

There are two fundamental reasons why the regionalization of water is taking place: first, given that water basins are defined by natural and not political boundaries, governmental jurisdictions are realizing they must work together within a shared basin; and second, as local sources of supply become more difficult to obtain, communities have to work cooperatively to bring in water from distant sources. These two driving forces are further described as follows:

Cooperation within Watershed Boundaries

Water is trans-boundary in nature. Although we humans may attempt to draw lines that define territory and mark interests, water has never been versed in the intricacies of human relations; it simply seeks to follow its natural course. As a result, even though a water right is, by state law, an item of real property, water because of its proclivity to ignore human boundaries and limitations is fundamentally a shared natural resource. Within its natural watershed, it sustains all forms of life. Because it is a shared resource, it has the characteristic of both bringing people together and creating conflict among them. Those living in the same watershed are inextricably connected, in the same way that parciantes of an acequia are dependent upon and directly affect one another. Yet our line-drawing instincts, particularly as the scale increases, can gravitate towards selfishness rather than cooperation. In the high desert of New Mexico this is a formula for disaster. As water supplies become tighter, those depending on a shared water resource are learning that in order to avoid conflict, including inter-governmental dispute, they must work together instead, thinking regionally within a common watershed. A well-known example of this trend is the creation by the city of Albuquerque, the village of Los Ranchos, and the county of Bernalillo of a regional water utility called the Albuquerque Metropolitan Water Authority.

Day Two

Distant Sources of Supply

Another prominent phenomenon is the ongoing search for increasingly distant sources of water. As local water supplies become overtaxed, local communities are banding together to bring in water supplies from distant sources. One good example of this is the proposed Ute pipeline that would bring water from Ute Reservoir to towns on the east side of the state. Another example is the proposed Navajo–Gallup pipeline that would divert water from the San Juan River and bring it south all the way to the city of Gallup, serving various water users, including on the Navajo Nation, along the way. One long-standing and vital example is the San Juan–Chama Diversion Project, which brings nearly 100,000 acre-ft/yr of water from the Upper Colorado watershed to the Rio Grande basin.

The Santa Fe and Española Areas

At the present time, two regional water or wastewater initiatives are in the study phase.

Pojoaque–Santa Fe Regional Water Authority—Water users in the Pojoaque and Santa Fe Basins, including the city and county of Santa Fe, pueblos, and non-pueblo water users, are in discussions regarding the creation of a regional water authority that would divert water from the Rio Grande and supply both basins. In order to govern and manage such a regional system, a utility would be created under both state and federal law, in order to give the water authority the powers of a state subdivision and to ensure and authorize participation of Indian tribes, as well as necessary federal agencies.

New Mexico law does not currently authorize formation of such a multi-jurisdictional entity. In order for the water authority to construct, operate and maintain a regional system, and receive funding, legislation enacted by the New Mexico Legislature would be needed to establish the water authority.

Board members of such a regional water authority could be appointed by the participating governmental entities (e.g. the Santa Fe County Commission, the Santa Fe City Council, the Tribal Councils of the four Pueblos of San Ildefonso, Pojoaque, Tesuque and Nambe, and other local water users) or a state official such as the Governor of New Mexico or the State Engineer.

The Española Valley, Pojoaque Valley Regional Wastewater Treatment Project—An effort involving the Pojoaque and Española Valleys proposes to address both water supply and ground-water contamination. The project in its current iteration began in the summer of 1998, when Mayor Richard Lucero of Española brought regional participants back to the table to discuss regional water contamination issues. A previous round of regional efforts in the late 1980s had led to the development of a septage facility at Pojoaque Pueblo to accept waste from septic tank cleaning operations and prevent the illegal dumping by commercial septic tank cleaners. By early 1999, the interested communities had formalized a steering committee that had representation from the city and county of Santa Fe, the city of Española, Rio Arriba County, the Eight Northern Indian Pueblos Council, and many of the acequias and mutual domestic water associations.

This project will require at least 18 months of groundwork, and the current technical study will continue until the spring of 2001. Completion of the technical study will lead to prioritizing construction activities. Construction decisions will require detailed Environmental Impact Statements and complex negotiations with such agencies as the Bureau of Land Management, the U.S. Fish and Wildlife Service, Indian Health Service, and the Bureau of Indian Affairs.

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Past Volcanism in Northern New Mexico—Key to Understanding Potential Future Activity

by *Nelia W. Dunbar*, New Mexico Bureau of Mines and Mineral Resources

Volcanoes are abundant in New Mexico. The black, barren, lunar-landscape rocks around Grants and Carrizozo and the black flat-topped mesas around Albuquerque are volcanic lava flows. Mount Taylor is a volcano, Capulin Peak is a volcano, and Los Alamos is built on the flank of a huge volcano. Shiprock is the remnant of a volcano, as is Cabezon Peak. Although not as easy to recognize, many of the rocks in the Gila Mountains and other southern and western New Mexico mountain ranges are also volcanic. Volcanic rocks ranging from as young as 3,000 years old and up to ~1.7 billion years old are found in the state.

This panoramic stop atop Cochiti Dam offers an opportunity to observe, from a distance, deposits from two of the most common types of volcanism in New Mexico. These two types of volcanism, not coincidentally, are the most likely to occur again. The large edifice of the Jemez Mountains, which forms most of the topography from north to west is a single large volcanic complex that began forming at least 16.5 million years ago . Much of this volcano was built by a large-volume and highly explosive, though infrequent, type of volcanic activity. The dark-colored hummocky hills visible from the north to the east, and the sloping, shield-shaped skyline to the south are also volcanic. These deposits formed mainly between 2 and 3 million years ago, and are the result of the same type of volcanic activity that occurs in Hawaii today.

The pink to tan-colored flat-topped bluffs that stretch from north to west in the near distance are a volcanic deposit called the Bandelier Tuff. This tuff erupted during two very large volcanic eruptions that occurred 1.6 and 1.2 million years ago. This is the same rock in which the Bandelier National Monument cliff dwellings are located. The darker colored, bare-looking outcrops between the Bandelier Tuff and the distant horizon are also volcanic rocks, but these were deposited in a series of smaller eruptions that occurred at least 5 million years earlier. The most distant skyline to the north and west is the Valle Grande area, which is the very large crater from which the Bandelier Tuff erupted.

Each of the two eruptions that formed the Bandelier Tuff was volumetrically more than 250 times larger than the 1980 Mount St. Helens eruption. No eruption this large has occurred anywhere in the world in historic time, and only six have occurred in the U.S. in the last 2 million years, including the two Bandelier Tuff eruptions, three from Yellowstone, and one from the Bishop area of California. The initial stages of the Bandelier eruption produced ash that rained out of the sky over most of New Mexico. Following the initial ash-fall part of the eruption, activity shifted to a pyroclastic-flow eruption. This stage produced a fast-moving, extremely hot cloud of ash, pumice, and gas traveling as much as 30 km from the central vent that would have destroyed anything standing in its path, and then solidified into volcanic rock. This eruption style produces such hugely explosive events that even an eruption in an adjacent area, such as Yellowstone, could cause ash to fall in New Mexico. Ash from the most recent Bandelier Tuff eruption (1.2 million years ago) has been traced eastward into Oklahoma, Kansas, and Texas.

Although there have not been any major eruptions from the Jemez Mountains volcanic field for the last million years, there have been a number of smaller eruptions, the most recent of which occurred about 60,000 years ago. The Jemez Mountain volcanic field may be entering a new phase of volcanic activity, based on geophysical measurements and measured periodicities of eruptions. Wolff and Gardner (1995) recommend geophysical monitoring of the Jemez Mountains area, so that if an eruption were to occur, forewarning would be possible. At this point, there is no evidence of any unusual activity in the Jemez Mountains.

In contrast to the Jemez Mountains style of eruption, most of the recent volcanic activity in New Mexico has been of a more passive eruption style, producing lava flows and small cinder cones. Some examples of this type of activity include the 3,000 year-old McCartys and the 10,000 year-old Bandera craters lava flows in the Zuni–Bandera volcanic field, near Grants; the 5,000 year-old Malpais lava flows near Carrizozo; and the 55,000 year-old Capulin Peak. This type of eruption is generally known as Hawaiian, because it is the type of activity that formed, and continues to form, the Hawaiian Islands. These types of volcanic rocks are called basalts, and are typically black in color. The large, hummocky hills to the north and to the east and the shield-shaped skyline to the south, called the Cerros del Rio and Santa Ana Basalts, are also examples of this type of volcanism. Distinct lava flows can be seen as benches on the Cerros del Rio. Several distinct vents on the Santa Ana Basalts can be seen as slightly raised areas on the skyline. If there were to be a volcanic eruption in New Mexico in the next 100 or 1,000 years, it would most likely form either a lava flow, a cinder cone, or both. The eruptions that form these features do not involve major explosive activity, instead they involve lower levels of explosivity to form the cinder cones and slow-moving, although very hot, lava that flows downhill from the vent of the volcano. Depending on where it occurs, this type of eruption would be unlikely to cause major loss of life or property although the initial stages of the eruption could be dangerous to any nearby onlookers.

How likely is an eruption to occur in New Mexico in the near future? There have been more than 700 volcanic eruptions in New Mexico in the last 5 million years. The eruptive styles range from dangerously explosive to passive. Based on the past occurrence of volcanism, Limburg (1990) estimates that there is roughly a 1% chance that some type of volcanic eruption could occur somewhere in New Mexico in the next 100 years, and a 10% chance that an eruption will occur in the next 1,000 years. Widespread seismic monitoring and continued study around the state would help provide forewarning, and predict where an eruptive event might take place.

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The Volcanic Foundation of Cochiti Dam, Sandoval County, New Mexico

by *Gary A. Smith*, Department of Earth and Planetary Sciences, University of New Mexico

During new geological mapping on Cochiti Pueblo (Smith and Kuhle, 1998) particular attention was given to the vicinity of Cochiti Dam (Fig. 1). The large footprint of the dam and flanking aprons of artificial fill obscure important features. Terrace gravel deposited during the last 300,000 years by the Rio Grande also partially buries older rocks that could otherwise be mapped and projected below the dam. However, careful mapping of natural-rock outcrops and information from 22 shallow wells drilled along the foundation line before construction (U.S. Army Corps of Engineers[USCOE], 1967) permit inference that the dam is located over a line of at least three extinct Pliocene (2.7 million years old) volcanoes (Smith et al., 1997).

A key consideration in the location of Cochiti Dam was the rare presence of hard bedrock, rather than unconsolidated alluvium, close to the surface in the Rio Grande channel. The bedrock consists of layers of brown silt, sand, and gravel. Most large clasts are rounded pebbles and cobbles of quartzite identical to those comprising the ancestral Rio Grande gravel exposed in this part of the Santo Domingo Basin. Geologists undertaking the foundation studies for the dam identified this bedrock as an unusually solid sedimentary layer within the Santa Fe Group and informally named it the Sacred Area sandstone, in reference to a Cochiti religious site now buried below the dam near the outlet works (USCOE, 1967).

Our examination of the Sacred Area sandstone shows it to be the product of explosive interaction of rising magma with shallow ground water (Smith et al., 1997; Fig. 2). The explosions excavated large volumes of the Rio Grande gravel that comprise the aquifer, accounting for the conspicuous rounded clasts in these deposits, and produced craters extending tens of meters deep. The magma was quenched and shattered into very small fragments of black glass. The sediment ejected from the craters accumulated in layers on the crater walls and surrounding countryside.

The previous inaccurate interpretation of the origin of the Sacred Area sandstone (USCOE, 1967) is completely understandable. The first descriptions of hydromagmatic eruptions by volcanologists were made in the mid-to-late 1960s, and the first critical scientific papers illustrating the nature of the resulting deposits did not appear until the early 1970s. Given the abundance of rounded pebbles and cobbles and layering and cross bedding similar to those found in normal sedimentary deposits, it is not surprising that the volcanic origin of these strata went unrecognized at the time of the foundation studies.

There are three recognized volcanic craters located along the axis of Cochiti Dam (Fig. 1). Thick deposits of volcanic tuff (née Sacred Area sandstone) fill two craters explosively excavated in aquifer gravel, and the third volcano is a more traditionally viewed low shield of lava. The explosion craters are located under the dam at the outlet works (Fig. 2) and in Cañada de Cochiti. The lava shield was located near where the dam crosses the Santa Fe River. This latter feature, visible on topographic maps and old photographs and described in the Corps of Engineers reports, was extensively quarried for facing stone during dam construction and then buried beneath dam-apron fill. Two lava flows erupted from this southernmost volcano to form conspicuous dark ledges extending southward from the Santa Fe River to the community of Peña Blanca (Smith and Kuhle, 1998; Fig. 1). The lava flows rest above and are interlayered with hydromagmatic tuff erupted from the two northern vents, indicating contemporaneity of eruptions at all three small volcanoes (Smith et al., 1997). The alignment of the three simultaneously active volcanoes suggests that magma rose to the surface along a fissure coincident with a fault paralleling the dam axis and verified by correlation of offset layers between Corps of Engineers wells (Smith et al., 1997; Fig. 1). This fault is, however, clearly an old structure that does not displace the Rio Grande terrace gravel and is not likely an active feature.

