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

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

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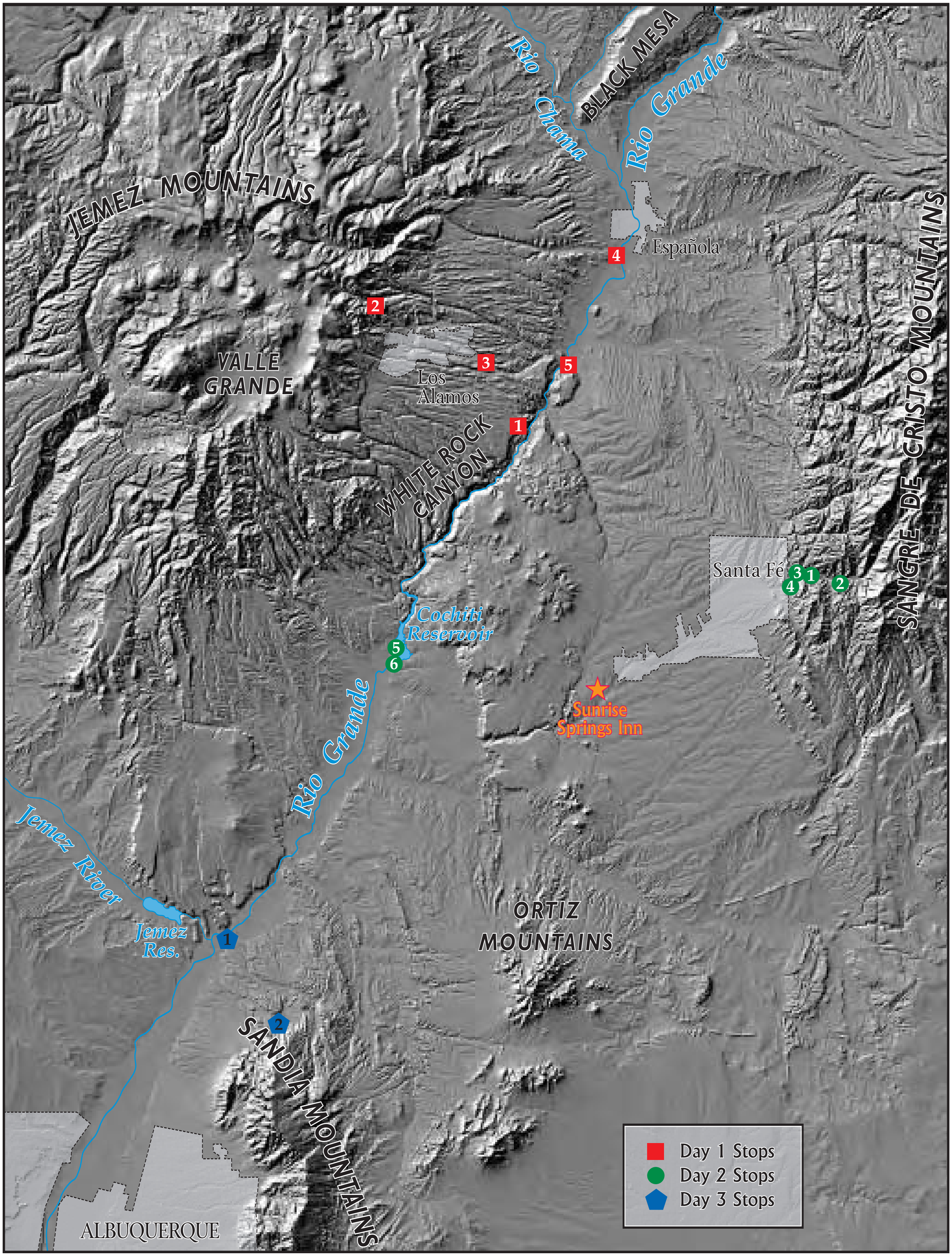
Shaded Relief Map of Field Conference Area



An Introduction from the State Geologist

by *Dr. Peter A. Scholle*, Director, New Mexico Bureau of Mines and Mineral Resources and State Geologist

Welcome to the inaugural Decision-Makers Field Conference, the first of a series of annual meetings dealing with geoscience issues in New Mexico. These conferences are designed to provide New Mexico decision makers with the opportunity to see, first hand, the influences and impacts of natural phenomena and human actions on our resources and landscapes. This year's meeting, on water and watershed issues in the Santa Fe–Los Alamos region, highlights some of the most important and contentious issues for New Mexico's future. Ecologists commonly speak of a limiting nutrient—the single element that controls the size of a species' population. Iron, phosphorous, and nitrogen are common limiting nutrients for plants, which is why we often apply these materials in our gardens as fertilizers. In a broader sense, water is the limiting nutrient for humans in this region. Essential for agriculture, for domestic needs, for many industrial processes, and for sustaining the natural flora and fauna of the state, water is our "life blood" (often and accurately summed up in the Spanish phrase "agua es vida").

How to deal with the conflicting demands of the many and rapidly increasing users of water is a social problem that you, New Mexico's decision makers, must wrestle with constantly. The major points of this field trip, however, deal with the science that lies (or should lie) behind those decisions. We will try to present the most up-to-date information from the state's scientific community; to show how that community agrees or disagrees on basic facts and principles; and to show that we can and should be a valuable resource for decision makers. The trip is specifically NOT designed to lobby for any point of view or pending legislation. Rather, it is an educational effort to show what is known, what isn't known, and perhaps what should be known in order to make rational decisions.

Non-scientists often expect scientists to fully agree on the "facts" that underlie societal issues and are surprised and dismayed when that is not the case. Thus, a goal of this conference is to show the reasons for those honest disagreements. Science after all represents a method for gathering knowledge, setting up and testing hypotheses and theories, and working ever closer toward a full understanding of the world around us. It is a complex world, however, one filled with multifaceted interactions in which information gathering is not always simple. Some things are easy to measure and understand, whereas others are not. We can easily measure rainfall and produce information on distribution of rain throughout the state, but it is much more difficult to predict future climate change and how it might affect water supplies. We know how much rain hits the ground, but how do we measure how much evaporates, how much is taken up by plants, how much descends as ground water, how fast and where such ground water moves in the subsurface, and when and where it picks up pollutants? We will need to do hundreds of detailed studies in many different areas before we can answer most of those questions, and the most complex of them will almost certainly defy answer in our lifetimes. Often we think we know the answer, but additional data will surprise us and cause substantial changes in our conclusions. Thus, part of the purpose of this conference is to help us all to "know what we know" as well as to "know what we don't know." That, too, is a fundamental process of science.

We should also recognize that, whether we like it or not, we either manage or greatly influence most things in nature. Earthquakes and volcanic eruptions remain beyond man's control, but most other processes do not. Our fire suppression and forest management policies, predator-control activities, agricultural practices and other land-use measures, our diversions of natural water supplies, and our urban growth patterns all profoundly affect natural systems. If we are going to influence the world around us so substantially, we should at least understand how and why that is happening so that we can make rational decisions on management plans. That will also be a focus of this conference.

One more thing is on the agenda—providing realistic solutions to the problems we discuss. For many of the issues that we tackle in this conference, we will attempt to present potential solutions that make scientific and technical sense. Whether these solutions can be worked into the complex political realities of New Mexico is your call. But we will strive to show that with careful planning, workable solutions (or at least approaches to solutions) are indeed possible.

Making this conference happen was no small organizational feat. We are deeply grateful to the many financial sponsors listed on the credits page; we are equally grateful to the many speakers and to the agencies that allowed them to speak and covered their expenses. The organizing skills of Peggy Johnson, Paul Bauer, and Susie Welch of the New Mexico Bureau of Mines and Mineral Resources will be clear throughout; the help of many others, from the bureau and from other agencies, may not be as immediately evident, but was critically important. We are very grateful to them all!

We ask of you, the attendees, only that you participate fully—ask hard questions of the speakers, contribute to the discussion, enjoy the entertainment, and when all is done, give us your honest opinions on what worked well and didn't work—so that we can make next year's conference even better and more useful to you.

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Peter Scholle has had a rich and diverse career in geology: 9 years of Federal governmental work with the U.S. Geological Survey, 4 years directly employed by oil companies (plus many additional years of petroleum consulting), 17 years of teaching at two universities, and now a career in state government at the NMBMMR. His main areas of specialization are carbonate sedimentology and diagenesis as well as exploration for hydrocarbons in carbonate rocks throughout the world. He has worked on projects in nearly 20 countries with major recent efforts in Greenland, New Zealand, Greece, Qatar, and the Danish and Norwegian areas of the North Sea. A major focus of his studies dealt with understanding the problems of deposition and diagenesis of chalks, a unique group of carbonate rocks that took on great interest after giant oil and gas discoveries in the North Sea. His career has also concentrated on synthesis of sedimentologic knowledge with the publications of several books on carbonate and clastic depositional models and petrographic fabrics. His wife and he have published numerous CD-ROMs for geology, oceanography, and environmental science instructors, and they currently are developing computer-based instructional modules and expert systems in carbonate petrography.

What Are the Challenges?

by *Dr. Frank B. Titus*, Middle Rio Grande Water Assembly

As Peter Scholle states in his introductory remarks, this Decision-Makers Field Conference focuses on the science that lies behind socio-political, water-related, and environmental decisions that you, the decision makers, will ultimately make. I suggest to you that your decision process is unavoidable; decisions will be made either by action on your part or by non-action. In fact the process rolls on as we speak and meet.

In this article I offer my perceptions on what the scientific realities of New Mexico's water future are likely to be. Obviously, this goes beyond science. Scientific reality in this process gets mixed with elements of politics, water management, philosophy, state law, and speculation about future conditions. So be it. Two points that I have made freely and often are: (1) the time to proactively take hold of the decision process is now, not later; and (2) we already understand the workings and complexities of our water systems quite well enough to make smart fundamental decisions.

What kinds of decisions are needed? Simple: How we are to manage our water resources in the future. Up to now we have been demanding that a Rio Grande water resource, which is of fixed and finite size, supply our ever more-expansive water needs. Because the natural flow of the river could not do it, we've imported water from the San Juan–Colorado River system that New Mexico owns and we've dramatically mined our ground water—in essence drawing capital from our savings account and spending it.

The Current Reality

For the past three decades we have been able to meet water-delivery requirements of the Rio Grande Compact at Elephant Butte Dam for three main reasons: (1) precipitation and runoff of native water in the Great River has been above average; (2) 96,000 acre-ft/yr average of water is brought out of the San Juan River headwaters and added to the Rio Grande system through the San Juan–Chama Diversion Project; and (3) the city of Albuquerque has been mining up to 120,000-plus acre-feet of ground water per year, evaporating half of it, and adding the remainder to the flow of the Rio Grande.

Nevertheless, the reality is that we are depleting from the river all of the water we are permitted under the compact, and there is no way we can force any change to that compact. Add to that three additional realities: (1) it is unlikely we will find any more water to import; (2) as we mine ground water in our river valleys the aquifers demand payback in the form of induced seepage out of the river (instead of seepage into the river that was the pristine process); and (3) droughts happen in New Mexico with some regularity. We dare not ignore droughts. Some are long and general; some are short and local; but they always come. The infamous one in the 1950s, quite within the memory of older residents, was severe, but we know of others in earlier centuries that were as bad or worse.

This discussion should force us toward the conclusion that if we are to live within our means, we must do it through a process of learning to manage better what we already have. We clearly have some decisions to make.

Some (but not all) Questions for the Future

Here, just to keep us flexible and somewhat humble, I'll toss in a near-random mix of questions that we'll have to answer sooner or later. There are many more where these came from. I'll leave the task of answering them to you in some future (possibly near-future) time. (Note that these are all reality questions, and some of my prejudices may be on display in them.)

- How Can We Keep the Rio Grande from Being Put in a Concrete-lined Channel?
- When the river fails to supply enough water to make compact deliveries below Elephant Butte Dam, what should we do?
- What would Santa Fe do if its reservoirs in the Sangre de Cristos Mountains were unusable? (Say from a fire, a priority call on the water, or for any other reason.)
- We've been cutting salt cedars for five decades then watching them grow back in a few years; will we get frustrated enough to find some truly innovative solutions?
- In recent years Elephant Butte Reservoir has been losing nearly 200,000 acre-ft/yr of water to evaporation; why aren't we searching for ways to reduce this?
- Should farmers' water rights be the only place we look for added municipal supplies?
- If litigation is used to define New Mexico's water future, will we all be sorry? (Court decrees produce winners and losers, not fair, balanced, complex tradeoffs.)
- Should acequias be included in the protection of water rights from being sold out of their service area?
- Why aren't state representatives having direct discussions with the Indian pueblos over ways to define Native American water rights?
- Are thinking people not aware that on the middle Rio Grande we will be forced to decide many water-rights and water-management issues before adjudication can even begin, much less finish?

Priority Calls—A Toothless Ultimatum

Let us hypothesize—for the purpose of illustrating a crucial point—a serious water debt at Elephant Butte Dam. Let's say we accrue a compact debt that is two and a half times the maximum debt that is permitted (as actually happened in 1956). What could we do? In simpler times past, when our laws were written and we only used surface water, the state engineer could issue a priority call, shutting down junior water right holders, and leaving more water in the river to flow to senior right holders downstream. Tough. But everyone understood how it worked.

Today a priority call in the middle Rio Grande valley would be quite impossible. To put it pithily, it would be both worse-than-useless in the short term and stupidly impolitic. The junior water rights on this reach of the river are mostly rights to pump ground water by the cities of Albuquerque and Rio Rancho, whereas most of the more senior rights are for surface water for irrigation. The cities' cones of depression, those that suck water out of the river, developed during decades of pumping the wells. The cones are extensive, coalesced, and deep. Shutting off the pumps would not reduce water loss from the river until the cones at least partially filled back in with water, possibly taking years. But shutting off the pumps would be even worse than useless, because it would stop the flow of mined ground water, through circuitous city routes to the water treatment plant and ultimately back to the river. That's the useless part. It would actually stop this contribution to the river. The impolitic part is that it would be unimaginable for the state engineer to try to shut down the only water supply of the people living in the largest metropolitan center in the state.

Santa Fe would fare no better in this totally improbable scenario. A priority call might well require that water stored behind Santa Fe's two dams in the Sangre de Cristo Mountains be drained into the Rio Grande. And so far, years of discussion have failed to produce any way for Santa Fe to get its San

Juan–Chama water from the river to the people.

What Are We Doing Now to Help Ourselves Later?

Fortunately, in spite of general nervousness over whether a drought might be in the offing, there is no water crisis right now, and New Mexico had a credit of about 170,000 acre-feet at Elephant Butte Dam in its water-delivery account at the end of 1999 (Annual Report of the Rio Grande Compact Commission). Wonderful news.

But during this period of calm, are we doing anything to help ourselves in the future? The answer isn't encouraging. Well, we are talking more and more about water, and that's healthy. The legislature last year was fairly generous in providing funding for the Office of the State Engineer and the Interstate Stream Commission. And a useful study was completed last year that compiles water data for the middle Rio Grande valley so it is more widely available. But did we make progress in heading off water crises in the future? Not much that is of substance, I'm afraid.

Vision? What Vision?

What is our vision for our state's water future? Where are we going? What are our aims and goals? What are our specific problems? And what are our future water priorities? Should our future priorities be the same as those of our past? Why is no one asking, or attempting to answer, these questions?

The following words summarize the official interpretation of the authority granted to the Office of the State Engineer and to the Interstate Stream Commission by state laws and the constitution. The state engineer "…is charged with the administration of the rights to use New Mexico's water, which the state's constitution declares to be the property of the public. As Secretary of the Interstate Stream Commission, [the state engineer assists] that body in investigating, protecting, conserving, and developing the stream systems of the state. The goals of [the Office of the State Engineer] have not changed since the offices were created…." (OSE/ISC 1998–1999 Annual Report, p. 4.)

Notice that nothing is said about planning for the future. Neither is it suggested that there be "management" of the state's water resources. Much of New Mexico's water laws, I am told, were written in and around the 1930s. The statements above seem to place us near the core of the reasons that few proactive moves are apparent in state government to bring New Mexico's control of its own destiny face-to-face with the wet-water shortfall looming in the future. The apparent resistance to change probably stems both directly and indirectly from a political climate reflecting fear of any change among many of the state's water-right holders.

The Way Out

One—and only one—path leads out of this complex, and that is to begin proactively planning for what we New Mexicans want our future to be. In the absence of an explicit plan, how can order be brought to the present arena wherein actions range from uncoordinated individual initiatives to unspoken acceptance of the no-action philosophy? Here is a task for you decision makers. You can begin to insist that planning must start now.

Here is how your insistence might be played out. The Interstate Stream Commission should be given explicit instructions by the legislature and the governor that it is to begin the process of developing a State Water Plan. At a minimum this new plan should be based on or incorporate:

- A comprehensive, balanced review of all existing state water laws and regulations
- A recommitment to the basic principle of priorities: first in time is first in right
- Introduction of the concept that the state's waters are to be managed (not just administered) for the benefit of all
- Recognition that physical conditions governing exploitation of ground water and surface water differ, hence priority enforcements cannot be identical for the two
- A workable concept of "public welfare," to replace the present undefined generality in water law that is so universally ignored
- Making conservation an incentive-based concept for all, but especially for agriculturalists

This is just a start, and most is process, not the plan. There will be a great deal more to it than is outlined here. But once started, maybe it will develop momentum of its own. One thing is especially important: it must explicitly be funded. This activity must not allow itself to be bureaucratically buried by those who would use the excuse that it was not funded.

There remains one critical central question, and it is this: What vision should guide development of the State Water Plan? The issue of where we need to go is, in my view, easy to address. In the following paragraphs of this guidebook introduction, Lisa Robert summarizes a statewide poll of New Mexicans on their understanding, their values, and their preferences about water (UNM Institute for Public Policy). You will find our citizens' opinions on water fascinating for their wisdom and for their usefulness as we plan for our future. The most obvious answer to the vision question is that we should go where the citizens of New Mexico want us to go. Thus, the guiding principle for defining our vision and our aims should be to ask the people (not their agents, not the marketplace) what they want New Mexico to look like 50 or 100 years from now. They have already given us an opening view of a vision that is thoughtful, workable, and might even help preserve our quality of life.

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1987–93 Jacobs Engineering Group, Inc., Albuquerque
1993–95 Consulting (mainly as hazardous-waste remediation expert), Albuquerque
1995–98 Technical Advisor to the New Mexico State Engineer, Santa Fe
1998–date An Agua Gadfly, Albuquerque

We New Mexicans have an opportunity right now to plan intelligently for our water future, adjust our water management to the hard realities of today and those of the predictable future, and perhaps to mitigate some of the hugely costly conflicts that loom in the future. We should not ignore the many wake-up calls we've received, not least of which is our lawsuit loss to Texas on the Pecos River, which has cost more than $85 million since 1988 (State Engineer/ISC 1999–2000 Annual Report, p.10–20), and it isn't over yet.