The volcanic, rather than sedimentary, origin of the Sacred Area sandstone has other implications for the Cochiti Lake reservoir. The tuff is a barrier to downward movement of

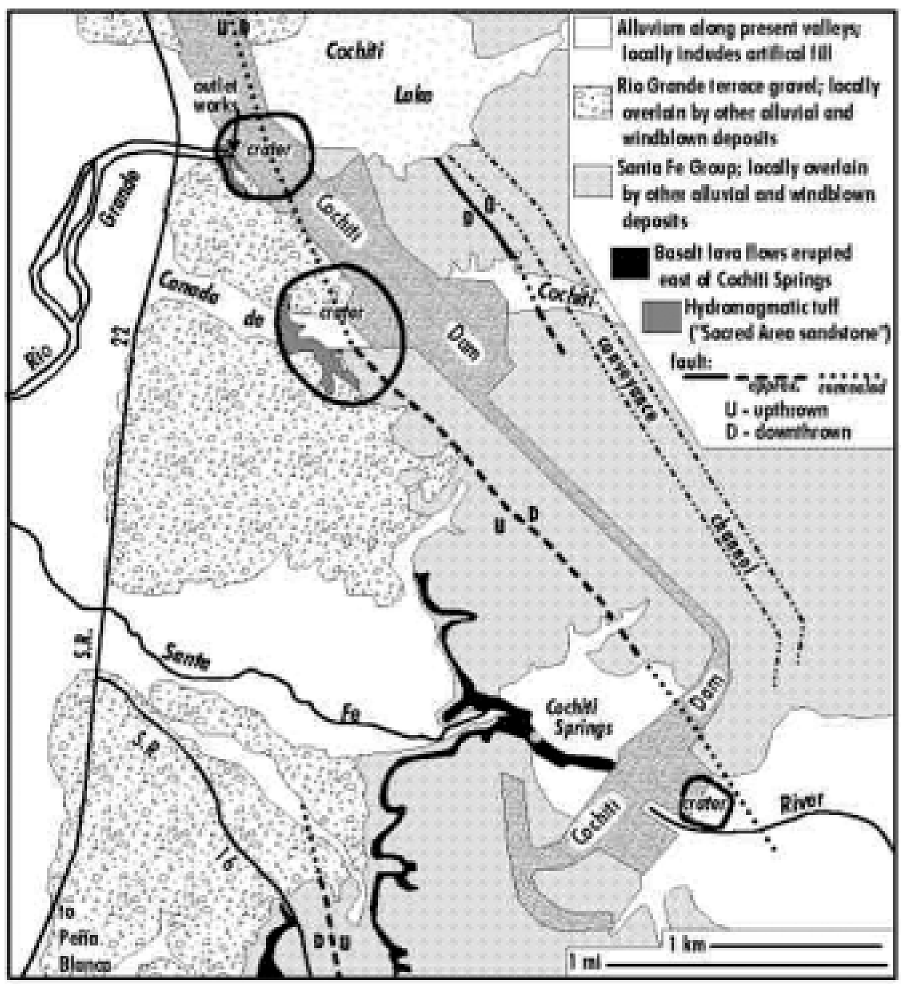

FIGURE 1—Geologic map (generalized from Smith and Kuhle, 1998) of the Cochiti Dam area emphasizing the distribution of basaltic lava flows and hydromagmatic tuff erupted from three known volcanic craters closely coincident with the dam.

FIGURE 2—Outcrop of hydromagmatic tuff, formerly called the "Sacred Area sandstone" alongside the stilling basin at the outlet works for Cochiti Dam. The layered volcanic ejecta dip inward along a margin of a crater centered beneath the dam. Small displacements of some layers were probably caused by slumping of ejecta into the crater rather than representing tectonic faults.

water, as illustrated by Cochiti Springs along the Santa Fe River where water emerges at the top of the relatively impermeable tuff at the base of the basalt (Fig. 1). Because the tuff is relatively thin (~ 90 m; Smith et al., 1997) and restricted to the proximity of the volcanoes from which it was erupted, it neither provides a barrier to ground-water flow beneath the dam nor for downward movement of water below the reservoir. The highly permeable nature of the gravel underlying the Rio Grande part of Cochiti Lake permits ready downward and lateral southwesterly movement of ground water under the pressure offered by the elevated head of the reservoir when it is filled. This ground-water movement substantially raised the water table downstream of the dam resulting in expensive drainage remediation and a subsequent mandate to maintain a relatively low reservoir pool.

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A Study of Plutonium and Uranium in Cochiti Reservoir Sediments

by *Bruce M. Gallaher*, LA-UR-01-14, Water Quality and Hydrology Group, Los Alamos National Laboratory

Cochiti Reservoir is on the Cochiti Indian Reservation in north-central New Mexico (Fig. 1). Since the closure of Cochiti Dam in 1973, the reservoir has been used for flood control of the Rio Grande, sediment control, irrigation, and recreation. An issue of concern to both the Pueblo de Cochiti and the Los Alamos National Laboratory is possible environmental contamination of the reservoir located approximately 8 km downstream of the laboratory boundary. Although the laboratory has tested bottom sediments and fish from the reservoir yearly since the early 1980s, for many years the sampling program was laboratory-driven and involvement with the pueblo was quite limited.

A formal cooperative agreement in 1994 between the pueblo and the laboratory allowed for partnering and the initiation of a broader study of the reservoir bottom sediments. After discussions with the pueblo leadership, we decided to initially focus on possible contamination with plutonium and uranium, two of the radioactive elements historically used at the laboratory. Specifically, the laboratory designed a study to measure the proportion of laboratory-derived plutonium and uranium that has accumulated in the reservoir bottom.

Both plutonium and uranium have been used in laboratory research since the Manhattan Project. Some waste materials from this research have ended up in canyons draining the laboratory. Decades of environmental monitoring by the U.S. Geological Survey and the laboratory have shown that a relatively small amount of these materials (dating principally from the 1940s and 1950s) have been carried offsite into the Rio Grande by floods, and over time into Cochiti Reservoir. Two key questions thus arise: how much laboratory contamination is found in the reservoir, and does it pose a large risk?

In this study, a new analytical fingerprinting technique was employed to better quantify the impacts of laboratory activities on Cochiti Reservoir. This method allows us to discern laboratory-derived plutonium and uranium from worldwide fallout or from natural sources. The Pueblo de Cochiti provided a total of 15 sediment samples collected from the bottom of Cochiti Reservoir for this analysis.

The analytical results confirm the presence of laboratory-derived plutonium in the reservoir sediments, but laboratory-derived uranium was not identifiable. The net increase in plutonium radioactivity from laboratory operations, however, appears to be relatively small and would be difficult to recognize using conventional analytical techniques. In all but two of the samples we found a larger proportion of fallout plutonium than laboratory-derived plutonium. The most current estimates are that from 60% to 70% of the plutonium in the reservoir is derived from fallout.

The plutonium in the reservoir sediments is not at levels known to adversely affect public health. The overall plutonium content is 1,000 times below levels that would generally trigger cleanup. High sedimentation rates are partly responsible for the relatively low-degree of laboratory impact in the reservoir. Large amounts of sediment from undeveloped parts of the watershed dilute any inputs of contaminants from the laboratory.

The laboratory will continue to work with the Pueblo de Cochiti on this and other related investigations. The Cochiti Environmental Protection Office (CEPO) is also managing a separate investigation of the water and sediment quality of the reservoir. The CEPO and the U.S. Geological Survey have concluded Phase One of that study and found limited effects by humans. Ultimately, the pueblo itself will have to evaluate the health and cultural impacts of contaminants trapped by the reservoir.

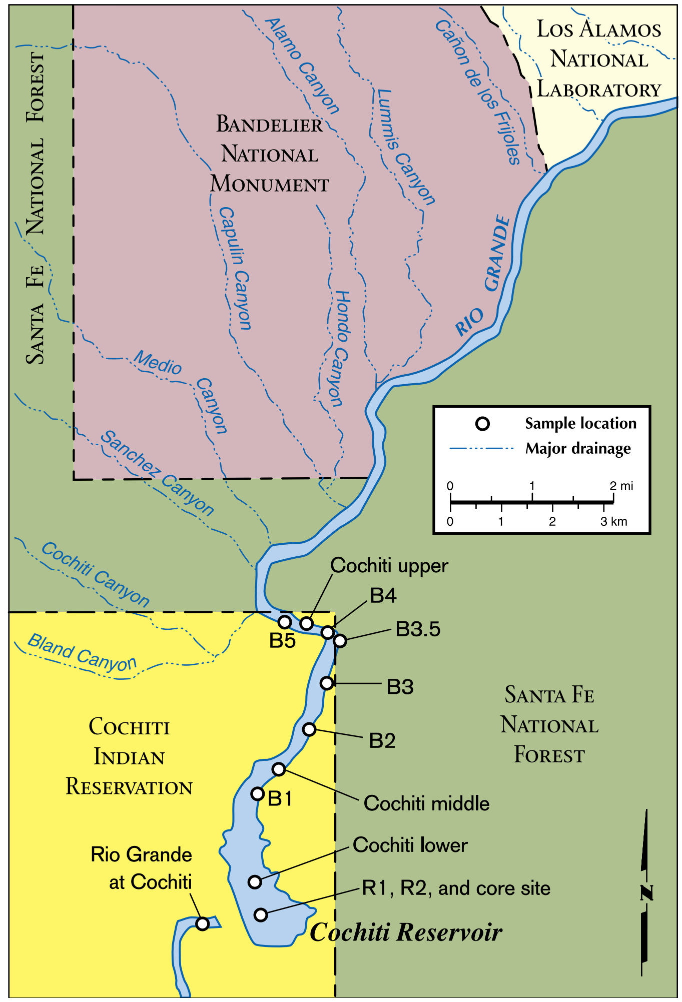

FIGURE 1—Sample locations for bottom sediments in Cochiti Reservoir.

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What Decision Makers Should Know About Earthquakes and their Associated Ground Shaking Hazard in New Mexico

by *Ivan G. Wong*, URS Greiner Woodward-Clyde, Inc., and
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The vast majority of New Mexico's population is located along the 400-mi-long Rio Grande valley that spans the entire state and includes the major cities of El Paso (Texas), Las Cruces, Albuquerque, and Santa Fe. The valley is situated within the Rio Grande rift, an area of major tectonic, volcanic, and seismic activity in the continental western U.S. It is unlikely that any earthquake larger than magnitude (M) 6.0 has occurred within the New Mexico portion of the rift since 1850, and no damaging event has occurred for the past 400 years. However, geologic investigations indicate that prehistoric earthquakes of M 6.5 and greater have occurred on average every 400 years on faults throughout the Rio Grande rift. The occurrence of a large earthquake today in many portions of the Rio Grande valley could result in significant damage and casualties particularly because of the extensive use of unreinforced masonry construction and the existence of many older structures.

As part of an effort to increase the awareness of the citizens of New Mexico to potential earthquakes and their hazards, a series of nine scenario and probabilistic ground-shaking maps have recently been developed. The maps cover the Rio Grande valley for the corridor between Belen and Española. They were developed by a team of scientists and engineers from URS Corporation, New Mexico Institute of Mining and Technology, and New Mexico Bureau of Mines and Mineral Resources. The project was sponsored by the U.S. Geological Survey under the National Earthquake Hazards Reduction Program.

The maps display color-contoured ground-motion values in terms of three parameters that are typically used in engineering design: peak horizontal acceleration and horizontal spectral accelerations at 0.2 and 1.0 sec periods. The maps depict surficial ground shaking and incorporate site-specific effects of unconsolidated sediments. This is critical since the Rio Grande valley is filled with such sediments and amplification of ground motions can be significant. The probabilistic maps are for the two return periods of building code relevance, 500 and 2,500 years. Figure 1 shows a scenario map for a M 7.0 earthquake on the Sandia–Rincon faults, which are adjacent to and dip west beneath the city of Albuquerque.

Based on this map, the ground-shaking hazard in the corridor can be viewed as moderate, in the context of other regions in the western U.S. The probabilistic hazard is significantly lower than in California and even areas in the intermontane west such as Salt Lake City, Utah. However, the hazard in the valley is higher than other areas of the Southwest, such as eastern and western New Mexico, and southern Arizona.

The level of hazard portrayed on the maps is controlled by the relatively low level of historical seismicity and by the comparatively low activity rate of the faults. It should be noted, however, that New Mexico's short and incomplete historical seismicity records are often a poor indicator of the earthquake potential of a region. The geologic evidence is irrefutable that large magnitude earthquakes ($M > 6.7$) have occurred in the past in the Rio Grande rift and will undoubtedly occur in the future. Thus, although large earthquakes may be infrequent on a specific fault, the high number of faults in the rift indicates that the probability of a large earthquake occurring somewhere in the valley is far from insignificant. The strong ground shaking from an event such as the M 7.0 Sandia–Rincon faults scenario (Fig. 1), could be very damaging. The potential exists that very large earthquakes are also possible outside the Rio Grande rift, such as the 1887 M 7.4 Sonora, Mexico, earthquake, which occurred on the Pitaycachi fault just outside the border of southwestern New Mexico. Ground motions from any large earthquake can be quite severe because of the presence of alluvial sediments that blanket the Rio Grande valley, which can amplify ground shaking to very damaging levels.

What Can the General Public Do?

Awareness and preparedness are the key actions. Many citizens in New Mexico do not regard earthquakes as a threat to their safety. They have a false sense of security because of the relatively low level of seismicity that has occurred during their lifetimes. However, scientists do believe that a large earthquake will someday strike New Mexico, and the citizens need to be prepared. They need to know how to react and what action to take when an earthquake occurs. It is wise to develop an earthquake response plan for various members of the family, while at work during the day and/or at home in the evenings. For example, emergency supplies should be easily accessible and should last for at least three days. The local office of emergency services or the Red Cross will have further information on earthquake preparedness and safety.

What Can Geologists and Engineers Do?

There is an increasing amount of new scientific research aimed at understanding the earthquake potential and its associated hazards in New Mexico. Geologists and engineers need to be informed and kept abreast of these new developments and results and implement them into their practice. In particular, it appears that earthquake hazards such as liquefaction and landsliding are not strongly considered in engineering design. More importantly, there are a large number of pre-building code structures in New Mexico that are not adequately designed to withstand earthquake ground shaking. Engineers need to consider more feasible and economical approaches for reinforcing these older buildings to make them more earthquake-resistant. They also need to become more proactive in terms of helping to inform the general public and encouraging them to take action to prepare for potential earthquakes.