A New Mexican Perspective on Water

by *Lisa Robert*, Editor, New Mexico Water Dialogue

In the spring of 2000 the University of New Mexico's Institute for Public Policy conducted a statewide survey on attitudes and preferences about water issues. The institute, which generates a Public Opinion Profile of New Mexico Citizens twice each year, polling a state and a national sample each fall and a New Mexico sample in the spring, surveyed a random sample of 1,391 state residents—including 589 residents living in the middle Rio Grande survey area—on a variety of water-related topics. At the same time, under a contract with the Middle Rio Grande Council of Governments, the institute administered the same survey to an additional "over sample" of 567 residents in Sandoval, Bernalillo, and Valencia Counties. The survey results offer some useful and perhaps surprising insights into the New Mexican psyche.

Survey questions were roughly divided into four categories: general views about water and the environment, knowledge and perceptions about water issues, personal values in relation to water, and water policy preferences.

Asked to agree or disagree on a scale of one to seven with statements about water and the environment, statewide residents gave top billing to the importance of "coming to an agreement soon on a plan for managing our water to avoid increasing conflict over water in the future." Next they agreed that "keeping water in rivers to provide a green corridor and protect habitat for wildlife and vegetation is important." The third statement with which residents strongly concurred was that "farmers shouldn't be put out of business just so cities can grow." At the other end of the scale, those questioned did not feel that water is too complicated a subject for the average person to have "much say in how to manage it well." Neither did they believe that "farmers waste a lot of water irrigating fields," or that things will "work out" even if New Mexicans can't agree on how to manage the state's water.

Respondents were asked to rate the importance of several specific water issues. At the top of everyone's list was having quality water for drinking and bathing. This was followed (in decreasing order of importance) by keeping enough water in the river for vegetation and wildlife, the increasing rate at which we are mining ground water, the imbalance between economic growth and available water, New Mexico's needs versus Rio Grande Compact obligations, attracting high tech industries, and maintaining residential lawns and gardens.

Asked to choose among various water uses, state residents ranked indoor household use first, irrigation for farms second, and providing food and refuge for fish, birds, and other animals third. Residents in the middle Rio Grande survey area placed preserving the native cottonwood bosque above water for irrigation, but ranked irrigation for farms slightly above providing food and refuge for birds, fish, and other animals. Second tier choices for both groups included use for new housing, cultural and religious uses, recreation, community parks and sports fields, and new industry. Water uses given the lowest ranking were existing landscaping, outdoor use for new development, golf courses, and private swimming pools.

In their replies to questions about specific policy issues, around 74% of respondents in the middle Rio Grande survey area and 70% of respondents in the rest of the state indicated they would rather keep more water in the river between Cochiti and Elephant Butte Reservoirs to protect the bosque than to use it to promote jobs and economic growth. More rural residents than urban dwellers favored leaving water in the river. More than half the residents (both in the middle Rio Grande survey area and statewide) strongly agreed with the idea that development should be "contingent on demonstrating that a long term water supply is available." More than half of those surveyed agreed that all water use should be metered. They also agreed with requiring limits on water use and setting rates so that the biggest users pay the highest rates. Opinion was mixed on the question of raising the price of water for all businesses and households. Seventy percent of the "rest of state" respondents and 65% of middle Rio Grande survey respondents felt we may be entering a period of extensive drought. A majority felt Indian and non-Indian water rights should be treated the same when developing water management plans. Finally, respondents were largely opposed to the buying and selling of water rights, and specifically to transfers away from the community of origin.

Some Conclusions

New Mexico is a desert state, and green space—whether agricultural lands or ribbons of riparian vegetation along precious waterways—provides respite for all who live here. In other places, farming, riparian, and endangered-species needs are perceived to be mutually exclusive, but New Mexicans are beginning to comprehend the connective tissue between those water uses.

John Brown, one of the principal authors of the IPP survey, offers this thought: "New Mexicans appear to value more than personal income growth and the creation of jobs—the kinds of things we've come to associate with development. There are cultures in this state that basically say, "appreciate what you have." They recognize that if they do some of the stuff that everybody says is important, they'll lose what they have that is important. Thanks to both Native American and Hispanic traditions, New Mexicans apply a different weighting system to things than people do in other places. And it's not only those who are native to the state—it's people who come here and buy into the philosophy. There's just another set of values at work here. Seeing environmental and social values consistently set above economic values in the survey suggests this about us."

To obtain a copy of the survey, contact the MRGCOG at 247-1750, or visit the MRG Water Assembly's web page at www.waterassembly.org.

(This article was adapted from "A New Mexican Perspective on Water," New Mexico Water Dialogue, April, 2000.)

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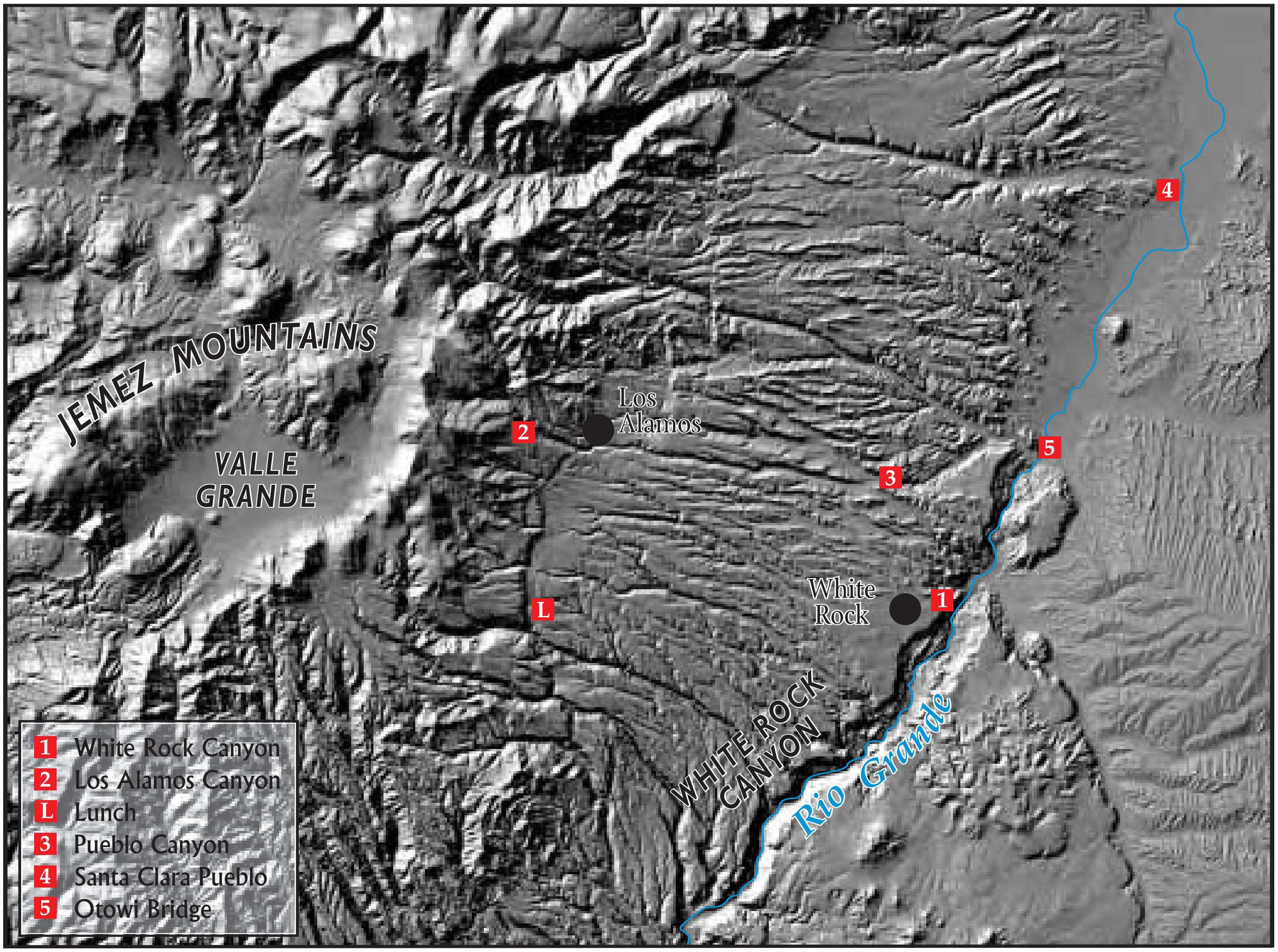
Lisa Robert has worked for the Dialogue since 1993 and served as Dialogue newsletter editor since 1995. She also edits the APA Watermark, a newsletter for constituents of the Middle Rio Grande Conservancy District.

Robert grew up in the Rio Grande valley, and spent her childhood riding horseback on its ditches, drains, riverbanks, and mesas. A basic geology course at UNM (back when continental drift was a hotly debated subject!) attuned her to the endless stories New Mexico's landforms tell. As a storyteller herself, she is in awe of their message: nothing is permanent, and the story is never finished.

Day One, May 9, 2001

The Pajarito Plateau—Earth, Water, and Fire



Wednesday, May 9, 2001

Stop 1 White Rock Canyon
Land use status of the Los Alamos area
Geologic overview of the Pajarito Plateau
Hydrogeology of the Los Alamos area
Runoff, erosion, and restoration studies

Stop 2 Los Alamos Canyon
Fire and vegetation history of the Jemez Mountains
The Cerro Grande fire
Impacts of the Cerro Grande fire
Watershed management on the plateau
Protecting wild land/urban communities

Stop 3 Pueblo Canyon
Cerro Grande ash, a source of elevated radionuclides
Runoff following the Cerro Grande fire
Ground-water monitoring at LANL
The role of risk assessment
NMED risk assessment
San Ildefonso risk assessment

Stop 4 Santa Clara Pueblo
Rehabilitation and fire restoration
Acequia communities on the upper Rio Grande
Collapsible soils in New Mexico

Stop 5 Otowi Bridge
The Rio Grande
The Rio Grande Compact
A collector well for the city of Santa Fe

Why Study Geology?

by *Paul W. Bauer*, New Mexico Bureau of Mines and Mineral Resources

The Earth is the basis for all human economic activity. The Earth provides us with the most basic resources for survival: clean water, fertile soils for agriculture, and the raw materials for adobe, concrete, steel, and glass for constructing shelters. We also extract many of our raw industrial products (iron, copper, aluminum, sand and gravel, and many others) and our most important fuels (oil, gas, and coal) from the Earth. The geologic environment is also the disposal site for all of our industrial by-products, hazardous materials, household trash, and human waste. One of our greatest immediate challenges is to balance our thirst for these finite Earth resources with our duty to protect and preserve the environment in order to sustain future generations of humans, animals, and plants.

Geology is the study of planet Earth. Studying the Earth means studying the **materials** that compose the planet, the **processes** that act on these materials, the **structures** formed by those processes, and the **history** of Earth and its life forms since planet formation.

Earth Materials

Whether we realize it or not, geology plays an important role in our everyday lives. Although we are continually in contact with Earth-derived materials, we typically do not think about their origins or the consequences of their consumption. But the mining of any commodity comes with costs—some are tangible costs (such as the market price), whereas other costs are intangible (such as societal costs due to the consumptive loss of non-renewable resources, pollution, political unrest, worker exploitation, international conflict, human health problems, habitat loss, and other environmental consequences). As supplies of some raw materials dwindle, the costs of exploration and mining increase, and as the true environmental costs of extraction and consumption are incorporated into the marketplace, prices of finished goods rise.

Geologic Processes

A great variety of geologic processes affect our lives, sometimes in unforeseen and catastrophic ways. Some processes produce instantaneous, dramatic impacts, including large costs to society, and sometimes a loss of life. Examples are floods, landslides, earthquakes, and volcanic eruptions—all of which are facts of life in New Mexico. Volcanoes have erupted in New Mexico in recent geologic time, and undoubtedly more will erupt in the future. Other processes operate at slower rates, although their societal costs can still be substantial. Examples include erosion, land subsidence, siltation of waterways, drought, corrosion, and the slow flow of ground water through an aquifer. As the planet has become industrialized, human activities have profoundly affected the rates and severities of many of these natural processes. Additionally, for the first time in human history, we now possess the capability to initiate dramatic and devastating global environmental modifications, such as climate change, nuclear winter, and ozone depletion.

Geologic Structures

Geologic processes are capable of producing a wide variety of structures in rocks and sediments, and some of these structures, such as faults and fractures, have far-reaching impacts on our lives. For example, seismic faults like the San Andreas fault have enormous destructive potential. In New Mexico, seismic faults are a less significant hazard, although moderate quakes have damaged buildings in Albuquerque, Socorro, and elsewhere. A more subtle, but profound, consequence of faults in New Mexico is that they can have an impressive effect on the distribution of ground water in areas such as the Albuquerque Basin and the Sandia Mountains. In places where water is pumped from bedrock, fractures in the rock actually control the productivity of wells.

Geologic History

The rocks and minerals that we depend on for raw materials, and the landscapes that shape our communities and activities, have evolved over millions, even billions, of years. Through careful study, we can use our knowledge of Earth materials, structures, and processes to construct a framework that relates all of the data and their interpretation in space and time. This approach allows us to infer past geologic events and to forecast future geologic scenarios. We can look at any New Mexico landscape and determine why and when it formed, and we can predict its environmental response to some human-induced stimuli. For instance, we can evaluate how a river responds to damming. We can also estimate the volume and value of geologic commodities, such as aggregate, coal, or copper, and we can gauge the environmental impacts of extracting those commodities.

Geologists study the Earth for a variety of reasons (exploration for natural resources, environmental protection and rehabilitation, prediction of natural hazards, pure science, and an appreciation of nature), but fundamental to all is a desire to gain a better understanding of our physical environment. We have only one Earth; to live on it wisely, we must understand it well.

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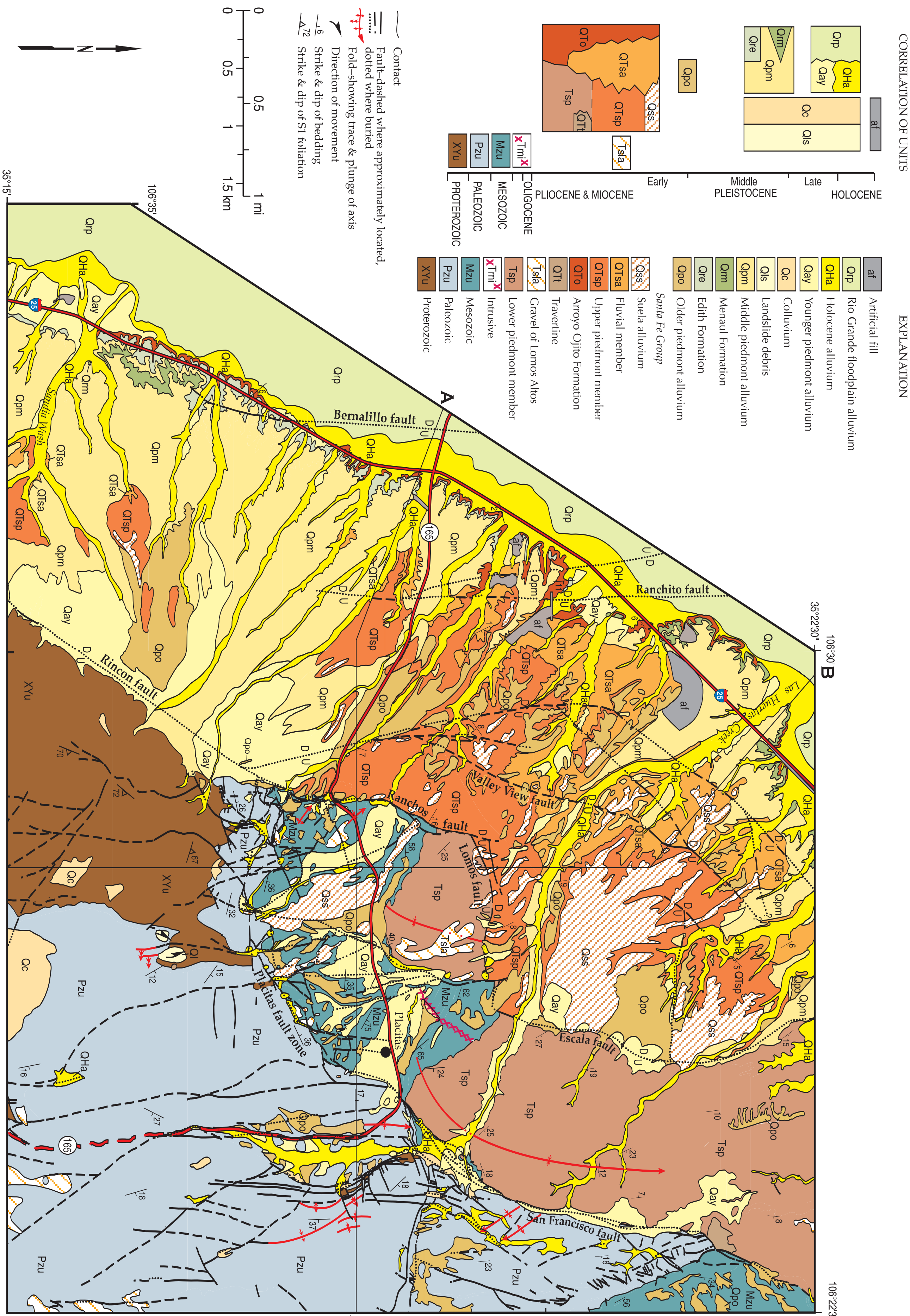
Most of Bauer's geologic research in New Mexico has been involved in field mapping and structural analysis designed to unravel the ancient geologic history of the state. Recently, he has been investigating the stratigraphy and structure of the Taos area, in order to support ongoing hydrologic studies. He is also very interested in promoting an appreciation of the state's landscapes and natural resources to the non-geologic public and has authored several non-technical books on New Mexican geology.