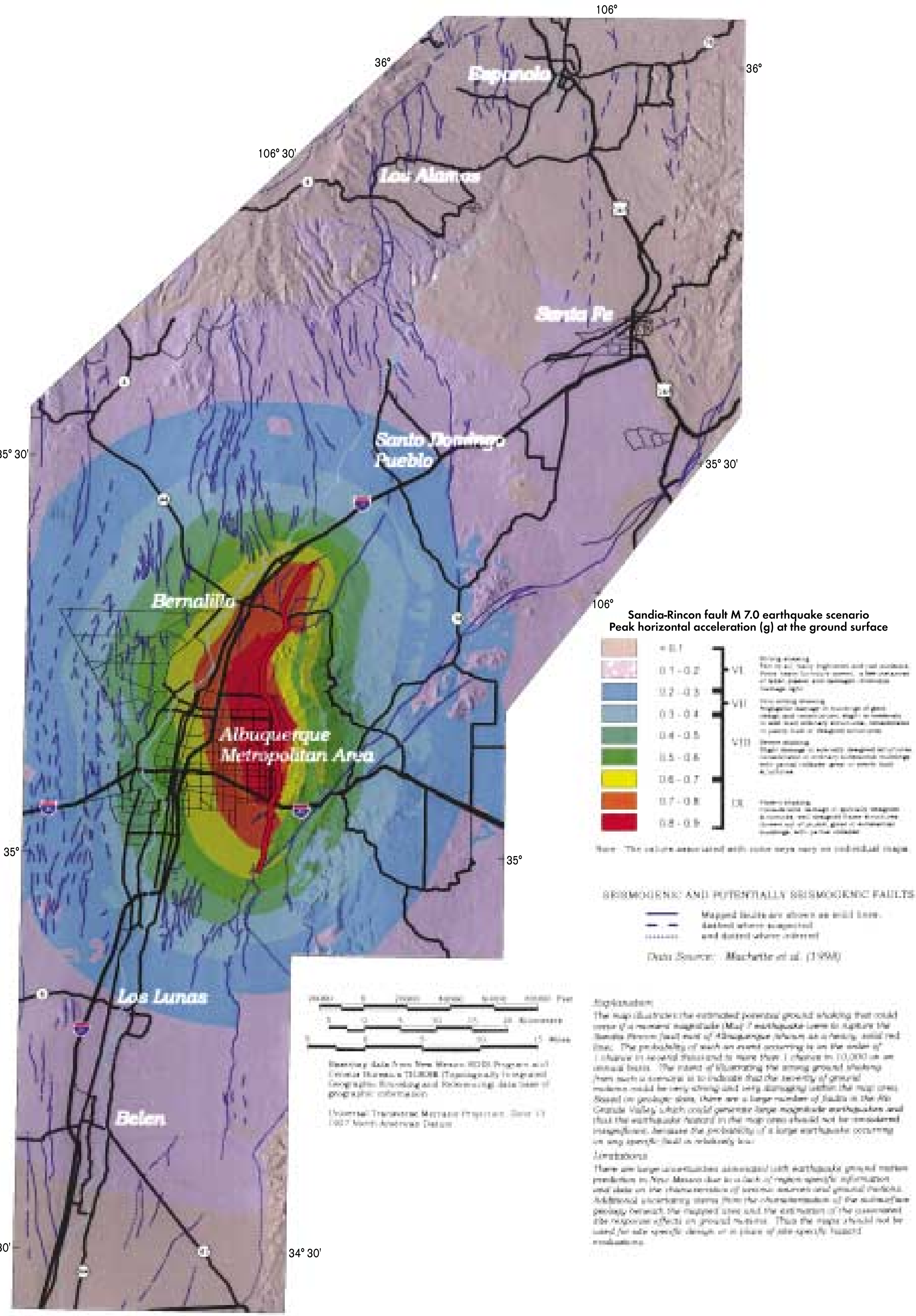
What Can Decision Makers Do?

Realistically, earthquake hazards are just one of several natural hazards and one of many public safety issues that New Mexico decision makers have to address. Because of the widespread damaging effects that a large earthquake could generate in New Mexico, there are no easy quick fixes and the economic cost of such fixes would be very large. However, the reality is that a large earthquake will strike the state in the future and increased efforts need to be made to prepare New Mexico for that eventuality. Of particular concern is the existence of a large inventory of older buildings that do not meet modern standards for earthquake-resistant design. A risk assessment of critical buildings (such as hospitals, police and fire stations, and schools) is a logical and cost-effective first step for communities in New Mexico to reduce earthquake hazards.

Despite the potential for surface faulting that could accom-

FIGURE 1—Earthquake scenario and probabilistic ground-shaking maps for the Albuquerque–Belen–Santa Fe, New Mexico, corridor.

Earthquake scenario and probabilistic ground shaking
Española - Santa Fe - Albuquerque - Belen corridor



pany a large earthquake in the Rio Grande valley, no state or local laws exist that prevent new building construction astride active faults. Even public facilities such as a library have been recently constructed across an active fault that has demonstrated surface rupture in the recent geologic past.

Decision makers need to be informed and continue to take actions that will protect New Mexico's citizens from earthquakes. Such actions can include legislation to enact laws that provide protection as well as to support funding of programs that are aimed at preparedness, response, and mitigation.

Where Can I Get More Information?

There are many publications which deal with earthquakes and earthquake hazards in New Mexico. The following are a few selected by the authors:

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Personius, S. F., Machette, M. N., and Kelson, K .I., 1999, Quaternary faults in the Albuquerque area—An update; *in* Pazzaglia, F .J., and Lucas, S. G. (eds.), Albuquerque geology: New Mexico Geological Survey, Guidebook 50, p. 189–200.

Sanford, A. R., Jaksha, L. H., and Cash, D. J., 1991, Seismicity of the Rio Grande rift in New Mexico; *in* Slemmons, D. B., Engdahl, E. R., Zoback, M. D., and Blackwell, D. D. (eds.), Neotectonics of North America: Geological Society of America, Decade Map, v. 1, p. 229–244.

Wong, I., Olig, S., Dober, M., Silva, W., Wright, D., Thomas, P., Gregor, N., Sanford, A., Lin, K., Love, D., and Naugler, W., 2001, Earthquake scenario and probabilistic ground-shaking hazard maps for the Albuquerque–Belen–Santa Fe, New Mexico, corridor: New Mexico Bureau of Mines and Mineral Resources, (Submitted for publication).

New Mexico Bureau of Mines and Mineral Resources web site: http://geoinfo.nmt.edu

American Red Cross web site: http://www.redcross.org/

New Mexico Department of Public Safety, FEMA, web site: http://www.dps.nm.org/emergency/em_index.htm

New Mexico Institute of Mining and Technology, Department of Geophysics web site: http://www.ees.nmt.edu/Geop/homepage.html

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Hydrologic History of the Middle Rio Grande Basin

by *Dan Scurlock*, Wingswept Research,
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The Rio Grande, the 5th largest river in North America, flows 1,885 mi from southern Colorado to the Gulf of Mexico, and extends across New Mexico, from just above Ute Mountain to the Texas border. In the middle valley, the Rio Grande flows for 160 mi, from Otowi to the base of Elephant Butte Reservoir. Climatic variability has been the most significant environmental factor in shaping the landscape and history of the middle Rio Grande basin. Episodic droughts and wet years are characteristic of the variability in the region's weather patterns. Since long before recorded history, periodic droughts and floods have affected, determined, and maintained streamflow, vegetative communities, wildlife populations, wild fires, agricultural productivity, and aquatic ecosystems. Over the last six centuries this climatic regime has remained relatively stable, with no major changes in regional weather patterns. One minor climatic change, known as the "Little Ice Age," occurred between about 1450 and 1850, when average temperatures were a few degrees colder than post-1850 averages and snowfall was somewhat greater. From the late 19th century to today there has been a general warming of a few degrees Fahrenheit, making the dry climate even more attractive to residents and visitors (Scurlock, 1998).

When the first Hispanics reached the middle Rio Grande in 1540, the valley ecosystem had been impacted relatively little by human activity. Perhaps some 25,000 acres of floodplain had been cleared by the pueblos for cultivation, primarily irrigated by bank overflow or runoff from tributary streams or arroyos. Wing diversion dams and irrigation ditches were probably rare. This ecosystem was one of dynamic equilibrium driven by a collection of environmental processes, including floods, associated shifting channels, erosion, and deposition of sediments. Riparian vegetation evolved and changed with the floods, deposition, and low flow caused by seasonal or more extended dry periods. In the 1600s, an extensive stand of cottonwoods stretched from Alameda Pueblo to Albuquerque on the east side of the river, and remained a prominent feature in the valley until at least the early 1700s. South of this forest were open wetlands in a mosaic of cienegas (marshes), charcos (ponds), and esteros (swamps). A high water table and periodic flooding sustained these riparian features. Prehistoric and early historic archaeologic evidence of large fish species, such as the longnose gar and shovelnose sturgeon, indicates that the Rio Grande "was a clearer, larger, and more stable stream than it is known to have been during the past century" (Gehlbach and Miller, 1961). Extinction of these species is presumably due to historic reduction in the river's flow, increases in sediment load, and rise in water tempertures.

Historic flows of basin springs were generally perennial, except for those periods of severe, extended drought. Flow levels were also seasonal, as they are today, with greatest flows in the late spring during runoff from snowmelt, or in mid to late summer from rain runoff. Low runoffs usually occurred in June and October-November. During high flows the river would sometimes shift from a higher channel to one of lower elevation on the valley floor, a process known as avulsion. Even during extended dry periods there probably was some flow, and relatively deep water holes in the streambed were maintained. A chronological reconstruction of the historical climate, floods, and droughts for the middle and upper Rio Grande, based on tree-ring and streamflow data, scientific weather records, and anecdotal observations (Scurlock, 1998), is summarized in Figure 1. Dendrochronology for the region is reasonably good, but there are few or no data for some locations. Weather data recorded by scientific instruments began in late 1849, but vary in reliability until late in the century. Streamflow records for regional rivers began in 1888, but most of the continuous records are from post-1900. Anecdotal data have been used to extend interpretations of scientific data, where those data are sparse or lacking. Hence, the most reliable reconstruction of the historical climate is from 1888 to the present.

Historic Floods

Historically, periodic floods impacted the valleys of the Rio Grande drainage until major flood control structures were constructed in the 20th century. A minimum of 78 moderate to major floods occurred in the middle valley between 1591 and 1942 (Fig. 1). Floods were caused by spring snow melt in April to June, by extended, regional summer rains (particularly following a heavy snow pack), and by intense local rainstorms between early July and the end of September. With European settlement, recording of adverse impacts due to severe flooding began, and a number of floods are documented during the Colonial and Mexican periods (1598–1846). Severe to major floods occurred in 1680, 1735, 1760, 1769, 1780, 1814, 1823, 1828, and 1830. The 1828 flood was a mega event, with an estimated flow of 100,000 cfs. The entire valley was inundated from Albuquerque to El Paso. Major floods commonly caused shifts in the course of the river. A westward shift of various reaches of the Rio Grande from San Felipe to south of Belen in the early 1700s to about 1769 is well documented.

With the arrival of the first Anglo–Americans in 1846, use of the middle and upper Rio Grande drainage intensified. Clearing of upland forests, grazing, and more sophisticated farming contributed to increased runoffs with associated problems. Some 50 floods have been recorded for the main stem of the river from 1849 to 1942. Major to moderate floods of 10,000 cfs are documented in the middle valley in 1849, 1852, 1854, 1855, 1862, 1865, 1866, 1867, 1868, 1871, 1872, 1874, 1878, 1880, 1881, 1882, 1884 (two), 1885, 1886 (two), 1888, 1889, 1890, 1891, 1895, 1896, 1897 (two), 1902, 1903, 1904, 1905 (two), 1906, 1909, 1911 (two), 1912, 1916, 1920, 1921, 1924, 1929, 1937, 1940, 1941, and 1942. Floods of this magnitude occurred on an average of every 1.9 years during this period. Among the greatest floods of the period were the 1872 and 1884 spring floods, which crested at an estimated 100,000 cfs.

Following the devastating floods of 1902–1921, the Middle Rio Grande Conservancy District was created by the legislature in 1923, in part to control flooding. The Army Corps of Engineers and the U.S. Bureau of Reclamation were also involved in flood control. Dams, levees, drainage canals, and other water control works were constructed by these agencies. Major flood control dams constructed by the corps include El Vado (1936), Jemez Canyon (1953), Abiquiu (1963), Galisteo (1970), and Cochiti (1975). With the completion of Cochiti Dam, the threat of flooding in the Albuquerque area virtually ended (Scurlock, 1998).