CORRELATION OF UNITS
HOLOCENE
Late
Middle
PLEISTOCENE
Early
PLIOCENE & MIOCENE
OLIGOCENE
MESOZOIC
PALEOZOIC
PROTEROZOIC
EXPLANATION
af Artificial fill
Qrp Rio Grande floodplain alluvium
QHa Holocene alluvium
Qay Younger piedmont alluvium
Qc Colluvium
Qls Landslide debris
Qpm Middle piedmont alluvium
Qrm Menaul Formation
Qre Edith Formation
Qpo Older piedmont alluvium
Santa Fe Group
Qss Suela alluvium
QTsa Fluvial member
QTsp Upper piedmont member
QTo Arroyo Ojito Formation
QTt Travertine
Tsla Gravel of Lomos Altos
Tsp Lower piedmont member
Tmi Intrusive
Mzu Mesozoic
Pzu Paleozoic
XYu Proterozoic
Contact
Fault–dashed where approximately located, dotted where buried
Fold–showing trace & plunge of axis
Direction of movement
Strike & dip of bedding
Strike & dip of S1 foliation
0 0.5 1 mi
0 0.5 1 1.5 km
N
106°35'
35°15'
106°30'
35°22'30"
106°22'30"
A
A'
B
B'
Bernalillo fault
Ranchito fault
Valley View fault
Ranchos fault
Lomos fault
Rincon fault
Escala fault
Placitas fault zone
San Francisco fault
Placitas
Sandia Wash
Las Huertas Creek

The Value of Geologic Mapping to Decision Makers in New Mexico

by *Paul W. Bauer*, New Mexico Bureau of Mines and Mineral Resources

Of the 121,667 mi^2 of land in New Mexico, less than 20% has been geologically mapped at the standard scale of 1:24,000 (1 inch = 2,000 ft). Why is this a concern? Decision makers at the local, state, tribal, and federal levels increasingly need specific kinds of scientific information to make informed choices concerning land, water, and resource use. For example, deciding to preserve certain pieces of land may limit economic opportunities and alter nearby land values; alternatively, failing to limit inappropriate development of land may provide short-term benefits, but cause hugely expensive and divisive long-term problems. Detailed, publicly available earth-science information is essential for making informed decisions that encourage sustainable economic development and prosperity. Modern geologic maps are the fundamental tool used to display the information that decision makers require to identify and protect valuable resources and make wise use of our land.

Geologic maps combine descriptive information (such as materials and structures) and interpretations (about process) into a conceptual framework that relates all of the geologic elements through time. This is a powerful tool, as it both describes the geologic environment and permits us to predict how natural systems are likely to behave in the future. For example, we might predict how pumping an aquifer may cause land subsidence and accompanying damage to foundations and buildings.

Geologic maps provide immediate economic benefits. In New Mexico, those benefits add up to many millions of dollars saved. For example, without geologic maps, project costs can be greater, exploration efforts have lower success rates, costly engineering errors can be made, and project completions can be delayed. In addition, high-quality maps made by objective scientists also have very important intangible values. In particular, users of geologic maps find that the quality of their work is enhanced and the credibility of their findings is increased.

Surveys have shown that geologic information is important to government and private industry for a variety of environmental and economic applications, with the following being the most common applications:

(1) Exploration and development (ground water, industrial minerals, metallic minerals, oil and gas, and coal);
(2) Environmental consulting (pollution prevention, site cleanup, and industrial issues);
(3) Hazard prevention and protection (landslides, earthquakes, soil stability, mine subsidence, sinkholes, volcanic eruptions, and floods);
(4) Engineering applications (buildings and foundations, roads, pipelines, dams, utilities, railroads);
(5) City planning (zoning decisions, landscape planning, and building codes);
(6) Regional planning (regional water plans, waste disposal, industrial permits, and planning transportation corridors); and
(7) Property valuation (land acquisition, property tax assessment, and cost-benefit analysis).

In this state, new geological quadrangle maps by the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) are being used to support a great variety of environmental and hydrologic work along the Rio Grande. A few of these recent projects are a hydrogeologic investigation of the Albuquerque Basin aquifer—in cooperation with the United States Geological Survey (USGS), a hydrogeologic study and water resource assessment for Sandoval County in the Placitas development area, a hydrogeologic study of the Taos Valley, and subsidence and aquifer consolidation modeling in the Albuquerque area. Geologic maps are also the primary source of information on the state's aggregate resources (sand, gravel, crushed stone). Aggregates are especially pertinent to geologic map making, as they are needed everywhere that construction occurs (including road-building projects), and their transportation costs must be minimized in order for their use to be economically feasible.

Only by understanding the distribution of geologic materials and structures, and by understanding past, current, and future work of geologic processes, can we minimize societal costs and maximize societal benefits in our dynamic New Mexican geologic environment. The only way to obtain such information is through the production of detailed, field-based geologic maps and derivative research.

New Mexico's Geologic Mapping Program

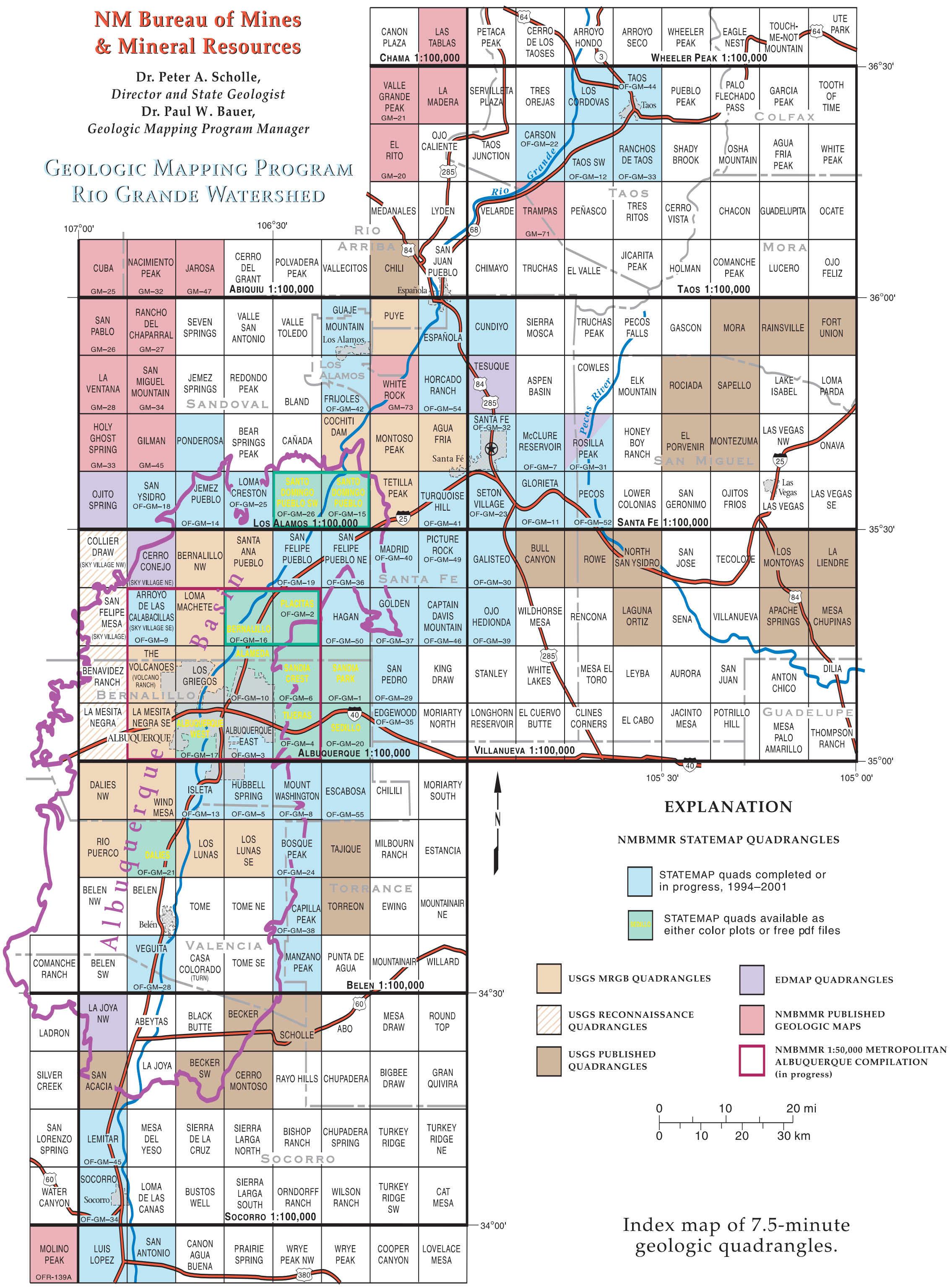
The New Mexico Bureau of Mines and Mineral Resources Geologic Mapping Program (STATEMAP) is partly funded by the National Cooperative Geologic Mapping Program, a federal program administered through the USGS. We are in the 8th year of a project designed to rapidly produce and distribute state-of-the-art, detailed geologic quadrangle maps of select areas of the state. New Mexico is one of the most successful state surveys in the country competing for STATEMAP funds. By June 2002, we will have mapped 60 quadrangles (approximately 2,800 mi^2), mostly along the Rio Grande watershed from Taos to Socorro (Fig. 1). As of July 2000, the NMBMMR had received a total of $1,164,893 from the USGS, the best total in the nation. The program is a matching-funds program; NMBMMR matches all federal monies dollar-for-dollar. Our mapping program is especially important to New Mexico because of the approximately 2,000 7.5-min quadrangles in the state, less than 20% have been mapped at the standard scale of 1:24,000. The most critical unmapped areas are along the population centers of the Rio Grande corridor. Most of the corridor is of vital economic, agricultural, social, and scientific importance to the state. The most pressing challenge to cities along the corridor relates to water. A combination of rapid population growth, permeable alluvial aquifers, large topographic relief, and the alternating scarcity and abundance of precipitation gives rise to a host of hydrogeologic and engineering geologic problems.

Our program is cooperative in the broadest sense. Mapping priorities are set annually by a 35-member State Geologic Mapping Advisory Board composed of hydrologists, geologists, and planners from state, local, federal, pueblo, and private agencies and entities. The quadrangles are selected based on their potential to provide essential earth-science data to planners, engineers, geologists, and hydrologists. The program also represents a cooperative effort between NMBMMR geologists, university faculty and students, private-sector consultants, and the Geologic Division of the USGS. The mapping produces mutually beneficial interactions with a great variety of New Mexican entities (e.g., pueblos, Kirtland Air Force Base, the national laboratories, the cities of Albuquerque, Santa Fe, and Taos, county governments, ranchers, state water agencies, federal land management agencies, etc.).

From the beginning, our project objective has been to characterize the geology of each area in sufficient detail to allow use of the information in matters of practical economic and environmental concern to governments, communities, and planners, as well as to satisfy the fundamental goals of basic science. Based on results of the mapping and the ever-increasing demand for our maps, we have achieved and surpassed this goal.

Congress increased the total funds available to STATEMAP from $4,033,821 in 2000, to $6,660,550 for 2001, an increase of 60%. Much of the success of STATEMAP is due to the requirement that maps be designed to address critical societal and/or scientific problems. In New Mexico, recent concerns about water quality, water availability, geologic hazards (earthquakes, floods, and unstable soils), mineral resources, transportation, and environmental problems throughout the Rio Grande corridor have illustrated the importance of modern, detailed geologic data. Our program has received widespread support and acclaim from political leaders, government agency scientists, university professors, professional hydrologists and engineers, water planners, and others. One of the most visible applications of our maps has been by the USGS to produce a hydrogeologic model of the Albuquerque region.

One of the basic conclusions of scientists involved in the production and use of geologic maps is that the value of geologic maps endures—in addition to their immediate value, there will always be unexpected future benefits from investing in good science now.



Index map of 7.5-minute geologic quadrangles.

Geography and Land Use Status of the Los Alamos Area—A Brief Overview

by *Dennis Erickson*, LA-UR-01-2053, Environment, Health, and Safety Division Director, Los Alamos National Laboratory

Los Alamos National Laboratory is located on 43 mi^2 of land in northern New Mexico, about 25 mi northwest of Santa Fe. The surrounding area is largely undeveloped, and large tracts of land north, west, and south of the laboratory are held by the Santa Fe National Forest, Bureau of Land Management, Bandelier National Monument, General Services Administration, and Los Alamos County. The Pueblo of San Ildefonso borders the laboratory to the east.

The University of California administers the laboratory for the Department of Energy. Since its inception in 1943, the principal mission of the laboratory has been the design, development, and testing of weapons for the nation's nuclear arsenal. Research programs in nuclear physics, hydrodynamics, conventional explosives, chemistry, metallurgy, radiochemistry, and biology support this effort. The laboratory's original mission to design, develop, and test nuclear weapons has broadened and evolved as technologies, United States priorities, and the world community have changed. Today, we use the core technical expertise developed for defense and civilian programs to carry out both our national security responsibilities and our broadly based programs in energy, nuclear safeguards, biomedical science, environmental protection and cleanup, computational science, materials science, and other basic sciences. As the largest institution and the largest employer in the area, the laboratory has approximately 6,800 University of California employees plus approximately 2,800 contractor personnel. Our annual budget is approximately $1.2 billion.

The laboratory is located on the Pajarito Plateau, which forms the eastern flank of the Jemez Mountains. The Pajarito Plateau consists of a series of finger-like mesas separated by deep canyons containing ephemeral and intermittent streams that run from west to east. Mesa tops range in elevation from approximately 7,800 ft on the flank of the Jemez Mountains to about 6,200 ft at their eastern termination above the Rio Grande valley. The eastern margin of the plateau stands 300–900 ft above the Rio Grande. Underlying the plateau is the Bandelier Tuff, a thick sequence of volcanic rock that emanated from the Jemez Mountains.

Most laboratory and community residential areas, Los Alamos and White Rock, are confined to the mesa tops. Laboratory research and development facilities are located in 33 active technical areas across the laboratory site. However, these developed areas account for only a small part of the land area. Most of the land provides buffer areas for security and safety and is held in reserve for future use.

The Pajarito Plateau is a biologically diverse and archaeologically rich area. The laboratory spans the ponderosa and piñon-juniper vegetation zones. Within those vegetation zones, approximately 500 plant species, 29 mammal species, 200 bird species, and 27 reptile and amphibian species are living. About 20 of those species have special status, either threatened, endangered, or species of concern at a federal or state level. About 1,400 archaeological sites on laboratory land document the prehistoric human occupation of the Pajarito Plateau, most from the 14th and 15th centuries.

A Geologic Overview of the Pajarito Plateau and Vicinity

by *David E. Broxton*, LA-UR-01-2055, Los Alamos National Laboratory

Day One

The Pajarito Plateau is a high, east-tilted tableland eroded into a series of narrow mesas separated by deep canyons. Mesa-top elevations range from approximately 7,800 ft on the west to 6,200 ft on the east. This field trip stop is at the White Rock overlook, where the Rio Grande has cut a 900-ft-deep gorge that marks the eastern margin of the plateau. From this vantage point, you can see the Jemez Mountains rising above the Pajarito Plateau on the skyline to the west, the Española Valley in the foreground to the east and northeast, White Rock Canyon and the Rio Grande below, the Cerros del Rio (hills by the river) across the Rio Grande, and the Sangre de Cristo Mountains on the eastern skyline (Fig. 1).

The geology of this region reflects the interplay of faulting, sedimentation, volcanism, and erosion over the past 25 million years. The Jemez Mountains are a broad highland built up by volcanic eruptions over the last 13 million years. During the latter stages of eruption (approximately 1.5 million years ago), cataclysmic explosions from a volcanic center in the central part of the Jemez Mountains deposited thick blankets of volcanic rock and ash (tuff) over the area that is now the Pajarito Plateau (Fig. 2). These eruptions incinerated all life in their paths and covered all existing valleys and hills. Ash layers

FIGURE 1—General geologic and geographic features of the Pajarito Plateau and surrounding areas.

from the eruptions can be found 150 mi south in Socorro. As they accumulated, intense heat and hot volcanic gases welded the tuffs into hard, resistant deposits (known as the Bandelier Tuff) that make up the upper surface of the plateau. As the tuff layers cooled, they developed a complex system of pervasive cooling cracks (known as joints). These joints now provide pathways for movement of ground water. Creeks flowing eastward across the plateau from the Jemez Mountains to the Rio Grande have cut canyons deep into the tuff, forming the scenic mesas and canyons that characterize the present landscape. The Jemez Mountains are not extinct; volcanoes have erupted here many times in the past and will surely continue to do so in the future.

The Española Valley is a basin that began to subside about 25 million years ago. This basin is part of the Rio Grande rift, a major geologic feature of the Rocky Mountain region that consists of north-trending, fault-bounded basins extending from central Colorado to northern Mexico. The Española Basin is a west-tilted trough that is filled with sediments (termed the Santa Fe Group) derived from erosion of the Jemez volcanic highlands, the Sangre de Cristo Mountains, and other highlands to the north. The deepest part of the basin lies just east of the Pajarito fault system, which forms the eastern front of the Jemez Mountains. In general, the rift basins contain major aquifers that are made up of thick wedges of sand and gravel deposited by the ancestral Rio Grande and that can produce large quantities of high-quality water. Sedimentary deposits in the basin also include important fossil localities that contain a variety of late Tertiary (less than 20 million years old) mammals, including species of early horses and camels that went extinct in North America. The Rio Grande became a major river flowing through the Española Basin at least about 5 million years ago. Some time after establishment of the through-flowing Rio Grande, the river stripped much sediment from the valley and transported it downstream toward the Gulf of Mexico. At present, the river seems to be fairly stable; that is, it is neither eroding nor depositing large amounts of sediment.

The present-day White Rock Canyon is a relatively young geologic feature. It was cut by the Rio Grande during the past 2.4 million years. The lower part of the canyon cuts into tan

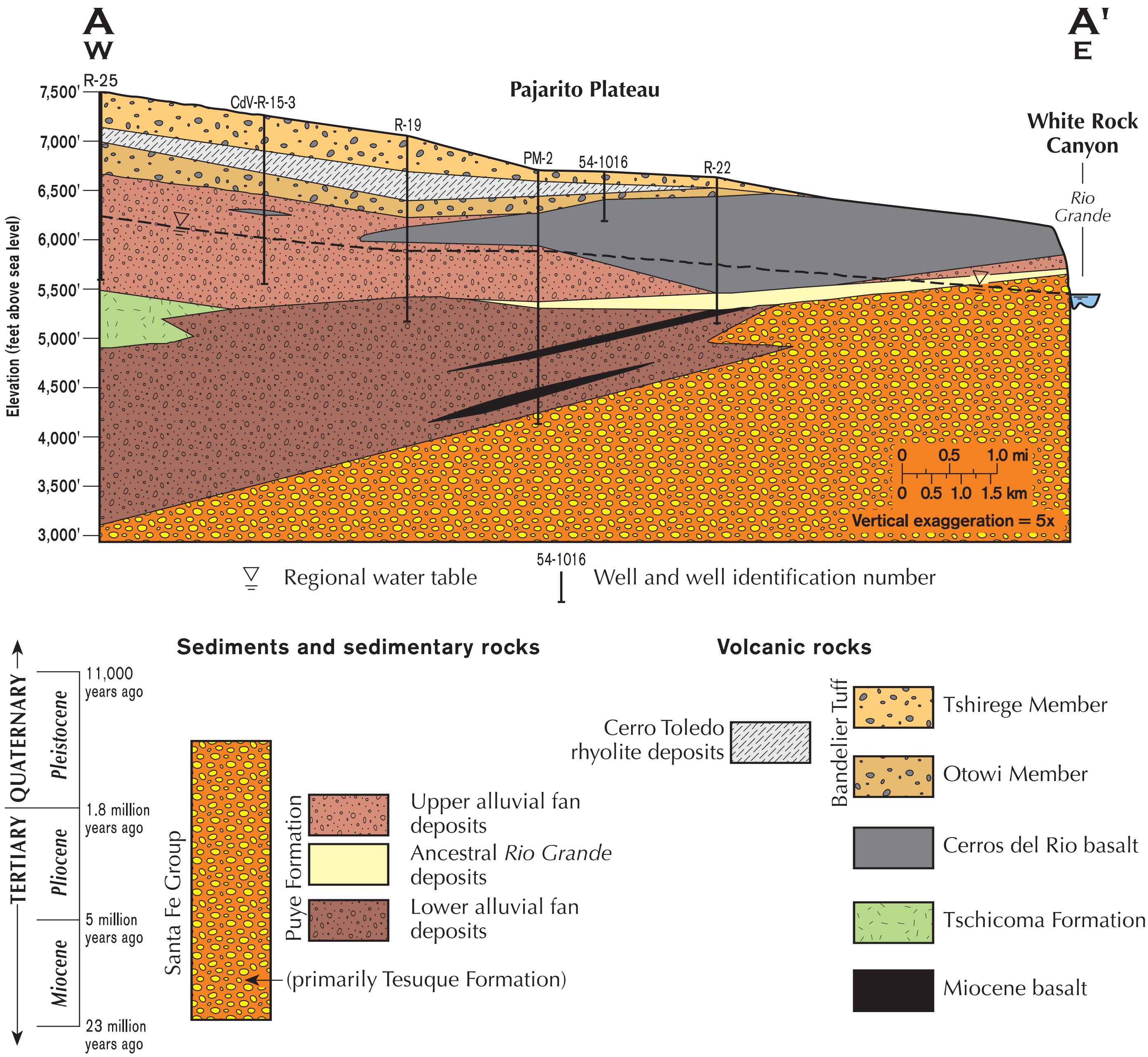


FIGURE 2—East-west cross section showing stratigraphic relations of geologic units making up the Pajarita Plateau. See Figure 1 for location of cross section.