Historic Droughts

Droughts perhaps have been the single most significant "natural" climatic event adversely affecting historic human population in the Southwest. Historic documentary data and archaeological evidence, including tree-ring data, show that periodic droughts of varying magnitude have impacted past human activity and other environmental components. At least 52 droughts lasting 1 year or more, totaling about 238 years, occurred in the middle Rio Grande basin in the historic period (last 448 years; Fig. 1). Droughts have had a mean occurrence of 8.6 years and a mean length of 4.6 years. Some of the more important effects of droughts have been decrease or loss of water sources, diminishment of indigenous and cultivated

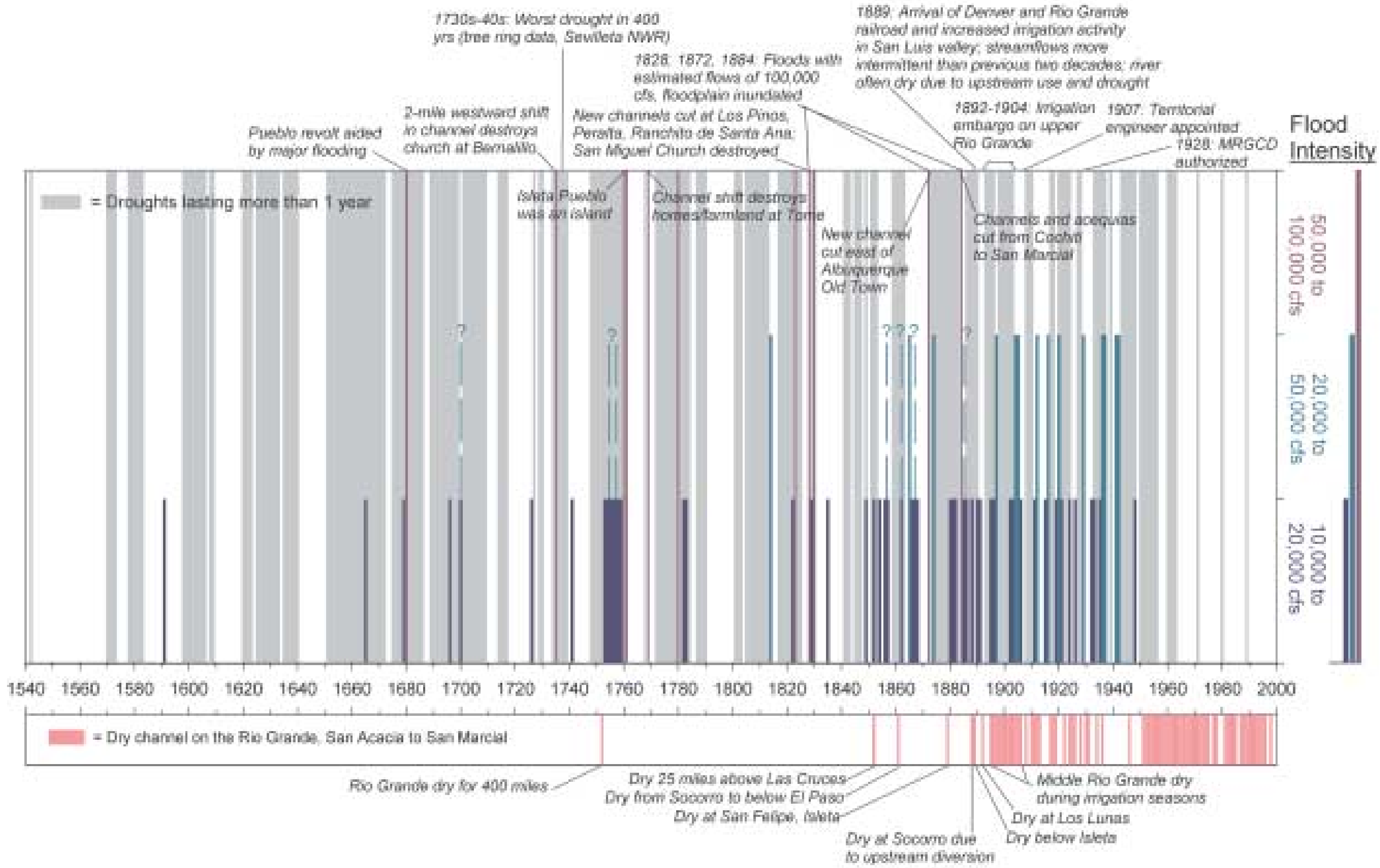

FIGURE 1—Historic floods and droughts on the middle Rio Grande, 1542–1990.

food plants, decrease in native fauna, and loss of domesticated animals. The extent and significance of droughts generally varied over the region. A given location might be less impacted than another due to more reliable sources of surface or ground waters. For example, sufficient irrigation water was sometimes available along the drought-stricken middle Rio Grande when the mountains in the upper watershed had a normal or above-normal snowpack. As can be seen in Figure 1, it was not unusual for the middle valley to experience droughts and floods in the same year (Scurlock, 1998).

Archaeological evidence and historical records reveal a relatively long succession of alternating periods of below-normal and above-normal precipitation, which are usually accompanied by warmer and cooler temperatures. During droughts, these above-normal temperatures contribute to adverse impacts. Extended, severe regional droughts have an average duration of 10–13 years and occur every 22–25 years (Thomas, 1963). Less severe and more localized droughts appear to occur more randomly and for shorter periods. Wet or strong El Niño years may have occurred every 9.9 years (Quinn et al., 1987). Tree-ring and historical evidence indicate that the most severe droughts occurred in 1578–89, 1598–1606, 1630s, 1663–1670, 1682–1690, 1734–1739, 1748–1759, 1772–1782, 1841–1855, 1895–1904, 1931–1940, and 1952–1964 (Bark, 1978; D'Arrigo and Jacoby, 1992; Fritts, 1991) (Fig. 1). With rapid population growth in the middle Rio Grande basin, drought increasingly poses a serious threat to human economic activities such as farming, ranching, recreation, and tourism.

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Downstream Effects of Dams on the Middle Rio Grande

by *Drew C. Baird,* P.E., U.S. Bureau of Reclamation

The middle Rio Grande has long been recognized for its striking characteristics and landscapes. Surrounding desert lands, large snowpacks, and summer thunderstorms produce wide ranges of water and sediment flows in the river. As the ancestral middle Rio Grande flowed from the mountains to the flatter middle valley, sediment was deposited resulting in river bed aggradation (build-up of the river bed by sediment accumulation). This ancestral river occupied a relatively wide, aggrading channel with a shifting sand bed and shallow banks. The channel pattern was braided, relatively straight, or slightly sinuous (Crawford et al., 1993). It is estimated that the middle Rio Grande valley in New Mexico (from the mouth of White Rock Canyon to the narrows of Elephant Butte Reservoir) has been aggrading for the last 11,000 to 22,000 years (Leopold et al., 1964; Hawley et al., 1976). Thus the river system is not in a state of dynamic equilibrium. The maximum degradation (lowering of a river bed due to sediment removal) is believed to have occurred about 22,000 years ago, when the Rio Grande was about 60–130 ft below the current valley floor. Since then, the middle Rio Grande has been slowly aggrading because tributary inflows contribute more sediment than the river can remove (Crawford et al., 1993).

A modern era of control began in the mid-1900s when the Middle Rio Grande Conservancy District constructed non-engineered spoil levees parallel to the river. Because of high flows and continuing aggradation, assistance was sought from the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers. The two agencies set out to accomplish the assignment through a variety of means including the construction of large dams and channel rectification to control floods and sedimentation. The channel has since narrowed and degraded resulting in a more stable channel that does not shift across the existing floodplain. However, these changes have also contributed to the declining populations of native fish and terrestrial species resulting in the Rio Grande silvery minnow and southwestern willow flycatcher being listed as endangered species. Current emphasis is being placed on understanding the recent geomorphic and hydraulic changes, their respective effects on the endangered species, and developing action plans that will restore more suitable habitat while still meeting water delivery obligations and protecting important riverside facilities.

Geomorphology

Hydrology and Sediment—Water and sediment flows in the Rio Grande have changed dramatically in the last century, affecting the shape and pattern of the river. Historic annual flows have varied significantly due to changes in weather patterns, river development, and management practices. At the San Marcial gage south of Socorro, annual flows between 1896 and 1945 averaged about 1,100,000 acre-ft, between 1946 and 1978 about 570,000 acre-ft, and during the particularly wet years from 1979 to 1993 again averaged about 1,100,000 acre-feet. Annual peak flows have steadily declined since the first discharge measurements in 1896 from a range of about 20,000–30,000 cubic feet per second (cfs) down to less than 10,000 cfs. Since 1975, typical spring runoff peaks have been reduced by control at Cochiti Reservoir by about 2,500 cfs. Reduced sediment loads have accompanied this reduction in annual and peak flows. The reduction in sediment load at four gages on the middle Rio Grande is shown in Table 1.

Channel Response—For most changes in a river system that involve a change in discharge and type or amount of sediment load, the river channel will respond by adjusting its shape, width, and depth. The historic changes in hydrology and sediment load in the middle Rio Grande have initiated a channel response similar to the qualitative model developed by Schumm (1977):

$$Q^-, Q_{sb}^- \longrightarrow w^-, d^\pm, (w/d)^-$$

where

Q = water discharge (for example mean annual flood),

Q_{sb} = bed material load (expressed as a percentage of total load),

w = channel width,

d = channel depth,

w/d = width/depth ratio, and

– and + superscripts indicate a reduction or increase in each parameter.

This equation shows that with a decrease in water and bed material load, the channel width and width/depth ratio decrease as well. The depth may increase or decrease depending upon the relative magnitude of the changes in Q and Q_{sb}. In the case of the Rio Grande, channel depth increases indicate that the decrease in the bed material load has a greater influence on the depth than does the reduction in discharge. The width narrowing trends for specific reaches of the Rio Grande are shown in Table 2, and Table 3 shows trends of increasing depth and velocity.

In many reaches, the river has not yet reached a new dynamic equilibrium condition, the bed elevation is still lowering, and the channel is continuing to narrow. Table 4 and Figure 1 show the amount by which the average bed elevation has lowered.

The bed material size in the Rio Grande has also changed over time. The Angostura to Bernalillo reach was historically sand and is now a gravel-bedded channel, the Rio Puerco to San Acacia reach is now a partially gravel-bedded channel as is the San Acacia to Escondida reach. It is estimated that in the San Acacia to Escondida reach the bed will be entirely gravel in about 3 years.

Management and Land Use Influences—Several other factors have affected the river channel hydraulic geometry by altering discharge and sediment supply. During the period of the late 1800s and early 1900s, overgrazing in the watershed likely

TABLE 1—Sediment load changes on the middle Rio Grande.

Gage location	Period of record	Average sediment concentration (mg/L)	% of historic sediment supply
Albuquerque	1970–1974	3,750	
	1974–1996	580	15%
Bernardo	1965–1977	2,760	
	1977–1996	740	37%
San Acacia	1946–1978	13,300	
	1978–1997	2,600	20%
San Marcial	1925–1974	12,100	
	1974–1997	3,800	32%

TABLE 2—Width changes on the middle Rio Grande.

Rio Grande reach	Period of record	Reach-average width (ft)	% of historic width
Cochiti to	1918	850	
Angostura	1962	400	
	1992	250	29%
Angostura to	1972	1,150	
Bernalillo	1995	400	35%
Rio Puerco to	1918	1,750	
San Acacia	1962	700	
	1992	400	23%
San Acacia to	1918	1,600	
San Marcial	1962	500	
	1992	425	27%

TABLE 3—Depth and velocity changes on the middle Rio Grande.

Rio Grande reach	Period of record	Reach-average depth (ft)	% depth increase	Reach-average velocity (ft/s)	% velocity increase
Angostura to	1962–1971	1.6		3.2	
Bernalillo	1999	3.6	125%	4.3	34%
Rio Puerco to	1962	2.5		3.7	
San Acacia	1992	3.6	45%	4.5	22%
San Acacia to	1962	2.0		3.7	
Escondida	1992	4.0	100%	4.5	22%

TABLE 4—Average bed elevations on the middle Rio Grande.

Rio Grande reach	Period of record	Average bed elevation lowering (ft)
Angostura to Bernalillo	1971–1995	7.3
Rio Puerco to San Acacia	1962–1992	3
San Acacia to Escondida	1962–1999	9.6

increased the sediment supply. During this same period extensive water diversions in the San Luis Basin near Alamosa, Colorado, reduced discharge. These water diversions coupled with increased sediment supply may have contributed to widening of the channel during the early 1900s. Large floods during the early part of this century also contributed to the large channel width. During the mid-1900s, channelization activities that included construction of large Kelner jetty fields and levees in the reach from San Acacia to San Marcial also contributed to the channel narrowing during the pre-1962 period. However, since 1962 the dramatic changes observed along the middle Rio Grande are due to lower flood peaks and lower sediment loads as a result of upstream reservoir construction accompanied by reduced sediment delivery in the entire basin.

Conclusions

During the last century, the middle Rio Grande has been reduced to from 23% to 35% of its historical width, has been increased from 45% to 125% in depth, and has changed its channel pattern from relatively straight to meandering. Many reaches, which were previously sand bedded are now gravel bedded. Many of these changes were goals of the Middle Rio Grande Project as authorized by Congress in 1948 and 1950. From an engineering perspective the project has been successful. However, the channel changes have contributed to the decline in the number of aquatic species, to the listing of the silvery minnow as an endangered species, and to a decline in the stability of the fluvial system.

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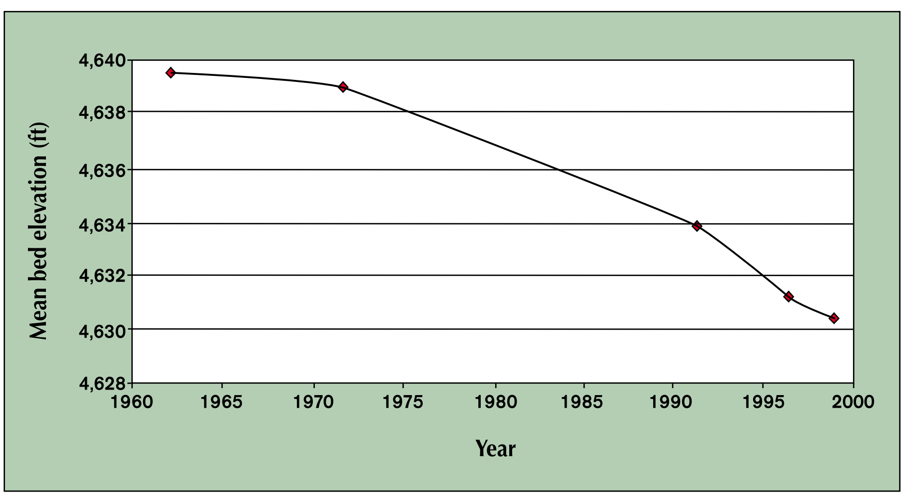

FIGURE 1—Lowering of the river bed elevation between San Acacia and Escondida on the middle Rio Grande, a total of 9.6 ft since 1962, has been most dramatic following upstream reservoir construction in the early 1970s.

Santa Ana River Rehabilitation Project along the Middle Rio Grande

by *Drew C. Baird,* P.E., U.S. Bureau of Reclamation

Historically, the middle Rio Grande (a 285-mi reach between Velarde, New Mexico, and the narrows near Elephant Butte Reservoir) has been a braided, relatively straight or slightly sinuous, aggrading channel with a shifting sand substrate and low banks. During the last 40 years, river rectification works have been constructed to improve water and sediment conveyance. More recently, the construction of Cochiti Dam (located approximately 47 mi upstream of Albuquerque, New Mexico) in 1973 has reduced downstream peak flows and trapped sediment (Baird, Downstream Effects of Dams on the Middle Rio Grande, this volume). These impacts on the fluvial system have altered the processes controlling water and sediment transport. The altered sediment and flow regimes have resulted in a transformation from a wide, braided sand-bed system to a single channel, incised gravel-bed system throughout much of the middle Rio Grande. The following changes in reach-average morphologic and hydraulic characteristics summarize the channel transformation through the 6-mi Santa Ana reach of the Rio Grande (located approximately 21 mi upstream of Albuquerque, New Mexico) between 1971 and 1998: (1) channel slope has decreased from 0.002 to 0.00090, (2) channel top width has decreased from 1,150 to 330 ft, (3) average channel depth has increased from 1.6 to 3.7 ft, (4) width/depth ratio has decreased from 710 to 90, (5) channel flow velocities have increased from 3.2 to 4.2 ft/sec, and (5) mean bed material size has increased from 0.3 mm (fine sand) to >20 mm (coarse gravel).

In its current state, the Santa Ana reach of the Rio Grande is an entrenched, slightly meandering, gravel-dominated, riffle/pool channel without a well-developed floodplain. The historic floodplain and much of the historic channel bed throughout the Santa Ana reach is no longer connected with the river hydrology. Since completion of Cochiti Dam, none of the flows passing through this reach have risen above the top banks of the current incised channel.

The channel incision has degraded the native aquatic and terrestrial ecosystems, including the reduction of habitat available for two endangered species, the Rio Grande silvery minnow (*Hybognathus amarus*) and the southwestern willow flycatcher (*Empidonax trailii extimus*). Juvenile and adult minnows require habitats having moderate water depths (0.5–1.3 ft), low water velocities (0.1–0.3 ft/sec), and silt-sand substrates (Dudley and Platania, 1997). The minnow generally is not associated with habitats having gravel or cobble substrates, strong currents, and narrow channels, characteristics similar to those existing in the incised channel throughout the Santa Ana reach. Suitable flycatcher habitat is generally associated with mature cottonwood stands with some willow plants in a dense understory and/or mid-aged and young stands of dense riparian shrubs at least 15 ft high and at least partially composed of willows (Ahlers and White, 1999). Little to no native riparian vegetation, including willow and cottonwood, exists along the steepened channel banks or on the abandoned floodplain of the Rio Grande throughout the Santa Ana reach.

The Rio Grande Restoration Project at Santa Ana was initiated to address the bed and bank erosion threatening riverside facilities and the degradation and loss of native habitats and ecosystems found throughout the Pueblo of Santa Ana. The project has developed into a reach-wide channel stabilization and rehabilitation effort. The rehabilitation of riverine habitats favorable to the minnow and development of a riparian bosque connected to the river's hydrology are primary objectives. Meeting these objectives also would protect riverside facilities and would allow natural fluvial processes to shape the system.

The project will ultimately encompass approximately 7,500 ft of the Rio Grande. The project realigns the channel, moving flows away from threatened riverside facilities. The project design includes many features that address the loss of habitat favorable to the minnow and flycatcher. These features include the design of a gradient restoration facility (GRF) with a fish passage apron, floodplain development, and extensive planting of native vegetation. This paper describes these features and the benefits to the minnow and flycatcher.

Gradient Restoration Facility

Installation of the GRF will halt continued channel incision, reduce upstream velocities, and raise the upstream water surface elevation. The design will allow the minnow to pass over the structure. However, because little physiological data are available for the minnow, available design criteria are limited. Because it is known that minnows pass through existing riffles (steep areas in the river), the GRF apron was designed to mimic the hydraulic characteristics of these riffles. The apron will be about 2 ft high with a 500-ft long mild slope, will extend completely across the channel, and have recessed areas to provide varied flow conditions. Excavated river gravels will be placed on top of the GRF riprap to fill interstitial spaces and increase similarity with the existing channel substrate. A profile of the GRF is shown in Figure 1.

The placement of the GRF not only halts future channel degradation, it creates an upstream slow water area or backwater. This backwater will result in increased sediment deposition, reduced velocities, shallower depths, and increased water surface elevations, flow conditions believed to be more favorable to the minnow and the riparian habitat.

Channel Realignment

Using various river characterization and classification methods, it was concluded that the current river and ecosystem would continue to decline if no work were done. The river would continue to narrow to a top width of approximately 250 ft, and degrade for several more feet.

Future river regimes were analyzed to approximate a future stable river at a top width of about 350–400 ft, and a shallower channel depth with velocities nearly 50% of the existing veloc-

GRF centerline cross section *(longitudinal)*

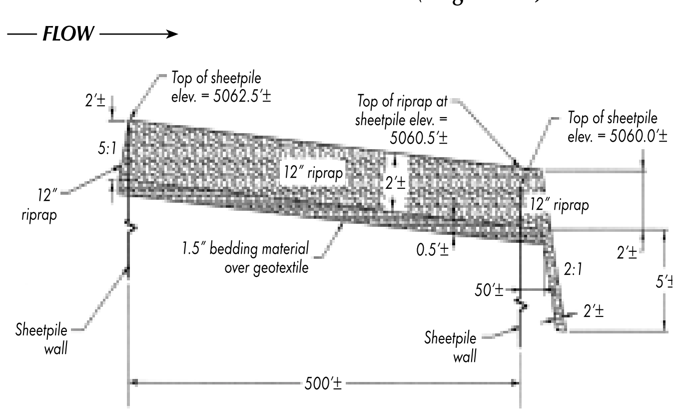

FIGURE 1—Profile of the gradient restoration facility.

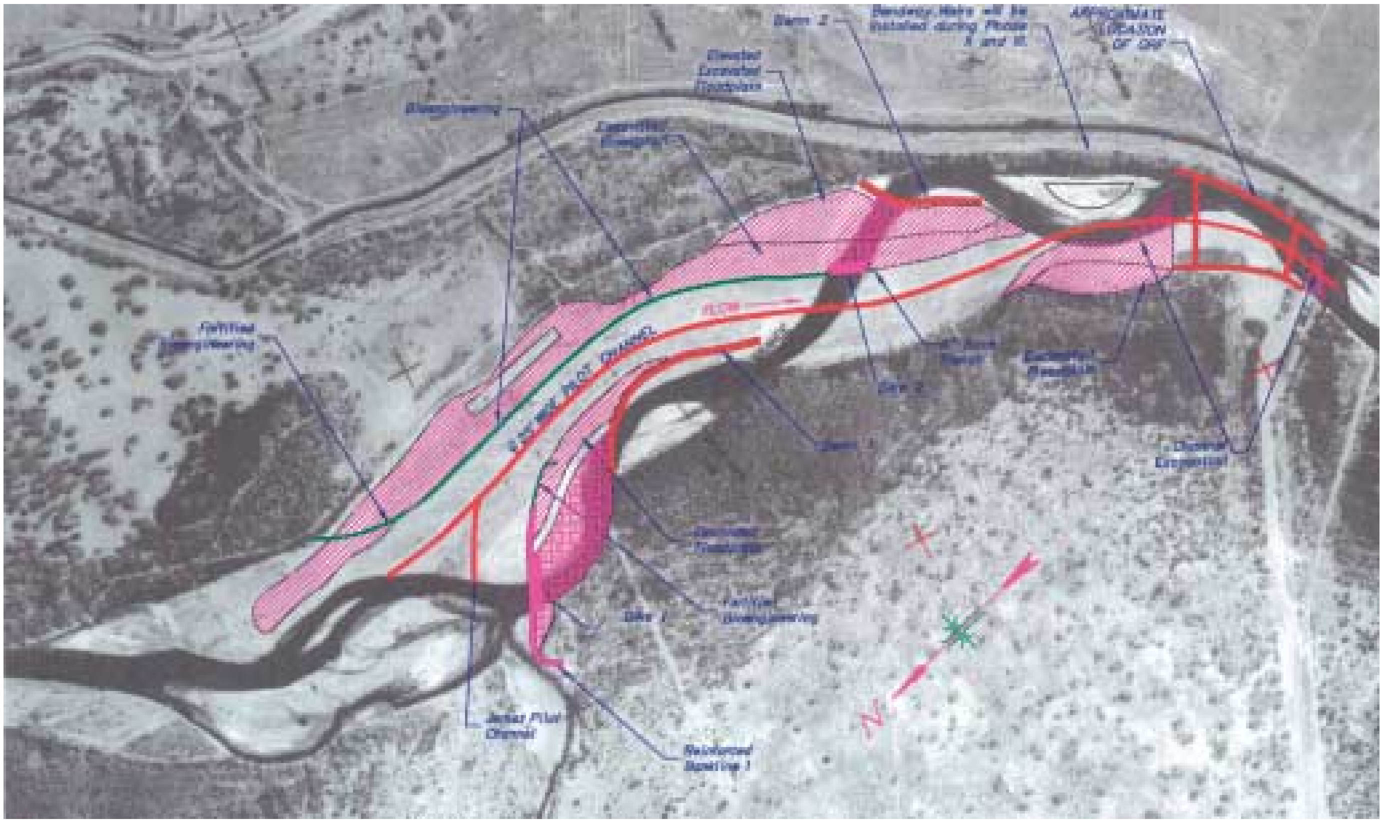

FIGURE 2—Realigned channel design.

ities. The river length in the realigned reach was kept relatively close to the present-day length because historically this stretch of the river has been slightly sinuous. The realigned channel design is shown in Figure 2.

Floodplain Development and Terrestrial Re-vegetation

In addition to realigning the channel, a floodplain will be excavated at an elevation that will be inundated at the channel-forming discharge of approximately 5,000 cfs. The floodplain excavation will provide approximately 45 acres of potential riparian area and flycatcher habitat (Fig. 2). The floodplain elevation will vary from 2 to 6 ft above the low ground-water elevation to provide depths to the water table that are adequate for survival of the various vegetative species to be planted. Various floodplain characteristics will be developed by gently sloping the ground surface, developing terraces, and providing individual areas of higher ground.

Twenty percent of the floodplain will be planted with cottonwood and blackwillow poles on approximate 50-ft spacing. The remaining 80% of the floodplain will be planted with coyote willow and containerized New Mexico olive and bacharris shrubs. The willows will be planted in bunches of approximately 10 whips at 20-ft spacings. The 1-gal containerized shrubs will also be planted on approximate 20-ft spacings. The actual planting layout will be determined in the field.

Two sections of the existing channel that are not incorporated into the new alignment will be developed as oxbow-type backwater areas. The downstream end of these backwaters will be connected to the active river channel. Ground water and the open lower end of the oxbows will provide water to these habitats. There will be no measurable flow through these backwaters. Both backwater areas will be densely planted with willows. Blackwillow and cottonwood poles will also be planted to achieve an overstory canopy in these areas.

Besides the backwater fringe vegetation, two densely vegetated patches of willows will be planted between the backwaters and the main channel. These 1-acre coyote willow patches are being established in the floodplain to provide variability in the terrestrial vegetation and to increase potential flycatcher nesting habitat. Flexibility with the vegetation design and planting schedule is essential. Adaptive management will be used to decide vegetation planting locations, timing, and extent of planting and to perform terracing.

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The Upper Rio Grande Water Operations Model—A Management Tool

by *Dick Kreiner*, U.S. Army Corps of Engineers

The Upper Rio Grande Water Operations Model (URGWOM) is a daily time-step water operations model for the upper Rio Grande basin utilizing a numerical computer modeling software known as RiverWare (Fig. 1). URGWOM is capable of simulating the hydrology, water storage, and delivery operations in the Rio Grande from its headwaters in Colorado to Elephant Butte Reservoir in New Mexico as well as flood control modeling between Elephant Butte Dam and Fort Quitman, Texas. The model will be used in flood control operations, water accounting, and evaluation of water operations alternatives.

The plan to develop a unified water operations model for the upper Rio Grande basin originated in late 1995 and early 1996 when federal agencies initiated discussions with stakeholders in the basin regarding a need for a water operations model. As a result of these discussions, six federal agencies—U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, U.S. Geological Survey, U.S. Bureau of Indian Affairs, U.S. Army Corps of Engineers, and the U.S. Section of the International Boundary and Water Commission—signed the *Memorandum of understanding (MOU) for the development of an upper Rio Grande water operations model for enhanced system management* (MOU, 1996). In 1997, the MOU was additionally signed by the cities of Santa Fe and Albuquerque, Sandia and Los Alamos National Laboratory, and Rio Grande Restoration. However, many agencies and entities have contributed to model development through data contributions, technical review, and other technical support from the beginning Plan of Study in 1997, through the Rio Chama test case in 1998, to the current backbone model that is being tested and documented.

URGWOM is a tool for water managers to reliably simulate the hydrology of the Rio Grande stream system, the operation of the reservoirs located within the basin, and the accounting of water. URGWOM is actually composed of four distinct models (Fig. 2). The accounting model represents the complete physical system and is designed to solve for reservoir inflows, given outflows, water elevations, weather, and other reservoir data. It deals strictly with the past, calculating all flows and storages through midnight of the previous day. The water operations model is the forecasting version of the accounting model. It uses updated historic data from the accounting model, along with other short-term forecast data to predict flows and storages for the future. It uses rules, as needed, to determine outflows. The forecasting model takes monthly spring runoff forecasts and uses historic inflow hydrographs (volume of water over time) to create daily forecast hydrographs for each of the inflow points in the water operations model. The planning model is designed to carry out long-term forecasts using less detailed data and rules. Water managers can use URGWOM on a daily basis. It will help them decide what releases to make on which reservoirs for the day, taking in consideration current and forecasted weather conditions. URGWOM also can be used as a tool to evaluate the impacts of changing water operations under different scenarios such as in the Upper Rio Grande Basin Water Operations Review and Programmatic Environmental Impact Statement.