Santa Fe Group deposits that sit beneath the Bandelier Tuff. White Rock Canyon is capped by thick, hard, dark-colored basalt flows derived from cinder cones and small shield volcanoes that make up the Cerros del Rio volcanic field. An excellent example of one of these volcanoes is exposed in cross section at Buckman Mesa, across the river from the White Rock overlook. Numerous landslides have moved large, intact blocks of basalt from the canyon rim to the lower canyon slopes. In the past, such landslides periodically dammed the Rio Grande, causing the formation of temporary lakes that extended as far upstream as Española.

The Sangre de Cristo Mountains are the southernmost range of the Southern Rocky Mountains. This north-trending mountain range contains the highest peaks in New Mexico (for example, the South Truchas Peaks, visible on the skyline to the northeast, are 13,103 ft high). Rocks in the Sangre de Cristo Mountains are considerably older than most other rocks in the area. Granite and metamorphic rocks in the core of the range are as much as 1.6 b.y. old. Sedimentary rocks exposed on the mountain flanks and in parts of the mountain interior range in age from 225 to 290 million years. The present-day form of the Sangre de Cristo Mountains represents two episodes of tectonic uplift. An earlier west- to northwest-trending mountain range formed about 70 million years ago during Laramide deformation of the Rocky Mountain region. This older range was deeply eroded before parts of it were reactivated along north-trending faults 15–20 million years ago during development of the Rio Grande rift. The latest sculpting of the high peaks occurred during the Pleistocene (from 1.6 million to 10,000 years ago) when glaciers and their melt-water rivers carved cirques and steep-walled valleys.

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David Broxton has been involved in a number of projects since joining the laboratory in 1977 including: exploration for uranium resources in Alaska and the Rocky Mountains region, exploration for precious and base-metal deposits in St. Lucia and in Costa Rica, geologic studies of silicic volcanic rocks erupted from the Timber Mountain–Oasis Valley caldera complex in southern Nevada, geologic studies of volcanic rocks as a potential nuclear waste repository in southern Nevada, and hydrogeologic studies of the Pajarito Plateau for the Environmental Restoration Program. His professional interests include the mineralogic and geochemical evolution of volcanic rocks and integrated geologic and hydrologic studies of complex natural systems.

Conceptual Hydrogeologic Model of the Los Alamos Area—A Brief Overview

by *William J. Stone*, LA-UR-01-15, Hydrology, Geochemistry, and Geology Group, Los Alamos National Laboratory

Los Alamos National Laboratory (LANL) is located on the Pajarito Plateau, a deeply dissected expanse of volcanic and sedimentary rocks situated between the Jemez Mountains and the Rio Grande. A sound conceptual hydrogeologic model (a simple, plausible description of the occurrence, movement, and quality of ground water and its relationship to the geologic framework) is essential for effective ground-water protection and environmental restoration. A conceptual model of the region's hydrogeology should address questions such as: Where is the ground water? Where does it come from? Where does it go? and What is its chemistry (or quality)? Despite much previous geologic and hydrologic work, the conceptual hydrogeologic model for LANL is incomplete (Stone, 1996). However, a program to install 32 deep wells under LANL's ground-water protection program (LANL, 1998) is contributing much needed additional information.

Ground-Water Occurrence

The location and extent of ground-water zones at LANL must be known in order to protect, monitor, and remediate them. Ground water exists under three situations at LANL: (1) perched primarily in volcanic tuff or canyon alluvium at shallow depth, (2) perched mainly in basalt at intermediate depth, and (3) in various geologic units beneath the regional water table at greater depth (Fig. 1). Perched ground water originates from the downward percolation of surface runoff through the alluvium in wet reaches of canyons cut into the plateau. This downward movement of water is hindered at fairly shallow depth by the presence of the Bandelier Tuff, which is less permeable than alluvium. Ground water builds up above the tuff, and a perched zone of saturation develops in the alluvium. In some places, downward moving ground water is also perched

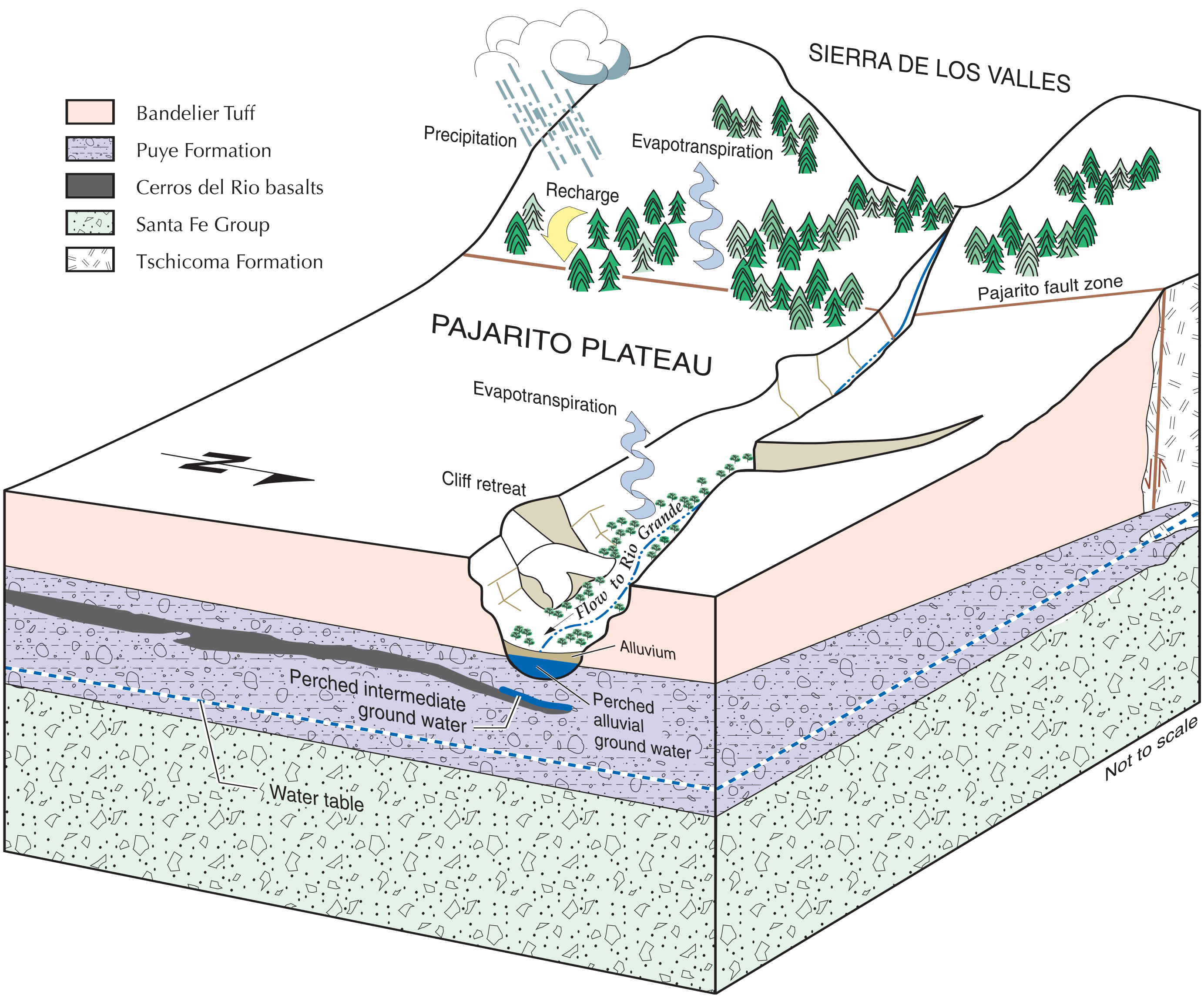

FIGURE 1—Conceptual hydrogeologic model for the Pajarito Plateau (LANL, 1998).

at intermediate depths within the Cerro Toledo interval, the Guaje Pumice Bed, or the Cerros del Rio basalt by underlying materials of lower permeability.

The regional water table lies at depths of less than (<) 100 ft to greater than (>) 1,200 ft below the ground surface, depending on location. Ground water beneath the water table in the deep zone of saturation occurs in various combinations of rock units making up the regional aquifer, including the Tschicoma Formation, Puye Formation, Cerros del Rio basalt, and the Santa Fe Group. This deep ground water is the main source of supply for the communities of Los Alamos and White Rock. Most ground water beneath the Pajarito Plateau is unconfined (not under pressure) and in direct contact with the atmosphere. However, in places near the Rio Grande, ground water in the deep system is confined (under pressure) and rises not only above the level at which it is encountered in wells, but even above the ground surface.

Ground-Water Movement

Understanding ground-water movement is also essential to environmental activities at LANL. The movement of ground water involves three basic elements: (1) recharge or addition of water to a saturated zone, (2) flow of ground water through a saturated zone, and (3) discharge or outflow of ground water from a saturated zone. Recharge and discharge each involve an area, a process, and a rate. Recharge occurs over areas of high elevation (mountains, for example), and discharge occurs at lower elevations (commonly along rivers). Ground-water flow is generally from recharge areas to discharge areas and involves both a direction and a rate.

On regional water-table maps for LANL (Fig. 2), water-level elevation contours have higher values in the west than in the east, indicating that recharge occurs in the mountains west of the laboratory, probably in response to greater precipitation. Recharge processes include infiltration of rainfall, snowmelt, or runoff, followed by deep percolation of any moisture that escapes evapotranspiration. Recharge is especially effective along the ephemeral stream channels in canyons (McLin, 1996), where large volumes of water are periodically concentrated. Rates of recharge of the shallow, intermediate, and deep ground-water systems are not known but probably differ dramatically.

Ground-water flow is generally perpendicular to water-level contours. Water-level maps for the deep regional system show ground-water-flow direction is easterly (Fig. 2). The flow direction for water in the shallow and intermediate systems is uncertain. However, in canyons where there are sufficient wells to make observations, such as Mortandad Canyon, the water table for shallow ground water perched in the alluvium slopes toward the east, like the canyon floor (Stone, 1995). Intermediate-depth perched ground water, monitored in wells R-9 and R-12 in the Cerros del Rio basalt, occurs at a higher elevation than Basalt Spring (Broxton et al., 2000a, b), which discharges from the same unit farther east in lower Los Alamos Canyon. These data suggest that flow in the intermediate system also has an eastward component.

The rate of ground-water flow beneath the Pajarito Plateau varies with the hydraulic properties (hydraulic conductivity and transmissivity) of the various saturated materials. Field tests at the new deep wells are providing much needed data. Slug-injection or pumping tests at wells R-9i, R-15, R-19, R-31, and CdV-R-15-3 have yielded preliminary hydraulic conductivity values ranging from <1 to 37 feet per day (ft/d) for the Cerros del Rio basalt, from <1 to 2 ft/d for the Puye Formation, and from 17 to 20 ft/d for the Santa Fe Group. These values may be revised after test data have been more thoroughly analyzed, but give a general idea of at least the relative potential rates of ground-water movement. Laboratory analysis of selected core samples provides additional data. Such analyses of samples from a wide range of geologic units encountered in wells R-9, R-12, and R-25 have yielded saturated hydraulic conductivity values of up to 0.5 ft/d (Stone, 2000).

The shallow, intermediate, and deep ground waters discharge in different ways in different settings. Shallow ground water in the alluvium is either forced to the surface by bedrock highs to support streamflow downstream, or seeps into the underlying geologic unit, presumably to continue downward or lateral percolation. Ground water in the intermediate-depth perched zones either discharges at down-gradient springs along canyon walls or continues to percolate downward toward the regional water table. The Rio Grande is the discharge point for both the easterly flowing deep ground water beneath the Pajarito Plateau and the ground water flowing west through the Española Basin.

Ground-Water Quality

An understanding of natural and impacted ground-water chemistry is essential to interpreting ground-water monitoring

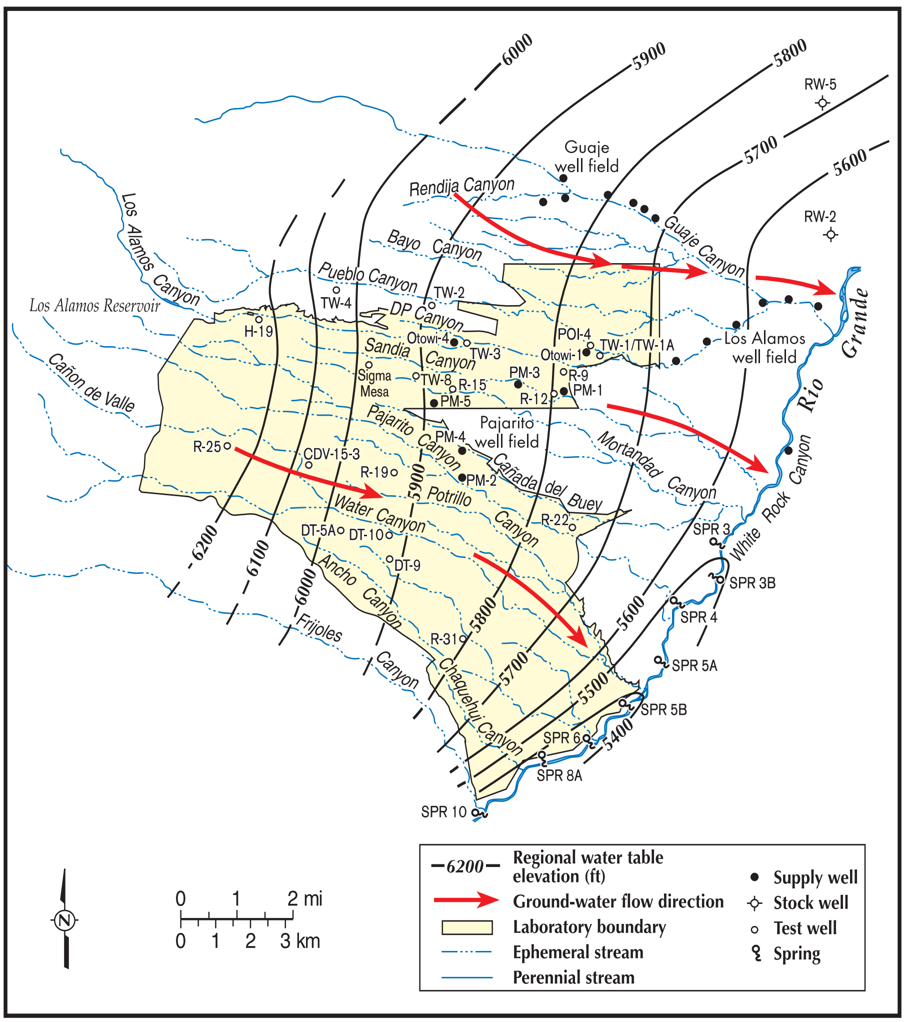

FIGURE 2—Regional water-level map for the Los Alamos area (Purtymun, 1984).

results and determining clean-up levels. The natural quality of ground water is a result of the chemistry of the recharging water(s), the mineralogic composition of the geologic materials through which it has flowed, and the length of time it has been in contact with that material. Although concentrations of major ions and trace metals have been observed to increase along flow paths and with depth in the regional aquifer, the water is classified as a calcium-bicarbonate type in both its recharge and discharge areas (Longmire et al., 2000). The distance the water travels and the variation in aquifer material between these points is not great enough to produce a change in major-ion chemistry.

The natural or background water quality is locally modified by the addition of contaminants from historical human activities at the laboratory. Ground-water quality is monitored at LANL by means of a surveillance network that targets each of the three aquifer systems. This network consists of wells in the shallow perched systems in the canyon alluvium (sampled when they contain water), two wells and one spring representing the intermediate-depth perched system, and 21 wells and numerous springs associated with the deep regional system. Samples are analyzed for a wide range of constituents (major ions, metals, radionuclides, and organics) and various chemical parameters. Results are reported annually in the laboratory's environmental surveillance reports (for example, Rogers and Turney, 1999). Some, if not all, of the new deep wells will eventually supplement this network and become a part of the surveillance program.

Conceptually, contaminants should show up first in the shallow and intermediate-depth perched ground waters, whereas their detection in the regional ground-water system should be less common because of its great depth. Monitoring has generally confirmed this. The occurrence of contaminants in the perched waters, sometimes at levels exceeding standards, is a serious concern as they could eventually migrate to the deep regional water supply. Deep percolation of contaminants is evidenced by their detection in the regional ground-water system. Ground-water flow and transport modeling (for example, Keating et al., 1999; Longmire and Counce, 2000) is providing insight as to the current and probable future extents of contaminant plumes at LANL. Recent improvements in waste-disposal practices and continuing contaminant-source-removal efforts, as well as the deep drilling program, are positive ground-water protection steps at the laboratory.