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MOU (Memorandum of understanding for development of an upper Rio Grande water operations model for enhanced system management), 1996.

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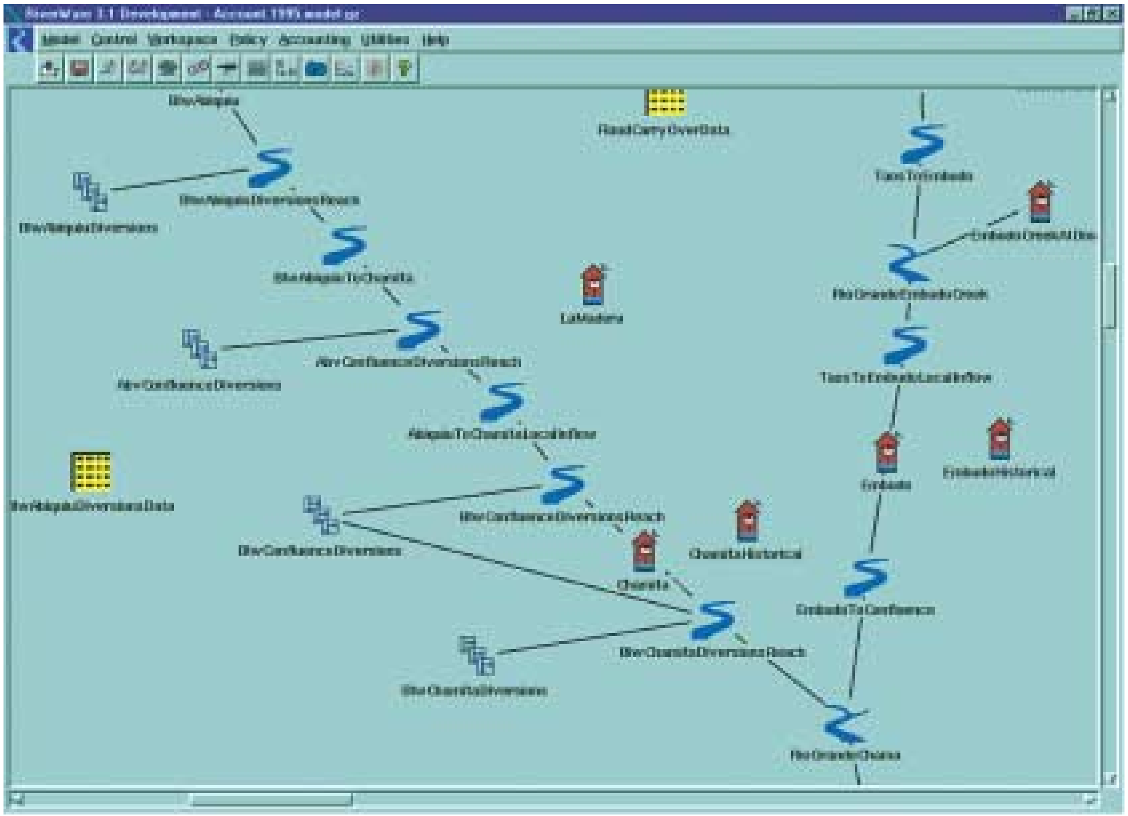


FIGURE 1—Example of RiverWare layout for the confluence of the Rio Chama with the Rio Grande.

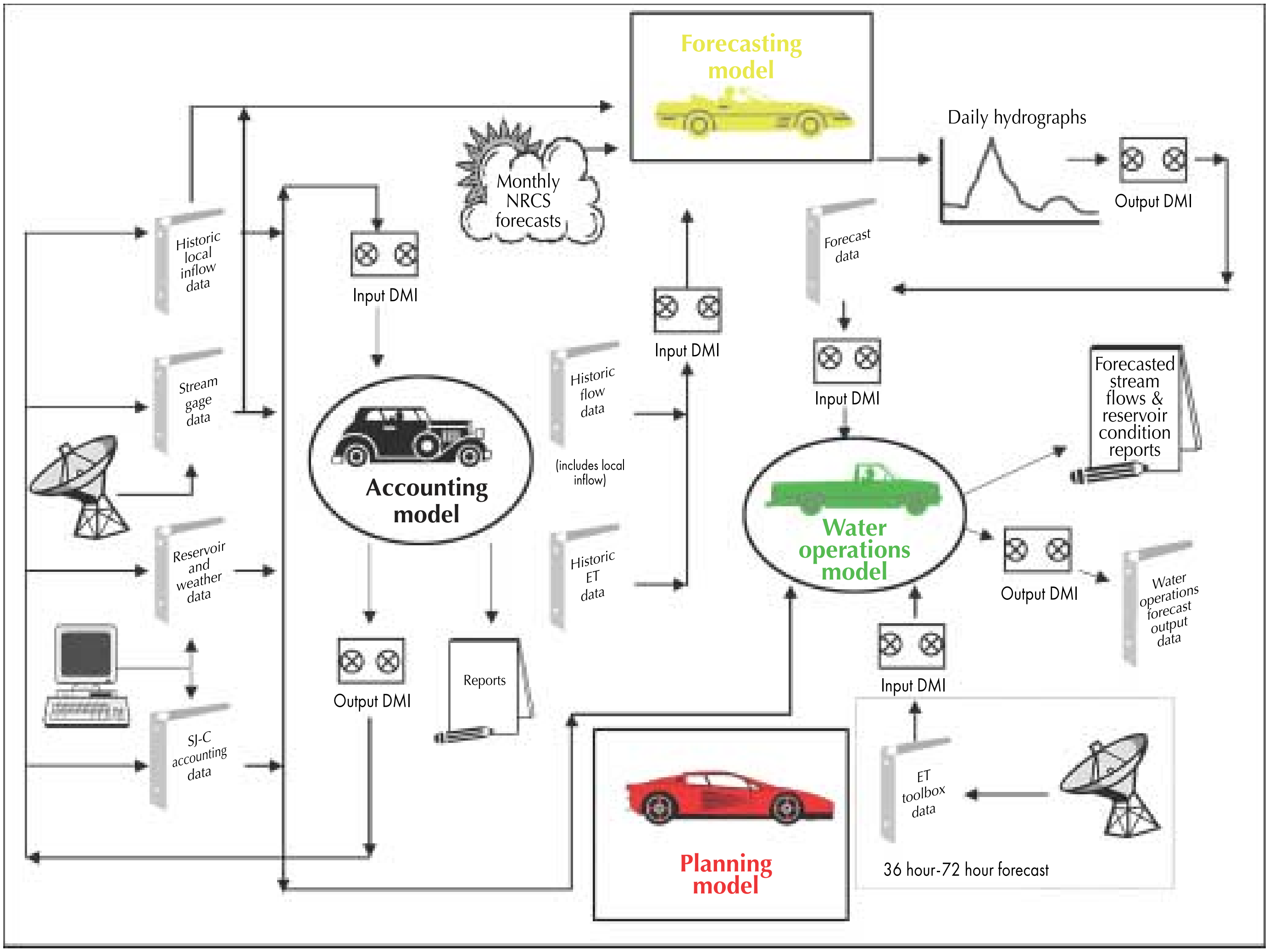


FIGURE 2—The set of four models that make up URGWOM, their input, and output.

Probabilistic Water Budget for the Middle Rio Grande

by *Deborah L. Hathaway*, S. S. Papadopulos & Associates, Inc.

A water budget is similar in concept to a financial budget: water inflow (supply) equates with income, water use (demand) equates with expenditures, and water stored equates with savings. The Middle Rio Grande Water Supply Study (MRGWSS; S. S. Papadopulos & Associates, 2000) developed a quantitative and probabilistic description of a water budget for the Middle Rio Grande Region. From this evaluation, and using the financial analogy, a profile of the middle Rio Grande water budget emerges.

Financial Profile of Mr. and Mrs. MRG Basin

Occupation	Day traders
Income	Substantial, but highly variable
Savings	A modest amount
Other income	Small annuity (gift from uncle)
Available credit	Excellent—100 year loan, escalating payments
Spending Habits	Growing
Debt	Growing
Recommendations	***See a counselor!***

Favorable conditions throughout much of the 1990s allowed Mr. and Mrs. MRG Basin to live reasonably well. A strong market (above-average water supply), annuity proceeds (San Juan–Chama water), and delayed impacts of borrowed resources (ground water) supported their spending habits (expanding municipal and industrial, agricultural, and riparian uses); while, obligations (the Rio Grande Compact) were met. One year, 1996, brought less favorable conditions, with dry reaches occurring in the Rio Grande—a reminder that wet periods don't persist. More recently, in 2000, Mr. and Mrs. MRG Basin tapped savings in upstream reservoirs to supply water for the silvery minnow. Ultimately, water management is a budgeting question—in leaner times, hard choices will be required.

The water supply of the middle Rio Grande is characterized by variability and limitation. Variability is exhibited in the historic record of inflow, including the Rio Grande mainstream inflow at the Otowi gage and tributary inflows below Otowi. The mean inflow at the Otowi gage in the past 50 years is on the order of 1.0 million acre-ft/yr, but values throughout the range of 0.5–1.5 million acre-ft/yr are not uncommon. Limitation on the water supply is a function of both physical and legal constraints. Physically, inflow is limited by climatic conditions. Legal limitations include the Rio Grande Compact obligation to deliver a portion of inflow to users below Elephant Butte and New Mexico statutes governing water rights.

The Middle Rio Grande Region's share of the water inflow at the Otowi gage is illustrated in Figure 1. This quantity, shown for the time period 1950–1998, is derived by subtracting the Rio Grande Compact obligation from the total gage inflow for each year (see also New Mexico Interstate Stream Commission, The Rio Grande Compact in New Mexico and the San Juan–Chama Project, this volume). The portion of this net inflow comprised of San Juan-Chama Project water is also shown. This figure depicts the variability in the Middle Rio Grande Region's share of inflow, with annual values typically ranging between about 200,000 and 500,000 acre-ft/yr.

The supply of surface water available to the Middle Rio Grande Region includes the portion of Otowi inflow as shown in Figure 1 and tributary inflow from the Santa Fe River, Galisteo Creek, the Jemez River, the Rio Puerco, the Rio Salado, numerous ungaged tributaries, and urban storm water run-off. These tributary inflows are estimated to average about 130,000 acre-ft/yr. However, tributary inflow exhibits a high degree of variability, as illustrated in Figure 2 for one of the tributaries, the Rio Puerco.

As part of the MRGWSS, a probabilistic analysis of the middle Rio Grande water supply was performed. This analysis provided a means of describing the combined variability of multiple inflow sources to the water supply. Figure 3 illustrates the probability distribution for the Middle Rio Grande Region's share of the surface water supply. This figure shows the probability, or chance, that the surface water supply will fall into a particular range in any given year. (Inflows from or outflows to ground water are not reflected in this illustration.)

The limited supply of water from the Rio Grande is apportioned among multiple uses. Figure 4 provides a pie chart indicating the relative magnitude of various water use categories in the Middle Rio Grande Region drawing from surface and ground water. The values shown here represent mean or average values. Variability occurs in the water use terms, particularly in the value for reservoir evaporation. As shown, crop and riparian evapotranspiration are each of similar magnitude; together, they represent approximately two-thirds of the water use in the basin. Reservoir evaporation (primarily, from Elephant Butte Reservoir) represents another significant component of the water budget for the Middle Rio Grande Region. This evaporation is considered part of the water budget for the middle Rio Grande because it is consumed geographically upstream from the delivery point under

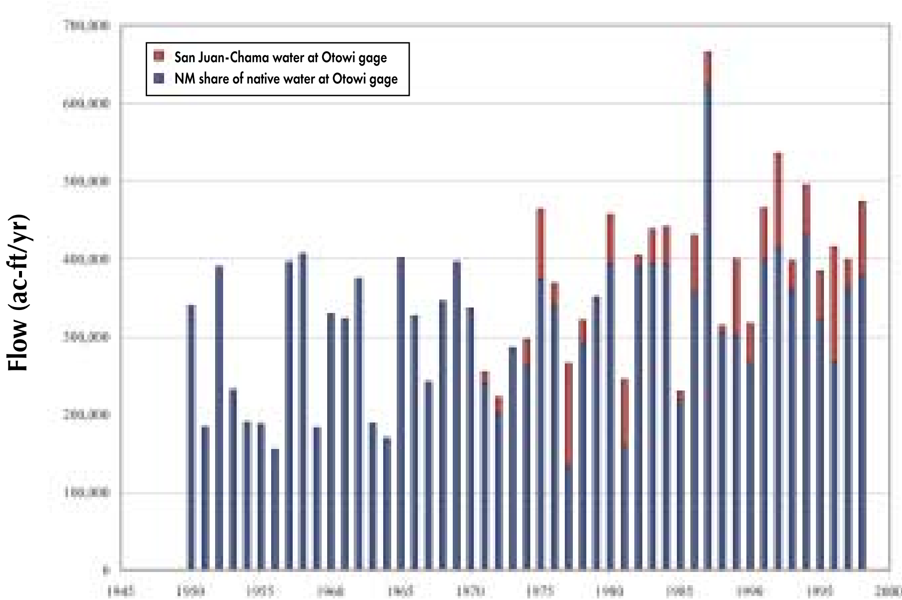


FIGURE 1—New Mexico's share of water supply at Otowi gage, 1950–1998.