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Runoff, Erosion, and Restoration Studies in Piñon-Juniper Woodlands of the Pajarito Plateau

by *Craig D. Allen*, U.S. Geological Survey, Jemez Mountains Field Station,
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Piñon-juniper woodlands are one of the most extensive vegetation types in New Mexico, including large portions of the Pajarito Plateau. The woodland soils on local mesas largely formed under different vegetation during cooler, moister conditions of the late Pleistocene; in other words, they are over 10,000 years old, and many are over 100,000 years old (McFadden et al., 1996). Changes in climate and vegetation in the early Holocene (8,500–6,000 years ago) led to at least localized episodes of soil erosion on adjoining uplands (Reneau and McDonald, 1996; Reneau et al., 1996). During this time, the dominant climatic and associated vegetation patterns of the modern southwestern United States developed, including grasslands, piñon-juniper woodlands, and ponderosa pine savannas (Allen et al., 1998). On the basis of local fire history, the young ages of most piñon-juniper trees here, and soils data, we believe that many upland mesa areas now occupied by dense piñon-juniper woodlands were formerly more open, with fewer trees and well-developed herbaceous understories that: (1) protected the soil from excessive erosion during intense summer thunderstorm events, and (2) provided a largely continuous fuel matrix, which allowed surface fires to spread and maintain these vegetation types (Fig. 1). In contrast, rocky canyon walls have probably changed relatively little through the centuries, as grazing and fire suppression had fewer effects on such sites.

Native American effects on local woodlands are thought to have been insignificant or highly localized until the late 12th century, when the Ancestral Puebloan population began to intensively occupy and utilize the Bandelier area (Powers and Orcutt, 1999). Piñon-juniper woodlands were the core area of occupation by these prehistoric agriculturalists—most of the more than 2,500 archaeological sites recorded in the part (~50%) of the park surveyed to date are found in piñon-juniper woodland settings. Cutting and burning of piñon-juniper trees for cooking, heating, building, and agricultural activities likely led to significant deforestation of upland mesas from about 1150 to 1550 A.D. Thus, Ancestral Puebloan land use practices favored herbaceous vegetation. Intensive soil disturbance certainly occurred in farmed areas and around habitations, but there was probably little net change in landscape-wide erosion rates due to the small size and dispersed locations of fields and villages.

FIGURE 1—Grassy ground cover and surface fires once maintained more open conditions in many piñon-juniper woodland settings.

Euro-American settlement of the adjoining Rio Grande valley and the introduction of domestic livestock grazing began in 1598. It is unlikely, however, that significant livestock grazing (that is, with substantial widespread effects on the herbaceous understory, fire regime, or erosion rates) took place in much of Bandelier until railroads linked the Southwest to commercial markets in the 1880s. Millions of sheep and cattle were placed in the New Mexico landscape at that time, with unrestricted grazing on public lands. Livestock grazing continued in Bandelier until 1932, and feral burros were similarly allowed to cause grazing impacts until about 1980 (Allen, 1989). Sharp reductions in the herbaceous ground cover and associated organic litter resulted (Fig. 2), effectively suppressing previously widespread surface fires (in concert with institutionalized fire suppression initiated by the federal government after 1910). Severe drought during the 1950s contributed to declines in ground cover (Allen and Breshears, 1998). Fire-sensitive piñon and juniper trees became established in densities unprecedented for at least the past 800 years. As these trees grew, they became increasingly effective competitors for water and nutrients. Thus, a positive feedback cycle was initiated that favors tree invasion and decreased herbaceous ground cover on mesa top.

This land use history has caused the degraded and unsustainable ecosystem conditions observed in many piñon-juniper woodlands today. Intensive watershed research over the past decade, involving collaborations among Los Alamos National Laboratory, U.S. Geological Survey, Colorado State University, U.S. Forest Service, and Bandelier National Monument, shows that the intercanopy soils of Bandelier's woodlands are apparently eroding at net rates of about one centimeter per decade (Wilcox et al., 1996a,b; Davenport et al., 1998; unpublished data). Given soil depths averaging only 1–2 ft in many areas, entire soil bodies across extensive areas will soon be lost (Fig. 3). Also, this accelerated runoff and erosion is damaging thousands of archaeological sites at Bandelier; over 90% of inventoried archaeological sites are being damaged by soil erosion (Powers and Orcutt, 1999; unpublished data). For example, we have found as many as 1,040 cultural artifacts (mostly potsherds) moved by a single thunderstorm into a sediment trap draining only ¼ acre of gentle hillslope (Fig. 4). To a significant degree, the park's biological productivity and cultural resources are literally washing away, posing major management challenges (Sydoriak et al., 2000). Similar histories and high erosion rates likely characterize many piñon-juniper woodlands in New Mexico (Gottfried et al., 1995; Bogan et al., 1998), resulting in considerable transport of sediment through watersheds, with associated impacts on water quality.

Ecological thresholds have apparently been crossed (Fig. 2) such that harsh physical processes are now dominant across Bandelier's degraded piñon-juniper woodlands (Gottfried et al., 1995; Davenport et al., 1998). The loss of organic-rich topsoils, impeded plant-available water (Breshears and Barnes, 1999), extreme soil surface temperatures, and freeze-thaw activity severely impede herbaceous vegetation establishment and productivity (Davenport et al., 1998). Reductions in ground cover cause increased runoff from summer thunderstorms (Reid et al., 1999), with associated increases in erosion (Wilcox et al., 1996a,b). Re-establishment of herbaceous ground cover under today's desertified mesa-top conditions may also be difficult due to depleted soil seed banks, highly efficient seed predators (particularly harvester ants; Snyderman and Jacobs, 1995), and an unnaturally large elk

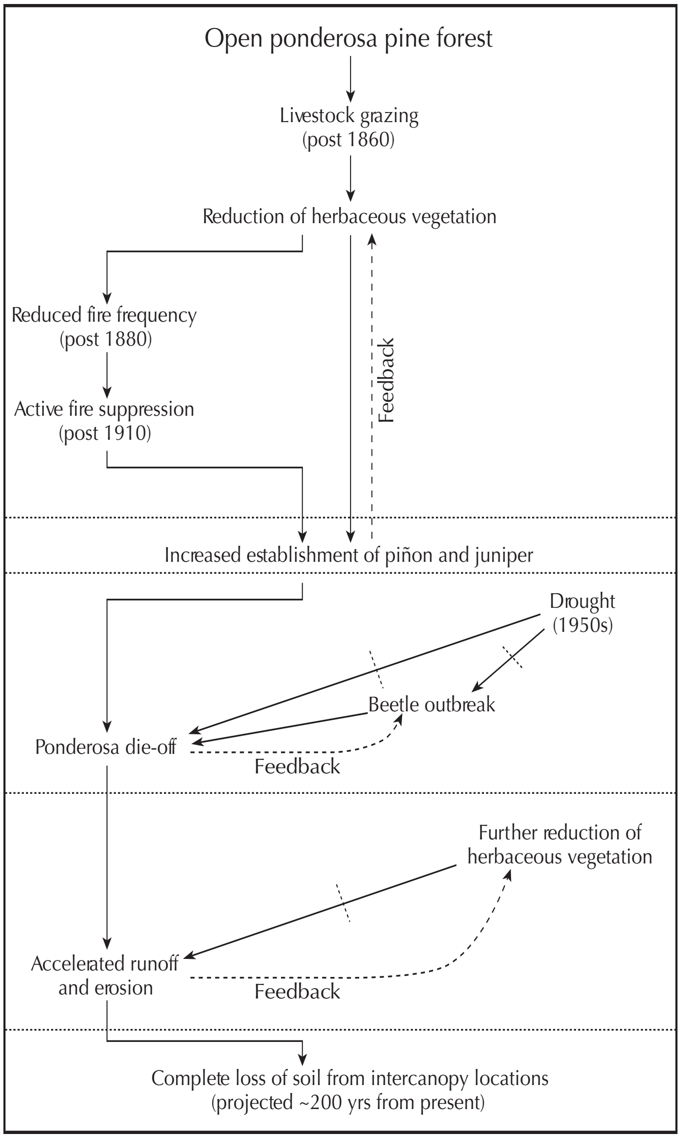

FIGURE 2—Historic changes in forest/woodland border (ecotone) areas on Frijolito Mesa, Bandelier National Monument (Davenport et al., 1998; Allen and Breshears, 1998). Short-dotted lines represent ecological thresholds.

population. Herbivore exclosures established in 1975 show that protection from grazing, by itself, fails to promote vegetative recovery in Bandelier's piñon-juniper ecosystems (Chong, 1992; Potter, 1985). Without management intervention, this human-induced episode of accelerated soil erosion appears to be highly persistent and irreversible (Davenport et al., 1998).

Happily, experimentation over the past decade shows that a simple, though labor-intensive, treatment can restore more stable ecological conditions (Chong, 1994; Jacobs and Gatewood, 1999; Loftin, 1999; Jacobs et al., 2000). By cutting many smaller piñon-juniper trees, and lopping and scattering the branches across the barren interspaces between trees, herbaceous ground cover and soil stability increase markedly (Figs. 5 and 6). It is likely that application of similar methods would restore more sustainable conditions to degraded piñon-juniper woodlands throughout the Southwest.

FIGURE 3—Bare soil and high erosion rates characterize the desertified interspaces between piñon-juniper trees across large areas of the Pajarito Plateau. Note the exposed roots.

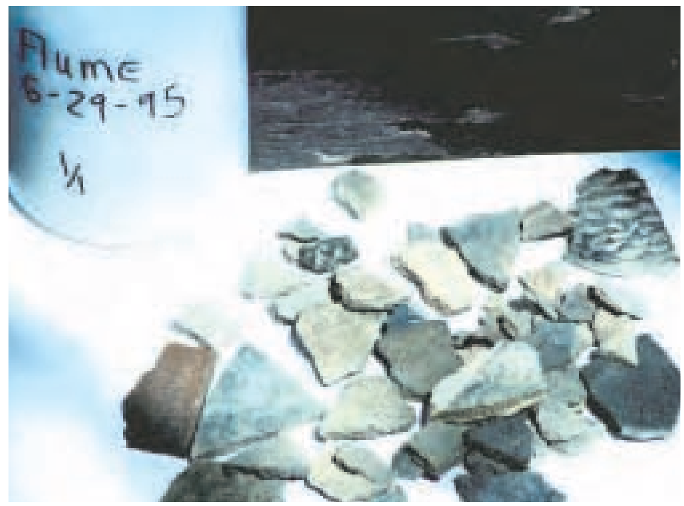

FIGURE 4—Immense numbers of ceramic and lithic artifacts are being transported by accelerated runoff and erosion at Bandelier, degrading the cultural resources for which the park was established. These artifacts were collected from a sediment trap after a single storm.

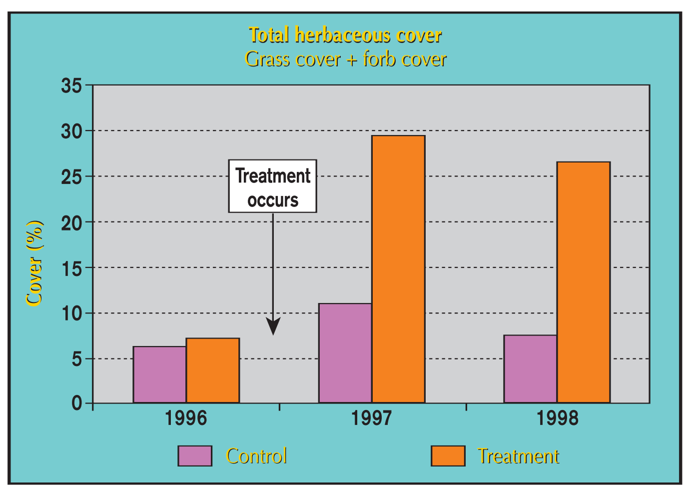

FIGURE 5—Herbaceous cover response to restoration treatment on Frijolito Mesa (Jacobs et al., 2000).

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Day One

FIGURE 6—View of herbaceous cover response to restoration treatment after first growing season.

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Craig Allen is a research ecologist with the U.S. Geological Survey. He received degrees in geography from the University of Wisconsin (Madison), and a PhD focused on forest and landscape ecology from the University of California (Berkeley). He has worked as an ecologist with the Department of Interior since 1989, beginning with the National Park Service through his current post with USGS. Allen conducts research on the ecology and environmental history of southwestern landscapes, oversees the USGS Jemez Mountains Field Station at Bandelier National Monument (New Mexico), and provides technical support to land management agencies in the region. Ongoing research activities with multiple collaborators include: development of vegetation and fire histories in the Southwest; fire effects on Mexican spotted owls, Jemez Mountains salamanders, and nitrogen cycling; responses of semiarid forests and woodlands to drought (and links to global change issues); development of long-term ecological monitoring networks across landscape gradients at Bandelier; dynamics of runoff, erosion, and restoration of piñon-juniper watersheds; and determining elk movements and habitat effects in the Jemez Mountains. Allen lives with his wife, Sharon, and children Kiyana, Benjamin, and Nikolas in Los Alamos.

The Buckman Well Field

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

The Buckman well field, located along the east side of the Rio Grande about 15 mi northwest of Santa Fe, was developed by Public Service Company of New Mexico and put into operation in July 1972 to supply the city of Santa Fe (Fig. 1). During the 1990s, the well field provided 40% of the city of Santa Fe's water, or 4,900 acre-ft/yr. The field consists of eight wells drilled to depths of 1,000 to 1,400 ft below land surface. Water is pumped through a pipeline and conveyed about 15 mi into town for a total lift of nearly 1,400 ft. The capacity of the well field is about 7,130 acre-ft/yr (6.36 million gal per day), much less than the originally anticipated yield of 10,000 acre-ft/yr. The yield of the wells has declined substantially in the last decade due to calcification of the well screen, declining water levels, and possibly formation damage (Fig. 2). Water levels have dropped as much as 700 ft in the last 28 years in production wells and about 90 ft in the shallow, unconfined aquifer. However, the estimated sustainable yield from the well field is about 5,000 acre-ft/yr, even less than the capacity of the wells, due to the relatively low transmissivity of the aquifer and insufficient recharge. The Buckman wells draw water from a confined aquifer that is not replenished at a rate equal to the amount pumped, and the hydrologic connection between the wells and the river is much less than originally conceived.

The Buckman wells are associated with several water rights. They are operated under a permit that allows a maximum pumping rate of 10,000 acre-ft/yr. Impacts to the Rio Grande, the Rio Tesuque, and the Rio Pojoaque from pumping the Buckman wells must be offset with existing water rights. Presently, the city uses San Juan-Chama (SJC) water to offset impacts to the Rio Grande. The city of Santa Fe and Santa Fe County together have SJC contract rights of 5,605 acre-ft/yr through December 31, 2016, with an option to renew. Irrigation rights have been obtained in the Rio Pojoaque and Rio Tesuque drainage basins to offset depletions of tributary streams.

The State Engineer Office uses a numerical model of the stream-aquifer system to calculate the annual depletions to the Rio Grande and tributaries. At this time the city of Santa Fe (and Las Campanas who have contracted for a percentage of the Buckman yield) have sufficient water rights to meet the offsets for about eight more years on the Nambe-Pojoaque tributary. Continued production of the well field at the historic rate will require purchase or lease of additional water rights on this tributary.

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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. Ms. Lewis is interested in being a sound technical voice as the community struggles to make difficult decisions.

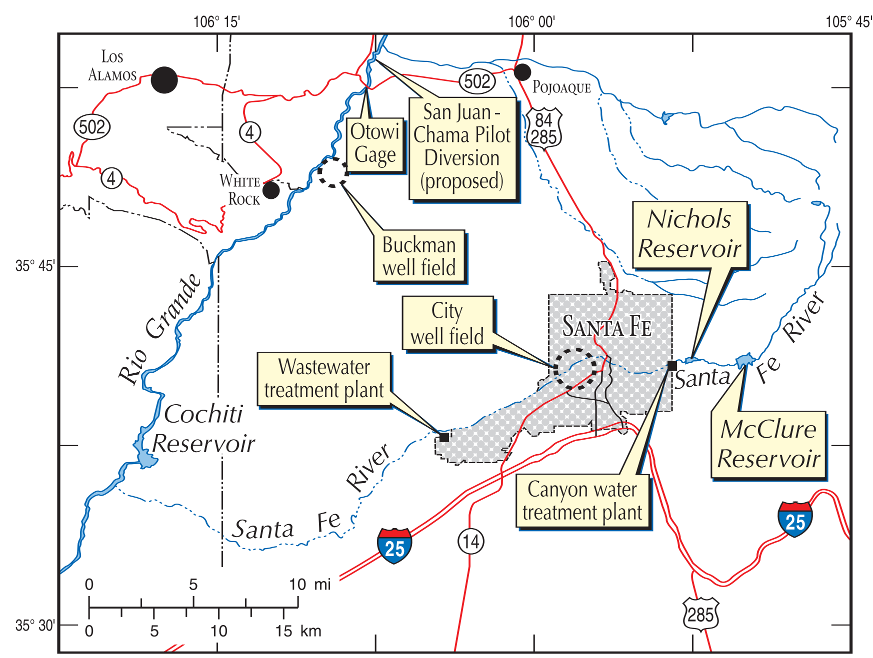

FIGURE 1—City of Santa Fe water supply.

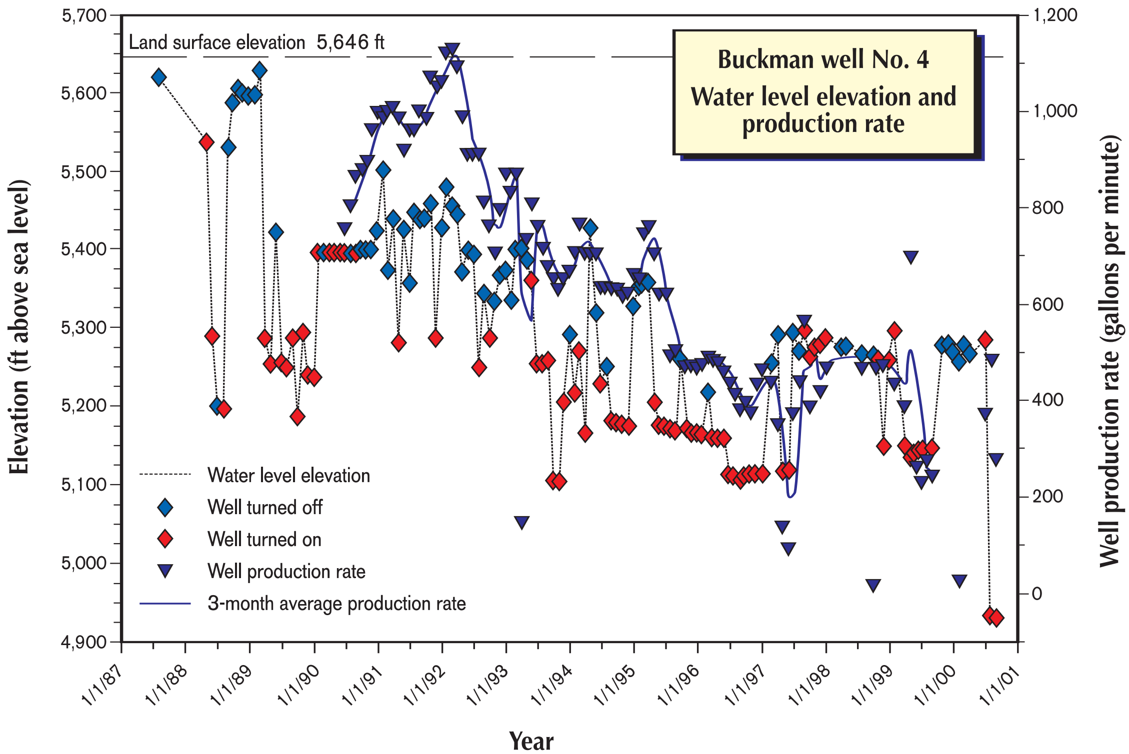

FIGURE 2—Buckman well no. 4 water-level elevation and production rate.