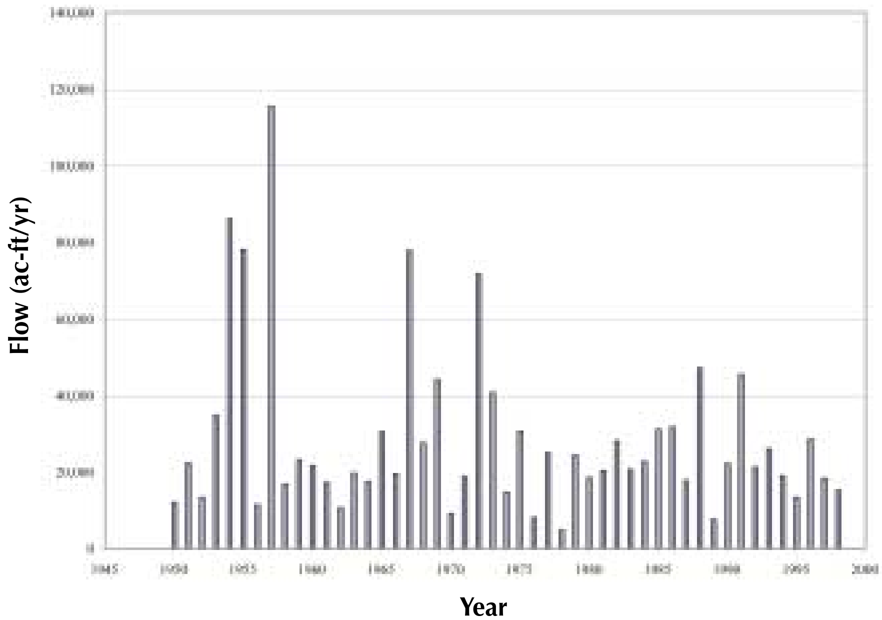


FIGURE 2—Rio Puerco tributary inflow, 1950–1998.

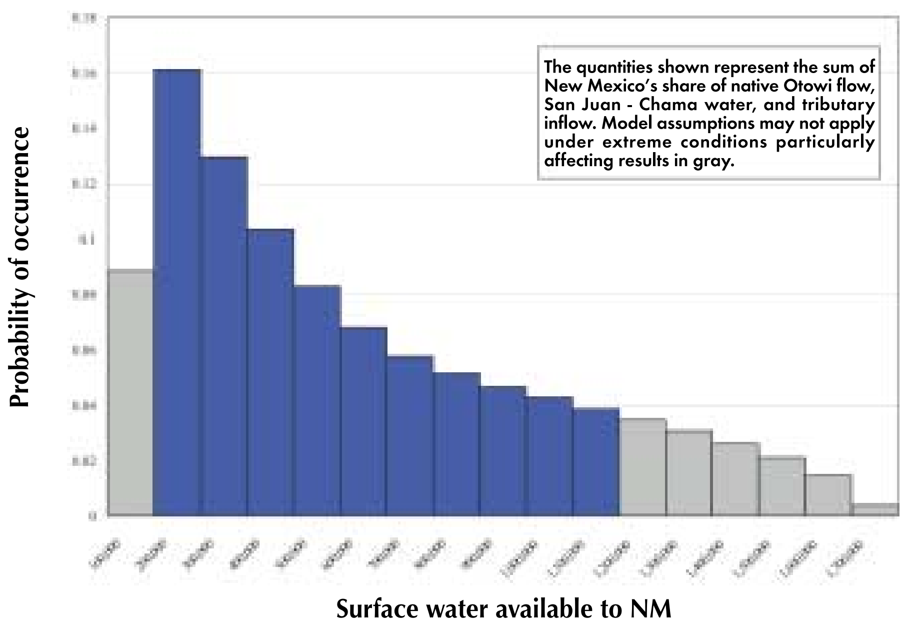


FIGURE 3—The middle Rio Grande share of surface water supply: probability distribution.

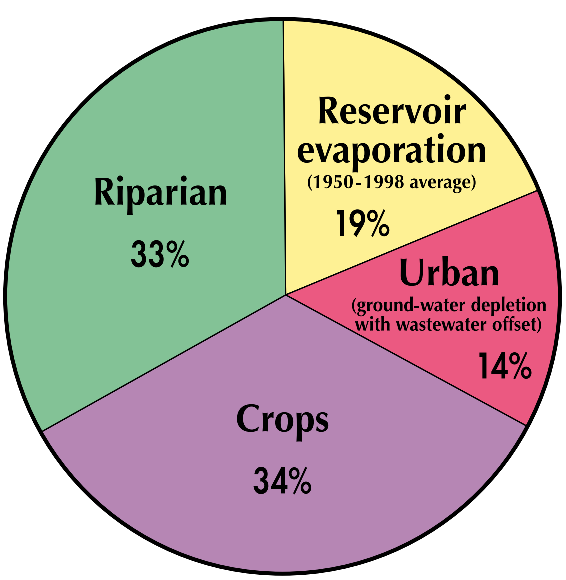
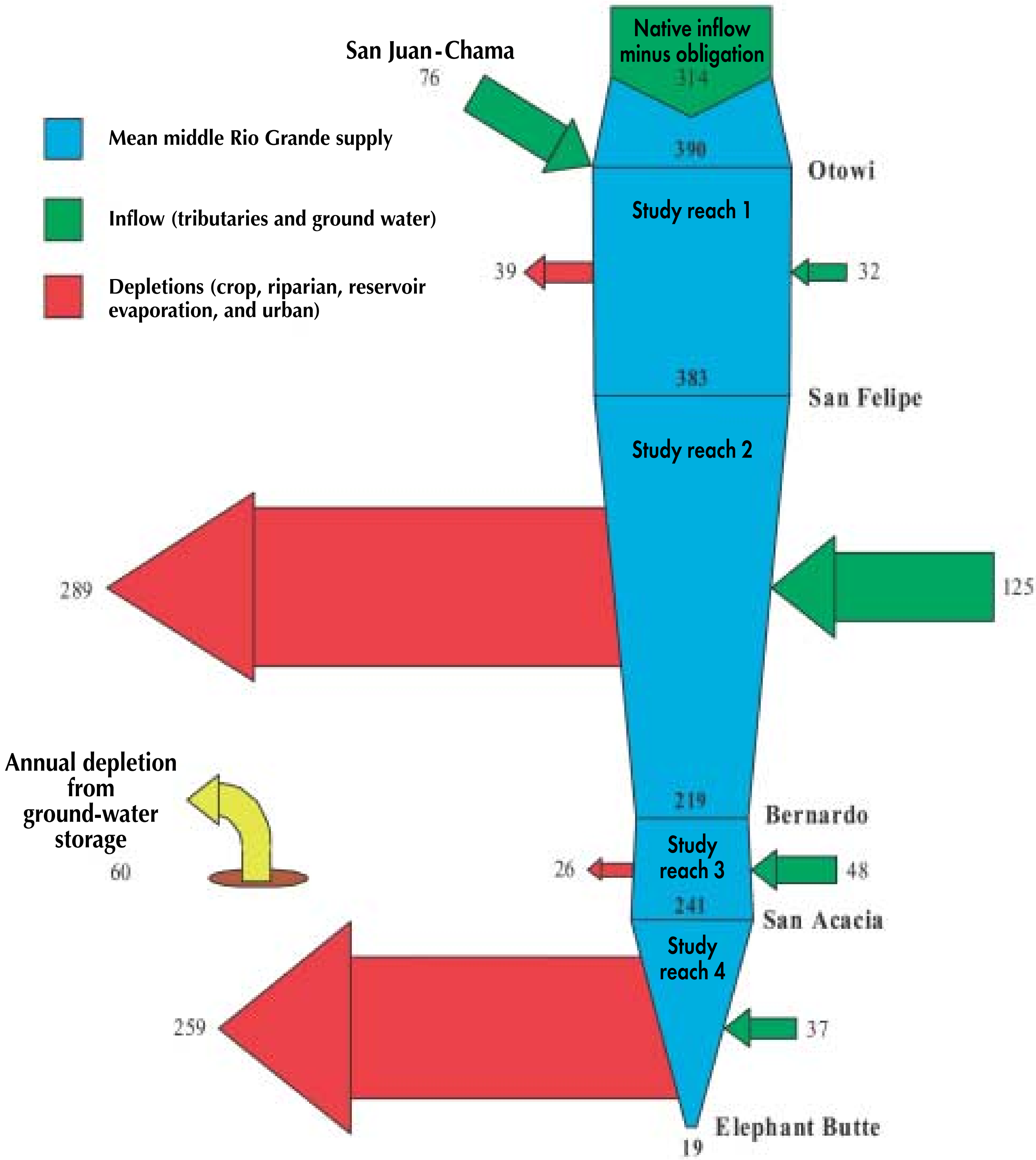


FIGURE 4—Summary of mean depletions.



Assumptions

- Present development conditions for ground-water pumping, irrigation, and riparian uses
- Inflows based on mean value of risk model output, sampling from probability functions incorporating climatic variability, 1950-1998
- Rio Grande native inflow and reach flows represent simulated flows minus mean Compact obligation derived from risk model output

FIGURE 5—Mean annual middle Rio Grande water budget under present conditions, excluding Elephant Butte scheduled delivery (in thousands of ac–ft).

the Rio Grande Compact. The percentage shown for urban use includes ground water—the impact of this use on surface water flow is delayed due to the distance of wells from the river. Ultimately, the effect of pumping ground water is diminished flow at the river.

The mean annual water budget of the Middle Rio Grande Region is depicted in Figure 5. This figure shows the mean available water supply at various points along the river system, after subtracting the compact obligation and the depletions resulting from water use. This budget is based on the probabilistic analysis conducted for the MRGWSS and includes ground-water exchanges. A risk analysis model was used to incorporate the variation in flow and identified dependency relationships among inflow or depletion terms. Given present uses, the available supply, including transmountain diversions and wastewater return flow, on average, is virtually consumed within the Middle Rio Grande Region.

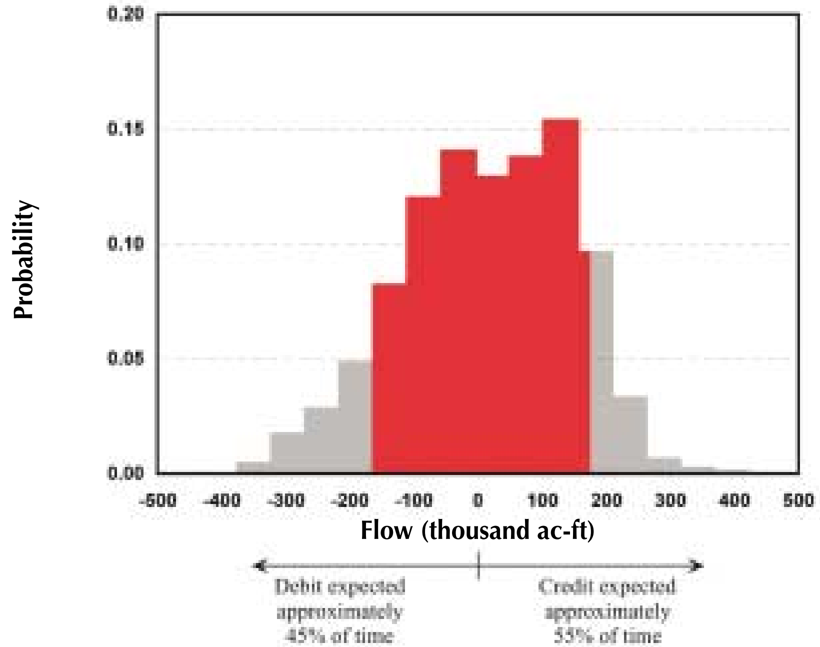


FIGURE 6—Rio Grande Compact credit-debit probability distribution, present development conditions, year 2000.

The variability in the water budget is reflected in Figure 6. This figure illustrates a probability that the credit or debit under the Rio Grande Compact will fall within a given range. Under the present water use conditions and the climatic variability represented in the past 50-year period, debits are expected to occur nearly as often as credits. A projection of present water use conditions into the future, when impacts of existing ground-water pumping are increasingly felt on the river, results in a shift of this balance towards a greater likelihood of debit conditions.

In summary, the water budget indicates that the water supply from the Rio Grande is barely adequate to meet present demands in the Middle Rio Grande Region. Under conditions of increased water use in any sector, a reduction of water use from other sectors will be required to maintain balance in the water budget. Planners are challenged to address increasing water demands with a highly variable and limited supply.

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Upper Rio Grande Basin Water Operations Review and Environmental Impact Statement

by *Norman Gaume*, P.E., New Mexico Interstate Stream Commission

This paper describes the Upper Rio Grande Water Operations Review and Environmental Impact Statement (Review and Water Operations EIS) and its importance to New Mexico. The description (see box) of the purpose, need, and scope of the Water Operations EIS is taken from the joint lead agencies' agreement to conduct the review and the notice of intent published in the March 7, 2000, Federal Register (http://www.uc.usbr.gov/ea_eis/abq/pdfs/riogr3_7.pdf) by the U.S. Bureau of Reclamation (BOR), the U.S. Army Corps of Engineers (COE), and the New Mexico Interstate Stream Commission (ISC) to prepare the Water Operations EIS. The discussion of the importance of the review represents only my agency's perspective and is not intended to describe the points-of-view of the federal agencies involved.

The Rio Grande, whose flow provides the water supply for a substantial majority of New Mexico's citizens and economy, is heavily developed and regulated by BOR and COE facilities and projects. New Mexicans have benefited substantially from these facilities and projects and rely on these facilities to deliver their water supply, to provide flood protection, and to reduce conveyance losses that deplete the available water. Reduction of conveyance depletions has been necessary historically for New Mexico to meet its downstream delivery obligations under the Rio Grande Compact.

For example, BOR's Middle Rio Grande Project, constructed in the 1950s, straightened and narrowed the channel of the Rio Grande through the middle valley, from Cochiti to Elephant Butte Reservoir. The Middle Rio Grande Project also constructed the Low Flow Conveyance Channel (LFCC), which extends from San Acacia to Elephant Butte Reservoir. The river channelization throughout the middle Rio Grande and operation of the LFCC both materially reduced conveyance depletions of water. Reduction of conveyance depletions reversed the serious annual deficits in New Mexico's Rio Grande Compact deliveries in the 1940s and 1950s. The floods of 1942 and 1943 deposited enormous amounts of silt in the floodplain of the San Acacia reach. Salt cedar infestations followed. The result was that the river channel disappeared. Photographs of the time show no discernable river channel in areas of the San Acacia reach. Figure 1 illustrates both the cumulative deficit in compact deliveries that accrued in the 1940s and 1950s, and the reversal of those cumulative deficits by the Middle Rio Grande Project in the 1960s and 1970s. The state of Texas' lawsuit against New Mexico and the Middle Rio Grande Conservancy District for violation of the Rio Grande Compact, filed in the United States Supreme Court in 1951, was dismissed in 1957 when the Middle Rio Grande Project was funded and began construction.

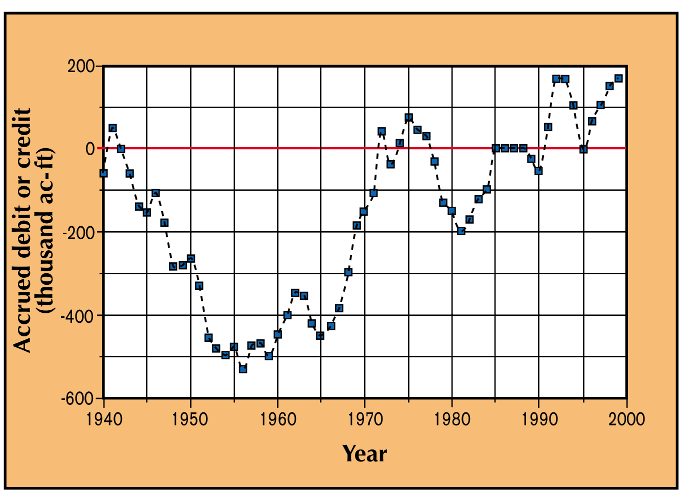

FIGURE 1—The cumulative deficit in Rio Grande Compact deliveries that accrued in the 1940s and 1950s, and the reversal of the deficits in the 1960s and 1970s.

Unfortunately, these federal facilities that are relied upon for use of water from the Rio Grande have also had detrimental impacts on the habitat of species that are now listed under the Endangered Species Act. For example, channelization of the river, operation of the LFCC, and reduction of sediment by Cochiti Reservoir have reduced habitat of the endangered Rio Grande silvery minnow and are believed to be at least partially responsible for the current perilous status of the species.

Compliance with federal environmental mandates is a requirement for federal water resources management and administration. Operation of federal facilities and projects is subject to compliance with federal environmental law, including the National Environmental Policy Act (NEPA) and the Endangered Species Act (ESA). Operation of federal facilities also is subject to state law and water resources administration, relevant federal authorizing legislation, and the Rio Grande Compact. The COE and BOR initiated the Review and Water Operations EIS due to the need for their projects and facilities to comply with the ESA and NEPA. Because the state of New Mexico relies heavily on federal facilities along these rivers for water supply regulation, flood protection, and efficient conveyance of downstream deliveries of water to meet New Mexico's water delivery obligations under the Rio Grande Compact, the ISC joined this effort and jointly shares the responsibility for its completion with the two federal agencies. An agreement between the three agencies signed in January 2000 specifies each of the three agencies' commitments and responsibilities to cooperatively conduct the review, prepare the EIS, and complete consultation with the U.S. Fish and Wildlife Service.

NEPA requires preparation of an EIS for a federal action that may have a significant impact on the natural or human environment. The proposed federal action that triggers the requirement for this EIS is the adoption of an integrated plan for water operations at existing COE and BOR facilities in the Rio Grande basin upstream from Fort Quitman, Texas. To date, the operation of these federal facilities on the Rio Grande has not been formally evaluated as an integrated system, for purposes of compliance with NEPA and the ESA. Figure 2 illustrates the location of these facilities, and also shows the 17 reaches used to describe the system's characteristics for the purposes of the Review and Water Operations EIS.

Federal regulations regarding implementation of NEPA require that a purpose of and need for action be articulated, which explains **who** wants to do **what** and **where** and **why** they want to do it. The purpose of and need for the federal action are used to guide the evaluation of alternatives and the preparation of the EIS. The purpose, need, and scope of the Water Operations EIS have been agreed upon between the three joint lead agencies (see box, p. 119).

The Review and Water Operations EIS will result in federal facility operations decisions that will be extremely important for New Mexicans who rely on the Rio Grande and its tributary aquifers for water supply. Three of these decisions stand out. They include storing native water in Abiquiu Reservoir, which currently stores only San Juan–Chama water; conveyance of water and control of water depletions by the LFCC;

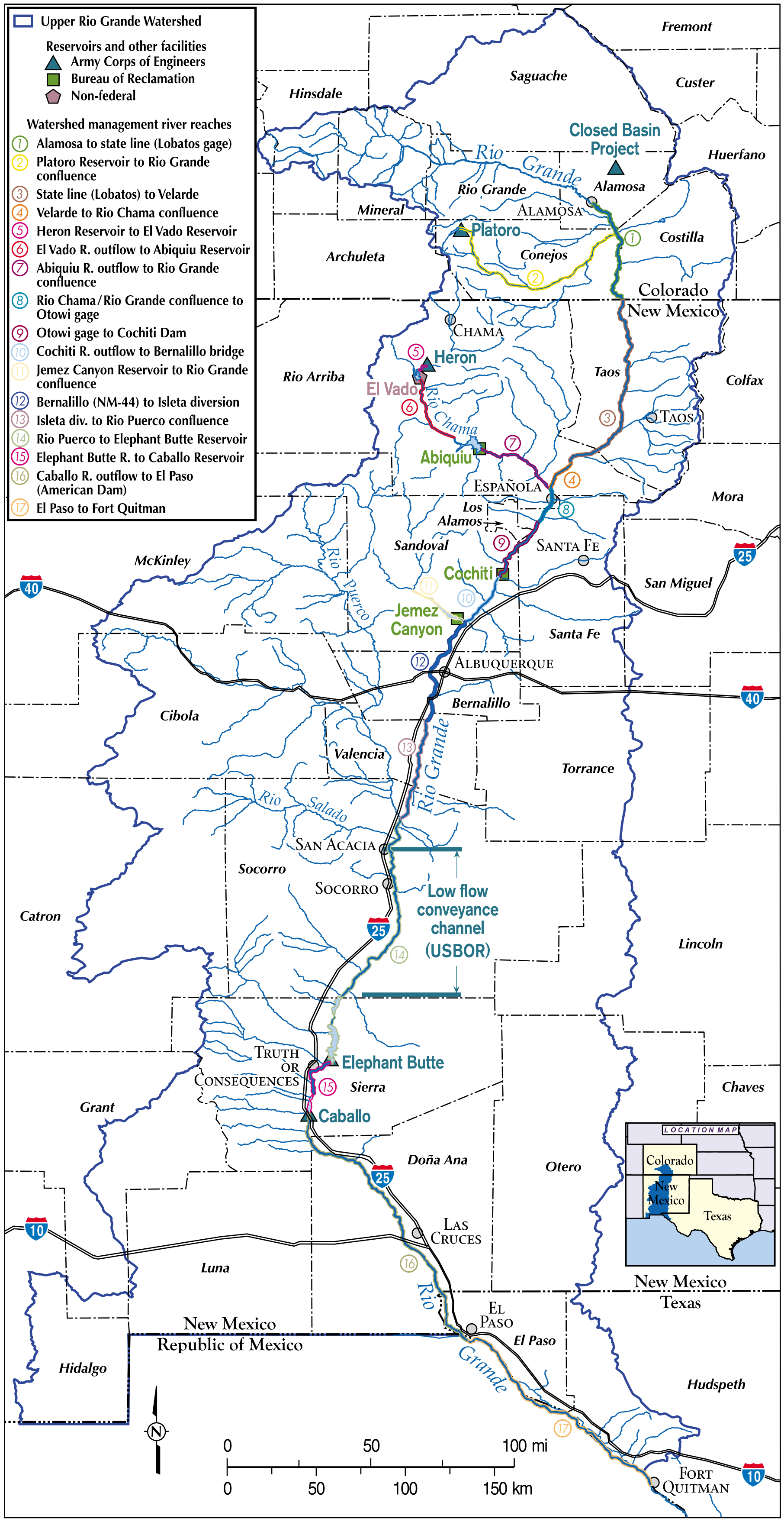

FIGURE 2—Location of rservoirs and other facilities in the upper Rio Grande basin and the 17 river reaches framing the Water Operations Review and EIS.

and operation of other facilities that may affect the Rio Grande silvery minnow and the southwestern willow flycatcher (a riparian-obligate listed species) and their habitat.

Storing native Rio Grande basin water in Abiquiu Reservoir may provide control and flexibility for managing New Mexico's compliance with the Rio Grande Compact that currently does not exist. BOR recently deferred operational decisions for the LFCC, which historically has been critical for controlling high depletions in the reach of the Rio Grande above Elephant Butte Reservoir, from a stand-alone EIS regarding the LFCC to the Water Operations EIS, so that the decisions could be made in the context of the operation of the integrated system of facilities, and with full consideration of the impacts on water supply and compact deliveries.

The Middle Rio Grande Water Supply Study published in August 2000 (located at http://www.sspa.com/ashu/Rio/ start.htm) concludes that the mean annual water supply available to the middle Rio Grande—given the historic climatic variability and the constraints of the Rio Grande Compact on depletions of water—is barely able to supply existing uses. The study also concludes that the water supply that exists from the Rio Grande and its tributary aquifers between Otowi gage and Elephant Butte Reservoir is a singular water supply. As a result, the third extremely important decision that may result from the Water Operations EIS—changing the operation of federal facilities to restore habitat for endangered species or improve environmental quality in a manner that will increase water depletions—must be balanced by discontinuing existing water uses in the same quantity. If offset of depletions does not occur, either New Mexico's available water supply or its fulfillment of compact deliveries will suffer. Non-compliance with the compact is likely to result in severe penalties for New Mexico and reduction of water supply for all users within the middle Rio Grande.

The Review and Water Operations EIS is scheduled to conclude in 2004. Please review the web page at http://www.spa.usace.army.mil/urgwops/ or contact any of the joint lead agencies for additional information.

Need, Purpose, and Scope of the Water Operations EIS

Need: Under various existing legal authorities, and subject to allocation of supplies and priority of water rights under state law, the COE and BOR operate dams, reservoirs, and other facilities in the upper Rio Grande basin to:

(1) store and deliver water for agricultural, domestic, municipal, industrial, and environmental uses;
(2) assist the ISC in meeting downstream water delivery obligations mandated by the Rio Grande Compact;
(3) provide flood protection and sediment control; and
(4) comply with existing law, contract obligations, and international treaty.

Purpose: The Upper Rio Grande Basin Water Operations Review will be the basis of, and integral to, preparation of the Water Operations EIS. The purpose of the Review and Water Operations EIS is to:

(1) identify flexibilities in operation of federal reservoirs and facilities in the upper Rio Grande basin that are within existing authorities of COE, BOR, and NMISC, and in compliance with state and federal law;
(2) develop a better understanding of how these facilities could be operated more efficiently and effectively as an integrated system;
(3) formulate a plan for future water operations at these facilities that is within the existing authorities of BOR, COE, and NMISC; complies with state, federal, and other applicable laws and regulations; and assures continued safe dam operations;
(4) improve processes for making decisions about water operations through better interagency communications and coordination, and facilitation of public review and input; and
(5) support compliance of the COE, BOR, and NMISC with applicable law and regulations, including but not limited to the National Environmental Policy Act and the Endangered Species Act.

Scope: The Review and Water Operations EIS will address water operations at the following facilities with the noted exceptions and limitations. The term "water operations," as used in this Agreement…refer[s] to physical operation of the identified facilities.

- Flood control operations at Platoro Reservoir (the Review and Water Operations EIS will include only flood control operations at Platoro that are under COE authority. None of the signatories to this Agreement have authority over water supply operations at Platoro).
- Closed Basin Division -- San Luis Valley Project
- Heron Dam and Reservoir
- Abiquiu Dam and Reservoir
- Cochiti Dam and Reservoir
- Jemez Canyon Dam and Reservoir
- Low Flow Conveyance Channel
- Flood control operations at Elephant Butte Dam and Reservoir…
- Flood control operations at Caballo Dam and Reservoir…

[Because of current litigation, water supply operations at Elephant Butte and Caballo will not be included in the Review or the Water Operations EIS.]

BOR and COE operate these facilities under federal authorities, state water rights permits, and various contracts. The Review and Water Operations EIS will be limited to actions that can be implemented within the existing authorities of the signatories in compliance with applicable international, federal, state, and tribal laws, regulations, and contracts, including without limitation the Rio Grande Compact.

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Gaume has served as Director of the New Mexico Interstate Stream Commission, New Mexico's water planning and development agency, since 1997. The commission's responsibilities include investigation, development, conservation, and protection of New Mexico's water resources and stream systems; interstate stream compacts administration; resolution of interstate and federal water resources issues affecting state water resources; and management of New Mexico's regional water planning program.

Previously, Gaume managed the city of Albuquerque's Water Resources Division from its creation in 1990 until 1997. He led the development and City Council adoption, including implementing rate increases of Albuquerque's sustainable water supply strategy. Before that, Gaume served for 16 years in various operations and engineering management positions in the city of Albuquerque water and wastewater utilities and as a water resources engineer for a national consulting firm. He received a national professional award for outstanding performance in utility works operations and management in 1986.

Gaume is a New Mexico native and has lived in Anthony, Deming, Hobbs, Las Cruces, Albuquerque, and Santa Fe. He is a Registered Professional Engineer and an avid whitewater canoeist.