Fire and Vegetation History of the Jemez Mountains

by *Craig D. Allen*, U.S. Geological Survey, Jemez Mountains Field Station,
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Historic patterns of fire occurrence and vegetation change in the Jemez Mountains of northern New Mexico have been described in detail by using multiple lines of evidence. Data sources include old aerial and ground-based photographs, historic records, charcoal deposits from bogs, fire-scarred trees (Fig. 1), tree-ring reconstructions of precipitation, and field sampling of vegetation and soils. The forests and woodlands that cloak the southwestern uplands provide the most extensive and detailed regional-scale network of fire history data available in the world (Swetnam and Baisan, 1996; Swetnam et al., 1999; Allen, in press).

Modern climate/vegetation patterns basically developed in the Southwest about 11,000–8,000 years before present. Substantial fire activity apparently emerged in the Southwest during that time, as evidenced by the contemporaneous and rapid spread of fire-adapted ponderosa pine forests across the region (Anderson, 1989), and by the abundant charcoal deposits found in lake and bog sediments (Brunner-Jass, 1999; Weng and Jackson, 1999). Charcoal sediments from Alamo Bog in the central Jemez Mountains indicate essentially continuous fire activity extending back almost 9,000 years (Brunner-Jass, 1999).

About 5,200 historic fires have been mapped in the Jemez Mountains for the period 1909–1996 from administrative records of local land-management agencies (Fig. 2). Lightning caused fully 75% of the recorded fires, with acreage burned

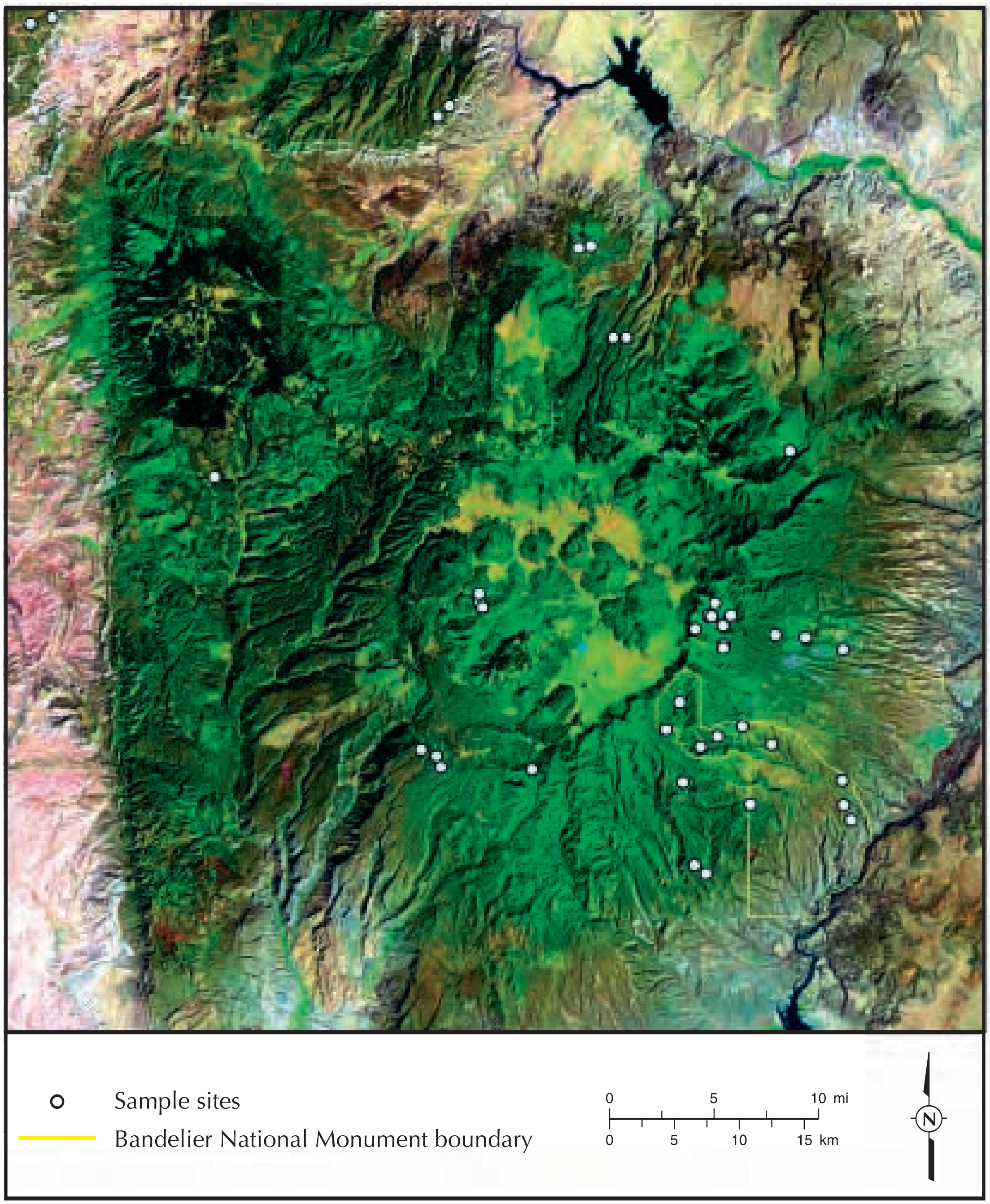

FIGURE 1—Map of fire scar sample site locations in the Jemez Mountains.

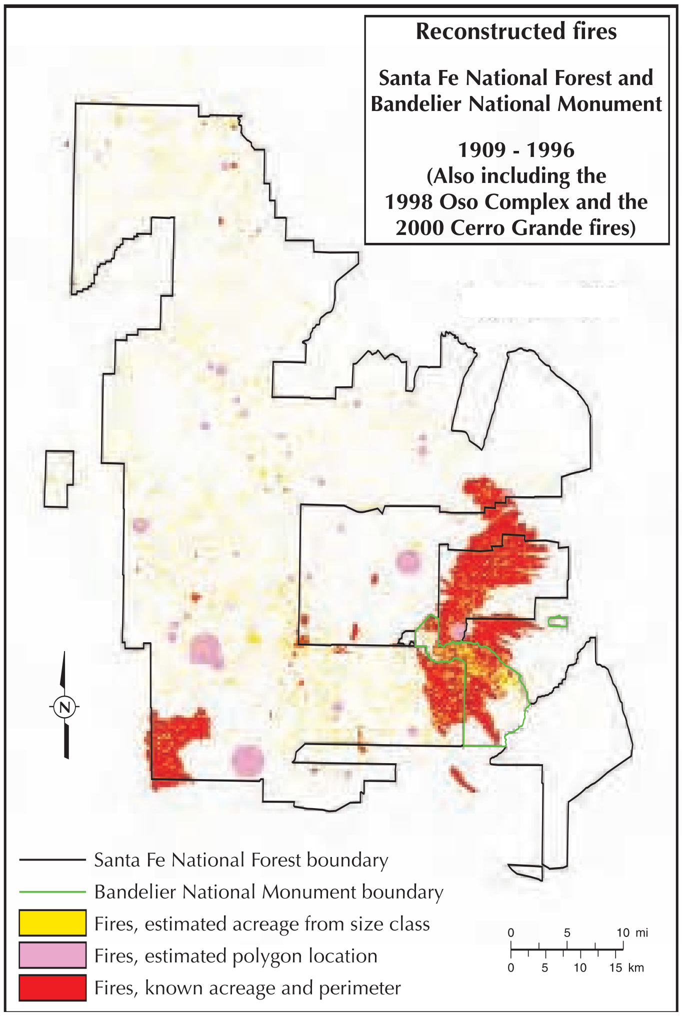

FIGURE 2—Point locations of more than 5,000 historic wildfires in the Jemez Mountains, 1909–1996, compiled from the administrative records of land-management agencies (Snyderman and Allen, 1997). Person-caused fires cluster near major roadways, campgrounds, habitations, and other human use areas.

peaking in the dry months of May and June before the onset of summer monsoon rains. High levels of lightning activity naturally foster fire ignitions here. For example, 62 thunderstorm-days/year are observed at Los Alamos, generating large numbers of lightning strikes. An automated lightning detection system recorded 165,117 cloud-to-ground lightning strikes over a 2,994 mi^2 area centered on the Jemez Mountains during the period 1985–1994 (Fig. 3). The annual number of recorded lightning strikes varied between 9,410 and 23,317. Particularly important for fire ignitions is the substantial lightning activity during the warm, dry, foresummer months of April through June. Lightning strikes during this period are the most significant sources of fire ignition because lightning is much more likely to start a spreading fire if it strikes dry fuels. Because lightning ignitions are so frequent and ubiquitous in the Southwest, climate and fuel conditions are the main drivers of fire regime dynamics in this region.

Fire scars were sampled from over 600 trees, snags, and logs at 42 sites around the Jemez Mountains in northern New Mexico (Fig. 1), resulting in over 4,000 dendrochronologically dated fire scars. Fire scar dates extend back to 1422 A.D. These data have been used to develop fire histories at multiple spatial scales, from individual trees to watersheds and finally the entire mountain range. Fire histories were reconstructed for vegetation types ranging from piñon-juniper woodlands up through ponderosa pine forests and mixed conifer forests into high-elevation spruce-fir forests (Touchan et al., 1996; Allen et al., 1996). These fire histories show that frequent, low-intensity surface fires naturally characterized most southwestern forests. These fires spread widely through grassy understory fuels, maintaining relatively open forest conditions (Fig. 4).

Pre-1900 mean fire intervals ranged from 5 to 25 years across the Jemez Mountains (Fig. 5). Significant spatial variation in past fire regimes is evident, depending upon such local factors as vegetation/fuel type, topography, and land-use history. Fire frequencies and area burned have been greatest in mid-elevation ponderosa pine forests. Fire activity commonly occurred over extensive areas (Allen et al., 1998); for example, watershed-wide fires occurred about every 16 years across the 9-mi-long Frijoles watershed in Bandelier before 1900 (Allen, 1989). In some years fires apparently burned across most of the Jemez Mountains (Allen et al., 1998), and indeed even across the Southwest (Swetnam et al., 1999; see graphics at: http://biology.usgs.gov/luhna/chap9.html).

Climate variability acted to regionally synchronize prehistoric fire activity, as major fire years were clearly associated with drought conditions, while wet periods recorded little fire activity (Touchan et al., 1996; Swetnam and Baisan, 1996; Swetnam and Betancourt, 1998). The most extensive fire activity in ponderosa pine forests occurred in dry years that followed within 1–3 years of wet conditions. This pattern of major fire years suggests the importance of both fuel production and fuel moisture in these fire regimes, with antecedent wet conditions stimulating the buildup of continuous fuels and subsequent drought conditions enabling the fuels to burn widely (Swetnam and Baisan, 1996). The common occurrence of persistent drought conditions in the Southwest likely allowed some fires to burn for months.

In most cases the seasonality of fire occurrence can be inferred by the relative position of a fire scar within the annual growth rings. The patterns of fire seasonality developed from prehistoric fire scars and modern fire records are generally

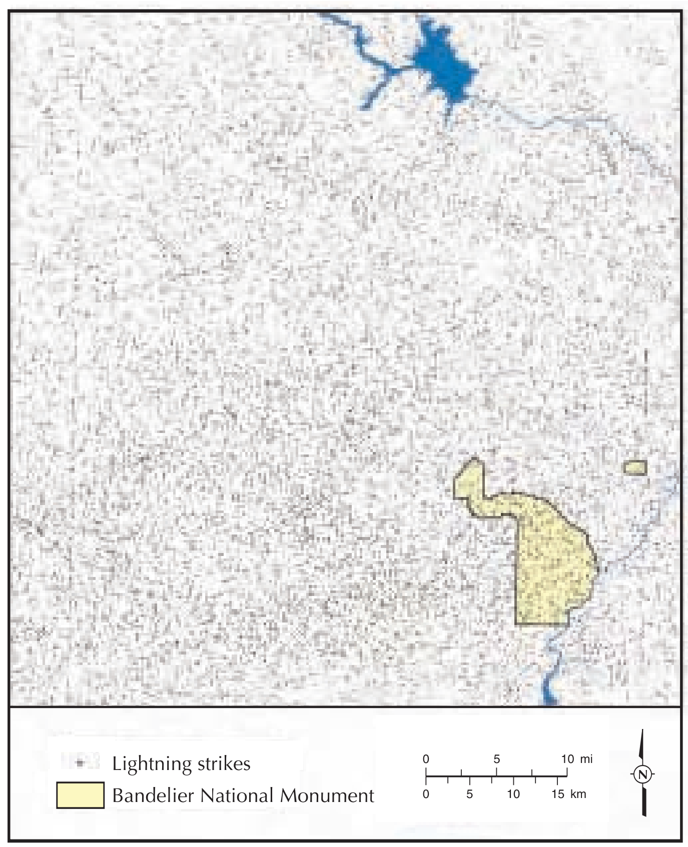

FIGURE 3—Map of 23,317 lightning strikes recorded across 2,994 mi^2 in the Jemez Mountains area during 1986 by the national automated lightning detection system. The nominal resolution of the locational data is ~± 2 km.

FIGURE 4—Open ponderosa pine forest representing "typical" pre-1900 conditions, with grassy understory and surface fire activity.

indistinguishable, indicating that prehistoric fires occurred during the same seasons as modern lightning-ignited fires—predominantly in the spring and summer. Fall fires were rare.

Spatial patterns of consecutive-year fire events indicate the importance of herbaceous fuels in supporting fire spread in pre-settlement forests. Railroads linked northern New Mexico to external markets by about 1880, leading to a local boom in livestock numbers. Abrupt declines in fire frequency throughout the Jemez Mountains in the late 1800s (Fig. 5), decades before active fire suppression, support the hypothesis that overgrazing induced suppression of surface fires as livestock (particularly sheep in mountain forests) literally ate the grassy fuels through which fires previously had spread. Fires would have repeatedly burned across widespread parts of the Southwest during the 20th century if the many natural and human-caused fires had not been vigorously suppressed after 1910 (Swetnam et al., 1999).

This history of livestock grazing and fire suppression in the Jemez Mountains has driven such landscape-wide vegetation changes as: increased density of woody species and accelerated erosion rates in piñon-juniper woodlands; conversion of ponderosa pine forests into thickets (or crown-fire-created grasslands and shrublands); changes in species composition and structure in mixed conifer forests (Fig. 6); and invasion of grasslands and meadows by trees and shrubs (Allen, 1989). Similar changes have occurred throughout the Southwest (Bogan et al., 1998; see graphics at http://biology.usgs.gov/s+t/SNT/noframe/sw152.htm). The increased densities of forests over the past century (often 10-fold increases) have markedly changed many ecosystem processes, including patterns of runoff and water yield from regional watersheds. For example, increased forest densities lead to decreases in total streamflow, peak flow, and base flow (Ffolliott et al., 1989), important concerns in the water-limited Southwest.

Fire behavior has also greatly changed due to the landscape-wide build ups of woody fuels associated with a century of fire suppression. As a result the frequency and severity of wildfire activity (including lightning-ignited fires) has been escalating despite increasing human suppression efforts, as the mean number of lightning fires/year in the Southwest grew by over 50% from 1940 to 1975 (Barrows, 1978) and the mean annual acreage burned has increased continuously since about 1960 (Swetnam and Betancourt, 1998). Unnatural stand-replacing conflagrations like the 1977 La Mesa fire (Allen, 1996), the 1996 Dome fire (Fig. 7), and the 2000 Cerro Grande fire are occurring more often in over-dense ponderosa pine forests

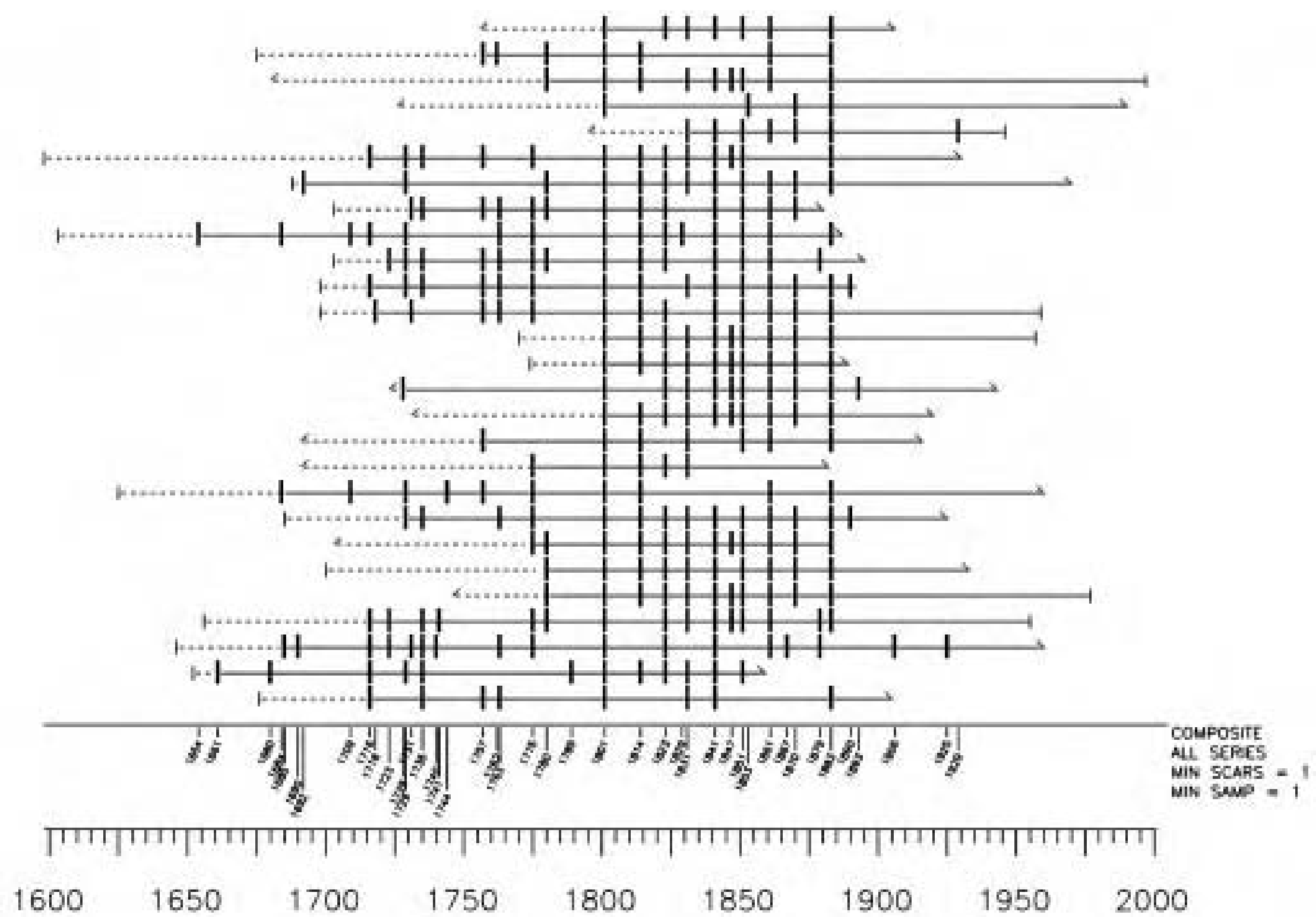

FIGURE 5—Fire scar chronology for Quemazon locality, western edge of Los Alamos townsite. Horizontal lines represent the life spans of individual trees, while fire scar events are shown by short vertical bars. Fire years are listed along the lower axis.

Day One

FIGURE 6—Altered ponderosa pine stand in need of restoration, showing changes in both stand structure and species composition. The dense midstory of mixed conifer trees provides ladder fuels that favor crown-fire development.

FIGURE 7—Dome fire, Day 2, April 26, 1996, near headwaters of Capulin Canyon.

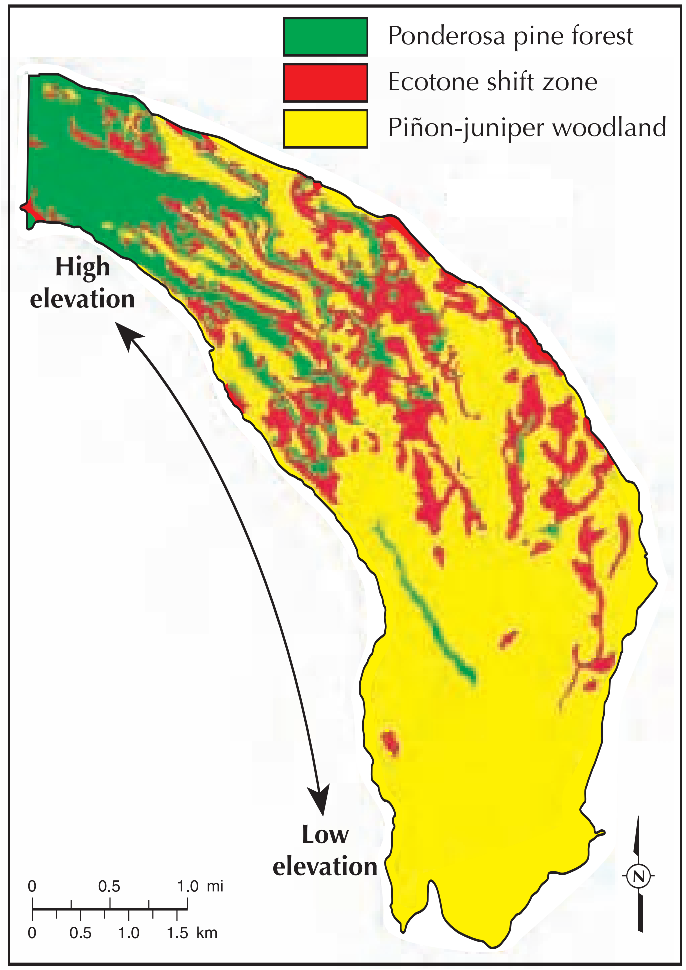

FIGURE 8—Changes in vegetation cover between 1954 and 1963 on Frijolito Mesa in Bandelier National Monument, showing persistent ponderosa pine forest (1.4 mi^2), persistent piñon-juniper woodland (5.9 mi^2), and the ecotone shift zone (1.9 mi^2) where forest changed to woodland due to the death of the overstory ponderosa pine trees.

(Covington and Moore, 1994). Extensive (>0.5 mi^2) stand-replacing fires rarely (if ever) occurred in pure, southwestern ponderosa pine forests before the middle of the 20th century. Severe crown fires typically cause major watershed impacts, including accelerated flooding and erosion. Twentieth century landscape scars created by stand-replacing fires in ponderosa pine and lower elevation mixed conifer are long-lasting legacies of human error in managing these ecosystems. Recovery of forest communities within such burned and eroded landscapes may not occur for centuries. Fire history data and evidence of extreme geomorphic responses following extensive crown fires provide strong justification for management programs aimed at preventing the future occurrence of these ecological and societal disasters (Covington et al., 1997; Allen et al., in revision).

It is interesting to note that droughts can also cause extensive ecosystem changes by rapidly killing vegetation. For example, a severe, regional drought occurred during the 1950s in the Southwest. Associated tree mortality in the Jemez Mountains caused the ecotone between ponderosa pine forests and piñon-juniper woodlands to shift upslope by as much as 1.2 mi in less than 5 years (Fig. 8), while mixed piñon-juniper woodlands were converted to overstories of only juniper at many sites (Allen and Breshears, 1998). The 1950s drought may have also reduced herbaceous ground cover in these ecotone zones, contributing to current high erosion rates (discussed in a separate minipaper). Projected global climate changes may render over-dense southwestern forests increasingly susceptible to rapid decline through drought-induced mortality, associated insect outbreaks, and crown fires (Swetnam and Betancourt, 1998).

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The Cerro Grande Fire, Santa Fe National Forest, May 2000

by *Kevin Joseph*, U.S. Forest Service, Santa Fe National Forest

The Cerro Grande fire began as a prescribed fire in the Bandelier National Monument on May 5, 2000. On the afternoon of May 6, 2000, the prescribed fire was declared a wildfire due to adverse fire behavior and the prescribed-burn parameters exceeding acceptable levels. The fire was torching and crowning in the canopies of the trees resulting in spot fires outside of the control lines and rates of spread and fire intensities that exceeded the capabilities of the suppression forces to control. In the end, the Cerro Grande fire was the most devastating forest fire in the history of New Mexico in terms of acreage burned (47,650; Fig. 1), homes and structures lost (over 235), disruption of the local economy, impacts to the Los Alamos National Laboratory, and impacts and disruption of the lives of the residents of Los Alamos County, which will be felt for years to come. Though there were no fatalities, the Cerro Grande fire was the worst prescribed-fire loss in the history of the United States in terms of size and property losses.

The final cost of the Cerro Grande fire is estimated to amount to over 1 billion dollars in suppression and rehabilitation costs, damage and loss of property, business/economic losses, and preparing for flood damage to roads and communities. Luckily, no human lives were lost. However, no economic price tag can be placed on the personal loss felt by those who were directly affected by the Cerro Grande fire.

The drought conditions in the Southwest for 3 years immediately before the Cerro Grande wildfire and the very dry winter and spring in 2000 caused fuel moistures of both live and dead fuels (trees, chaparral, shrubs, and grasses) to be extremely low. Very dry and drought-stressed-forest fuels contribute to active fire behavior, which includes high fire intensities, long flame lengths, rapid rates of fire spread (including the initiation and sustained spread of crown fires in standing timber), and spot fires up to 1 mi in front of the main fire. This is the type of fire behavior that manifested itself when the fire made a very rapid downhill run toward the city of Los Alamos on Sunday, May 7.

Fire behavior in forest fuels is a result of the dynamics of weather, fuels, and topography. The timbered fuels in the Cerro Grande fire area, and in and near the city of Los Alamos, were very dense as they are throughout much of the Jemez Mountains. The heavy fuel load, made up of very dense stands of ponderosa pine and mixed conifer trees, which were extremely dry due to drought conditions, and the adverse fire weather during the initial escape of the Cerro Grande fire resulted in "blow-up" fire behavior conditions.

On Sunday, May 7, when the fire made its initial run toward Los Alamos and again on Wednesday, May 10, when the fire burned through residential areas in Los Alamos destroying homes, the fire weather conditions forecasted and observed included record high temperatures, low relative humidity of approximately 8% to 12%, a very dry and unstable atmosphere, and very strong southwest to west winds. These were the conditions that existed during the first 12 days of the fire when the fire exhibited extreme fire behavior and made large increases in acreage.

On Sunday, May 7, the Cerro Grande fire made an afternoon run of 4 mi in approximately 5 hrs (Fig. 1). Driven by extremely strong winds, the fire moved off Cerro Grande Mountain and spread downhill at sustained rates of ½–¾ mph and maximum rates of spread as high as 1½ mph. Observed spot fires were up to 1 mi in front of the main fire. Observed flame lengths were up to 200 ft higher than the tops of the trees. This was a sustained, crown-fire run. The direction of spread was northeast, and the fire was moving for the Camp May Road and NM–501 area.

A backfiring operation along the Camp May Road and NM–501 successfully stopped the head of the fast moving fire. This allowed 3 days to begin the evacuation of Los Alamos before Wednesday, May 10, when the fire burned through residential areas of Los Alamos destroying homes and leveling subdivisions. This dramatic fire run spread approximately 8 mi in 12 hrs (Fig. 1).

The Cerro Grande fire spread approximately 13 mi north from its point of origin before slowing down and finally stopping in Santa Clara Canyon in response to more favorable weather and topographic conditions. This allowed suppression forces to begin line construction and burnout operations that were successful in containing the fire spread from continuing to the north.The fire was contained on July 20, 2000, and was declared *out* on September 22, 2000.

The Cerro Grande fire certainly was historical for the state of New Mexico not only in terms of acres burned, structures/homes lost, and economic loss and hardship but also in terms of the severity of the burned area and the subsequent long-term rehabilitation that will occur. The Viveash fire that burned in the Pecos–Las Vegas Ranger District (Santa Fe National Forest) in the summer of 2000 exhibited the same extreme fire behavior, including extremely rapid rates of spread; sustained, high-severity, crown-fire runs; long-range spotting; resulting runoff damage to infrastructure; and the need for long-term, burned-area rehabilitation.

The Cerro Grande fire aftermath resulted in changes to the way we plan and conduct prescribed-fire operations in the federal land-management agencies. More extensive and detailed planning and peer agency review is required. The changes include adding extensive fire-use policies covering implementation planning, personnel certification, fire-use projects, prescribed-fire project assessment, interagency cooperation, contingency planning, prescribed-fire implementation actions, and line officer reviews. In essence, plans are required to be more detailed and thought out with additional plan reviews at several levels.

What we are now experiencing in the state of New Mexico, in terms of fire behavior, fire severity, and large-fire growth, is a mirror of what has occurred nationally for the past 15 years. In the past decade, in the Southwestern Region of the Forest Service, we have seen very large, rapidly spreading crown fires with long-range spotting—these fires threaten communities and lives.

In the past 4 years, the Santa Fe and Carson National Forests and surrounding areas have experienced fires more severe than have been seen here before (Dome fire, 16,774 acres, 1996; Hondo fire, 8,500 acres, 1996; Oso fire, 5,200 acres, 1998; Cerro Grande fire, 47,650 acres, 2000; Viveash fire, 28,500 acres, 2000).

Nationally, since the mid 1980s, we have seen very large, rapidly spreading fires that we were unable to suppress (California, 1987; Yellowstone, Northern Rockies, 1988; Idaho, 1989, 1992; Colorado, Utah, Idaho, 1994; Utah, 1996; Texas, Florida, 1998; Southern, Central, Northern Rockies, 2000). Only late fall or winter rain or snow is successful at stopping these types of fires, which burn for months and occur in all western states. These fires are very destructive and dangerous as well. There has been a dramatic increase in the number of fire shelter deployments and entrapment situations in the past 15 years. Unfortunately, there has also been a dramatic increase in the number of fire line fatalities—there were 34 fatalities in 1994 alone!

This type of fire behavior and the huge increases in acreage burned are a direct result of the buildup of fuels throughout

Cerro Grande fire progression
5 May 2000–18 May 2000

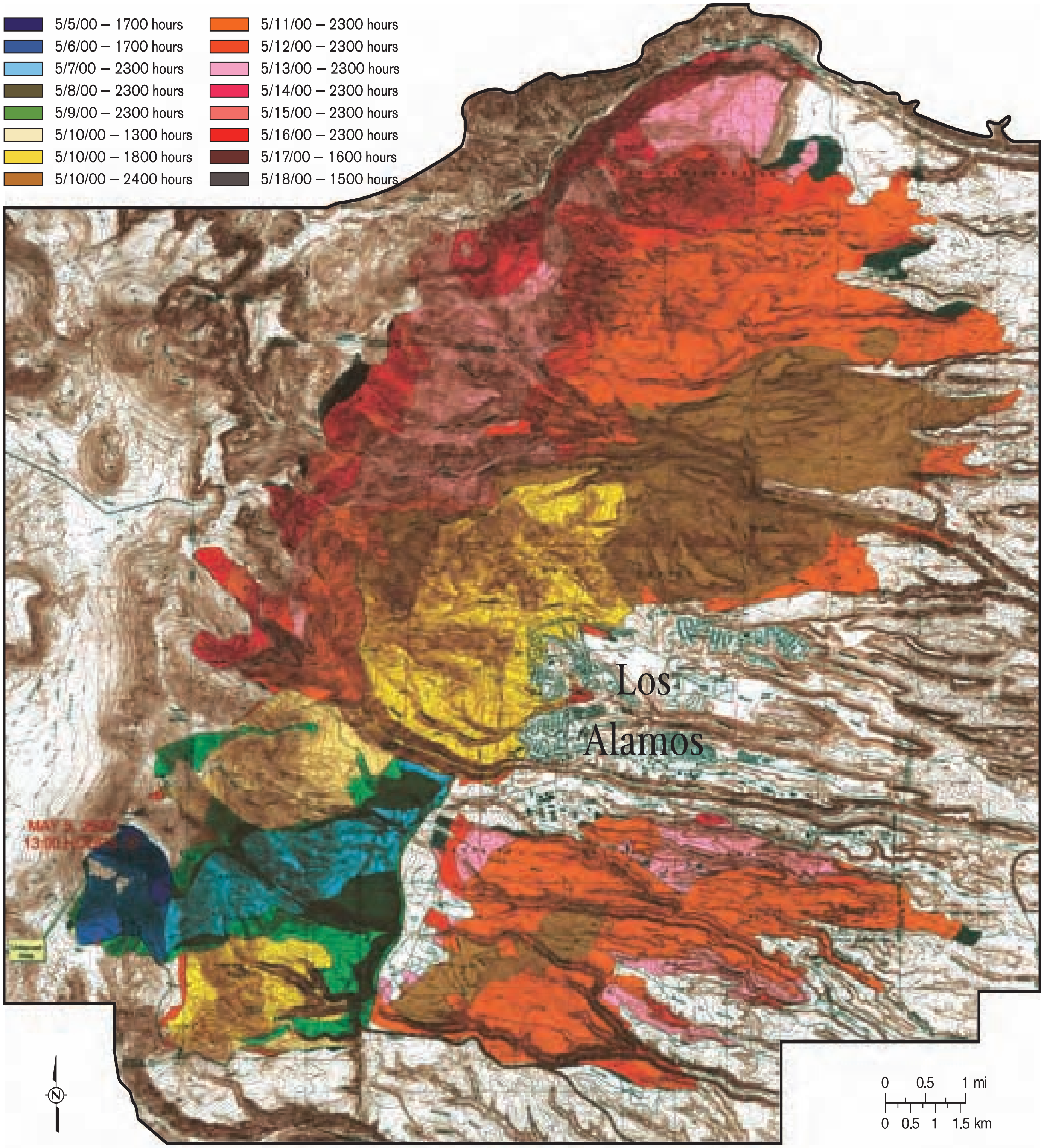

FIGURE 1—Fire progression by time of Cerro Grande fire, May 2000.

the western forests due in large part to forest-fire suppression for the past 100+ years. Drought years that reduce fuel moistures in forest fuels, coupled with heavy fuel loads that have a high dead-fuel component within the fuel bed, are conducive to large, fast-spreading, high-severity wildfires. These are conditions that prevail in New Mexico. Consider the past 10 years. The big fire in the Lincoln National Forest in 1990 was at that time the largest forest fire in New Mexico's history, with 30,000 acres burned. The Cerro Grande fire in 2000 was 47,650 acres burned!

The outlook for the future is dim. Because of dense and deteriorating forest stand conditions throughout the western United States, large, high-severity wildfires that destroy communities and threaten lives are common. Our only defense against these conflagrations is an aggressive fuels-management program where all forest-management tools are at our disposal. These management tools include mechanical treatments such as thinning and prescribed fire. Fire prevention and education programs geared specifically for homeowners and communities in the wild land/urban interface are equally important. Additionally, we must continue to improve and increase our federal fire-suppression forces at all levels.

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Aspen grove burned by the Cerro Grande fire of May 2000, just west of Los Alamos. Photograph by David McCraw.

Impacts of the Cerro Grande Fire on Santa Clara Pueblo

by *Alvin Warren,* Santa Clara Pueblo

Santa Clara Pueblo is a community deeply rooted in the natural environment that encompasses it. A federally recognized Indian tribe with about 2,500 members, Santa Clara is located in northern New Mexico 30 mi north of Santa Fe along U.S. Highway 84/285. Since time immemorial, the Santa Clara people have used and occupied the 25-mi-long Santa Clara Creek and over 100,000 acres of the land surrounding it in the Jemez Mountains, Pajarito Plateau, and Rio Grande valley of northern New Mexico as our ancestral homeland. Currently, the total land area within the exterior boundaries of the Santa Clara Pueblo Reservation is 55,091 acres and comprises two patented Spanish land grants, a reservation created in 1905 by Presidential executive order, and several purchase areas. From traditional potters to Los Alamos National Laboratory technicians, and from tribal officials to construction workers, all Santa Clara people turn to the land as part of our daily lives: to hunt or fish, to gather firewood or building materials, to collect clay or ash for pottery, to conduct cultural activities, to bring water to irrigate our crops, and to graze our livestock. From this perspective it is understandable why the devastation wrought by the Cerro Grande fire on Santa Clara lands was felt deeply and personally by every individual at Santa Clara Pueblo and will profoundly affect the community as a whole for many generations.

The Cerro Grande fire began on May 4, 2000, as a prescribed fire by the U.S. Park Service, raced across the Pajarito Plateau, and burned approximately 13,300 acres of Santa Clara Pueblo's ancestral homeland. This included 6,681 acres of the Santa Clara Indian Reservation, approximately 6,129 acres currently under U.S. Forest Service management, and approximately 490 acres in private ownership. Overall, this represents about 13% of Santa Clara's ancestral lands and 12% of its current reservation. In addition, the fire burned approximately 6,087 acres of the Santa Clara Creek watershed, consuming more than 19% of this critical drainage upon which Santa Clara Pueblo relies. The fire also devastated the Garcia Canyon watershed, ancestral to the Santa Clara people, with 3,771 acres burned or almost 42% of the drainage. In addition, the fire burned almost 18% of the Chupaderos Canyon drainage and about 57% of the Guaje Creek watershed, portions of which are within Santa Clara's ancestral lands. The fire consumed large tracts of sensitive timber and grasslands, which provide critical resources for the Santa Clara Pueblo as well as habitat for wildlife upon which the Santa Clara people depend. This paper will summarize impacts of the Cerro Grande fire upon the Santa Clara people and the lands and resources that sustain them.

Thousands of acres of closed timbered forest were burned in the fire, including ponderosa pine, piñon/juniper, and mixed conifer. A significant portion of this fire burned in spruce-fir mixed conifer forests. These forests have a longer natural fire cycle than that of ponderosa pine, and their regeneration occurs more slowly, taking many decades. In addition, large areas of open ponderosa pine and piñon were also burned. Even where the fire intensity did not cause total mortality, burned trees have become susceptible to infestations of woods imps and wood beetles. These have the potential to build in population and spread to unburned portions of the forest. Finally, mudslides and debris flows in the interior of the Santa Clara Canyon have resulted in repeated closures of the Santa Clara Canyon Road and in pueblo members losing access to large tracts of unburned forested tribal land as well.

The loss of these trees as well as interference with access has hampered the pueblo's customary uses. These forestlands hold a vast number of values for the people of Santa Clara Pueblo. Pueblo members use this forest for personal construction materials, including logs for vigas, small diameter trees for latillas and fence posts, and branches for other purposes. The pueblo issues permits to tribal members to gather fuel wood. Many pueblo members depend upon fuel wood as their source of heating and traditional cooking. The pueblo burns fuel wood in its ceremonial buildings for cultural and religious purposes. Also, pueblo artists use fuel wood to fire their clay pottery. Pueblo members also use these trees for cultural purposes, from the entire tree to parts such as branches and bark. This material is critical to the continuation of the unique and ancient cultural practices of the pueblo. Finally, the pueblo conducts periodic timber harvests to improve the health of the forest and bring important income to the tribe.

A large variety of wildlife existed in the areas burned by the fire, including mule deer, elk, mountain lion, coyote, bobcat, raccoon, deer mouse, and striped skunk. There are also several species of frog, salamander, and lizard constituting the amphibian and reptile population. Bald and golden eagles are found, as well as red-tailed hawk, turkey, grouse, orioles, flickers, and mountain bluebird. Native cutthroat trout, introduced rainbow trout, and hybrid cutbows are present in the Santa Clara Creek. Threatened, endangered, and sensitive species are also present in the area.

This fire has caused both direct and indirect impacts to this wildlife. Certainly some of this wildlife was killed during the fire. A much larger number have been stripped of their habitat for a period of at least 5 to 10 years. The Santa Clara people depend upon this wildlife for subsistence and cultural materials. Again, this is not just for the acreage actually burned, but also for the areas of unburned tribal land that may be inaccessible due to potential floods and debris flows in the Santa Clara Canyon and other areas. Tribal members also depend upon the fish in the Santa Clara Creek for subsistence. The fisheries and water quality necessary to sustain fish have been severely impacted by runoff from the burned areas.

The fire burned thousands of acres of forage, grass, and open timbered lands that Santa Clara livestock owners depend upon to graze their livestock, and may make inaccessible for several years other grazing lands in the Santa Clara Canyon that were not burned. Cattle owners are accustomed to turn out their livestock in the mountainous areas of the reservation from April through October. During these months, the cattle subsist entirely on the native vegetation and water from the natural streams, springs, and constructed dirt stock tanks.

Due to the fire—in combination with the smaller acreage of lands lost on the north side of the canyon to the 1998 Oso fire—the Santa Clara livestock owners have been placed in an expensive and difficult situation. They have had to pen up their livestock in the agricultural fields near the pueblo during the season when such livestock normally are removed to prevent destruction of agricultural fields. This required additional fencing materials and other items such as cattle guards to prevent impacts on farming lands. In addition, livestock owners were forced to pay out of their own pockets for feed and other supplies for their livestock. It will take decades for these forage areas to fully recover, particularly where high fire intensity has caused soil sterility.

The areas within the burn constitute the heart of Santa Clara's ancestral homeland. As such they contain many cultural sites, including the remains of ancient villages and cavate dwellings, agricultural fields and features, field houses, petroglyphs, game pits, and pottery and lithic scatters. Several of these sites were damaged due to exposure to the intense heat and wind conditions of the fire. In addition, the loss of ground cover has exposed many sites making them susceptible to further impacts including wind and water erosion, pot hunting, and damage from falling debris. These sites are touchstones of Santa Clara history and culture and are remembered in the pueblo by names and stories in the Tewa language. The pueblo is particularly concerned with the vulnerability of sites outside the reservation over which it has limited control.

The Cerro Grande wildfire has also severely impacted the integrity and water quality of various watersheds significant to Santa Clara Pueblo. These include the Santa Clara Creek, the Guaje Creek, the Garcia Canyon drainage, and the Chupaderos Canyon drainage. Particularly in the Santa Clara Creek watershed, the fire has caused general dysfunction of the riparian corridor and stream channel. This is due to the accumulation of large dead and down debris from burned areas and increased runoff and soil loss due to destabilized slopes. Over the next decade, large quantities of debris and ash will accumulate in the drainages of the Santa Clara Creek and other watersheds. This debris material forms dams that can wash out and cause erosion downstream. The pueblo is particularly concerned with the Santa Clara Creek watershed as this watershed provides water for the entire community of Santa Clara.

The most significant direct impact of the fire upon the water resources will be in the area of irrigated agriculture. The Santa Clara Canyon irrigation canal, one of the pueblo's primary irrigation canals, draws its water entirely from Santa Clara Creek. Pueblo farmers depend upon this source of water to irrigate orchards as well as various crops, including several varieties of corn, chile, squash, and beans. Flooding of the Santa Clara Creek stream channel has damaged this irrigation canal and caused the ditch to be closed during the irrigation season. Farmers were forced to haul water to their field to keep crops from dying. With the risk for flooding in the creek bed, it is likely that the irrigation ditch will be entirely or periodically unusable for many years until flooding risks have subsided. This may reduce the productivity of planted crops and even prevent farmers from using fields that depend upon this source of water.

In addition, the fire has caused significant increases in runoff and erosion that have on multiple occasions overburdened, filled, realigned, and damaged culverts, catchment basins, irrigation structures, low-water crossings, and the various stream beds. Downstream structures threatened by flooding in the Santa Clara Creek include Santa Clara's senior citizen's center, day school, administrative building, and traditional village and other residences. In particular, large amounts of sediment have accumulated behind Sawyer Dam on the Santa Clara Reservation resulting in a near breach. Several pueblo-owned culverts have been damaged and will need to be replaced.

The fire has also directly and indirectly affected Santa Clara's tourism-dependent economy, both to the tribal members and the tribal government. The Puye Cliff Dwellings, listed on the National Historic Record, is usually open to the public throughout the year. In addition, the Santa Clara Canyon Recreation Area is usually open from March through September annually. Both of these places had to be closed to the public and will remain so for the indefinite future. Both of these attractions allow the pueblo to share portions of its lands with the general public and to bring in critical revenue to the tribe. In addition, individual Santa Clara Pueblo members who sell arts and crafts depend heavily upon this traffic of visitors through the pueblo headed for Puye or the canyon.

While the fire did not burn the historic cliff dwellings and structures at Puye, several direct and indirect impacts have caused Puye to remain closed to the present. These include damage to the parking lot, the natural setting directly south of Puye and around the historic Harvey House buildings, the entrance to Puye that crosses the Sawyer Canyon wash, and the pristine natural appearance of the lands surrounding Puye to the west. The extensive coverage of the fire by the media may also discourage tourist visitation due to misinformation about the ruins themselves being burned or safety concerns. The Cerro Grande fire has burned almost 19% of the Santa Clara Canyon including parts of the recreation area in the bottom of the canyon. It has visually impacted the upper portions of the canyon with large areas of severe burn. These severe burn areas, entirely wiped clean of vegetation with a potential for hydrophobic soil conditions, have led to flooding and debris flows into the canyon. This has impacted half of the constructed fishing ponds in the canyon, causing them to remain drained and unusable. Thus, for safety, quality, and aesthetic reasons it is likely the recreation area will be closed to the public for the indeterminate future.

The Santa Clara Canyon Recreation Area and Puye Cliff Dwellings attract many tourists within and outside the state of New Mexico to Santa Clara Pueblo, many of whom purchase arts and crafts from pueblo members. Tribal members depend upon the revenue from these arts and crafts for their livelihood and for supplemental income. The closure of these two attractions has seriously curtailed the tourist traffic upon which the artists and craftspeople depend. There are currently seven arts and crafts shops and galleries within Santa Clara Pueblo and approximately 450 resident artists and craftspeople who sell from their homes.

In addition, the fire will require a large increase in demands upon the Santa Clara Tribal Government to provide services. The fire has placed the pueblo at increased risk for additional wildfire, flooding, erosion/sedimentation, and ill health through sediment transport of contaminated soils. Overall, these increased risks will require the pueblo to employ additional staff to conduct and coordinate damage assessments and disaster relief, coordinate the Burned Area Rehabilitation Plan (BAER) development and implementation, conduct environmental and health assessments, and provide for law enforcement in areas damaged by the fire (BAER, 2000). Consultants and legal experts will have to be hired to assist the tribe with rehabilitating the damaged lands and resources as well as obtaining adequate compensation. Equipment will also have to be purchased for rehabilitation as well as for future fire response. Repairs to damaged infrastructure will also be needed, including realignment and resurfacing of roads, building of low-water crossings, and installation of erosion-control structures in affected areas.

In conclusion, the Cerro Grande fire will have a lasting and profound impact upon Santa Clara Pueblo's unique and ancient culture. As a land-based culture, the destruction of these resources and potential denial of access to a large part of our land will impose great burdens upon our community. It is not simply a matter of destruction of archaeological and cultural sites; it is a profound alteration of our relationship with areas, plants, and animals upon which our culture depends. No similarly destructive wildfire has occurred in our ancestral homeland in the memory of our oldest living members. Nevertheless, we know that hundreds of generations of our people have lived in this region and survived countless changes and cycles—both natural and human caused. In this spirit, our people intend to persevere through the changes wrought by the Cerro Grande fire and do our part to steward the restoration of our ancestral homeland.

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Alvin Warren, an enrolled member of Santa Clara Pueblo, assists his and other indigenous communities with identifying, protecting, and recovering traditional lands and resources. Born and raised in northern New Mexico, Alvin received his BA in history with high honors and certification in Native American Studies from Dartmouth College. From 1997 to 2000 he successfully led his pueblo's efforts to regain over 5,000 acres of their ancestral homeland; the largest land reacquisition by the Santa Clara Pueblo in almost a century. He is currently serving his 5th term as a member of the Santa Clara Tribal Council, including one term as the Tribal Treasurer and one term as the Tribal Interpreter, two of the pueblo's six elected officials.

In addition, he served 3 years on the Board of Education for the Santa Clara Day School, including one term as Vice-Chairman. He serves in several capacities with the Trust for Public Land, a national conservation organization, including as a founding member of the New Mexico Advisory Council, a member of the Tribal Lands Program Advisory Council, and a founding member of the National Working Group on Land-and-People Conservation. He also serves on the Board of Directors of the Chamiza Foundation.

Watershed Management on the Pajarito Plateau: Past, Present, and Future

by *Ken Mullen*, LA-UR-01-2056, Water Quality and Hydrology Group, Los Alamos National Laboratory;
Kelly Bitner, Neptune and Company; and
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Los Alamos National Laboratory (LANL) developed a draft watershed-management plan that pertains to the 43-mi^2 area within the LANL boundaries. The watershed-management plan was started in 1996 with a number of overall goals: (1) to be a good steward of the natural resources entrusted to the laboratory, (2) to provide long-term evaluation regarding success of the Environmental Restoration Project in acceptably cleaning up sites, (3) compliance with the storm water National Pollution Discharge Elimination System program, and (4) upgrading the LANL environmental surveillance program that has been ongoing since the 1940s.

LANL has an extensive network consisting of 53 surface-water-monitoring stations located in every major canyon, upstream and downstream of LANL, and at most confluences (Fig. 1). Monitoring of the network has been ongoing for about 20 years. The stations are equipped with ultrasonic transducers that trip automated samplers to collect water samples from every flow event. These data have been reported every year in the report series *Environmental Surveillance at Los Alamos*, but have not been used to analyze watershed health. The focus of the LANL watershed-management plan is to use water quality data to monitor watershed health and to implement manage-

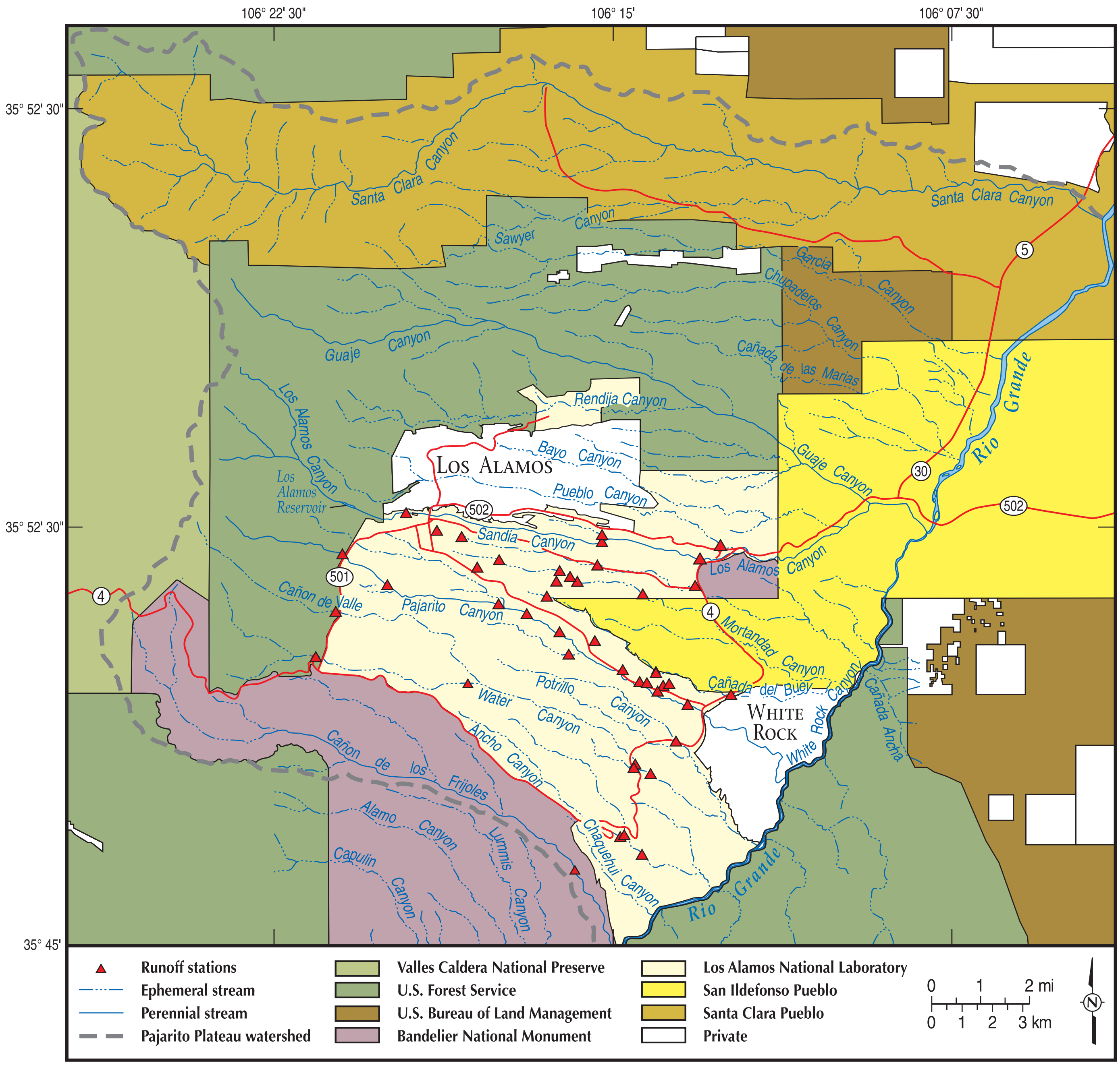

FIGURE 1—Los Alamos National Laboratory surface-water monitoring stations.

ment actions when LANL activities, past or present, adversely impact the health of the watershed.

Comments from stakeholders on the draft watershed-management plan criticized the development of a plan that did not include the entire watershed or the perspectives of the stakeholders that share the watershed: the U.S. Forest Service, National Park Service, Los Alamos County, U.S. Bureau of Land Management, San Ildefonso Pueblo, Cochiti Pueblo, and Santa Clara Pueblo. In response, LANL has sought stakeholder participation in revising the draft plan to include the entire watershed comprising the eastern flank of the Jemez Mountains. At a meeting held on September 16, 1999, most land managers within that watershed and the New Mexico Environment Department committed to participating in the development and implementation of a Pajarito Plateau Watershed Management Plan that covers the entire area.

LANL initiated the formation of the Pajarito Plateau Watershed Partnership, composed of the major stakeholders in the watershed, whose purpose is to plan and implement a program to identify and address the primary issues that affect water quality in all parts of the watershed and are shared by all members of the partnership. One such issue that unifies the partnership and requires a shared-management strategy is erosion. One example of a shared-management strategy to address erosion is vegetation thinning to encourage growth of herbaceous cover. The herbaceous cover holds soil in place, increases surface roughness, and encourages infiltration—all of which decrease erosion by slowing down water. Storm water flow in the aftermath of the Cerro Grande fire has demonstrated how important vegetation is to flood protection.

The Pajarito Plateau Partnership, through grant funding from the NMED or other sources, hopes to implement watershed restoration activities that include reforestation, replanting vegetation in the urban/forest interface, and thinning of ponderosa and piñon-juniper to enhance herbaceous growth in Los Alamos County, Bandelier National Monument, Santa Fe National Forest, and Santa Clara Pueblo.

Other important goals of the Pajarito Plateau Watershed Partnership are outreach and education. These are critical elements of the Pajarito Plateau Watershed Management Plan, and all members of the watershed partnership have agreed to develop and participate in outreach and education activities. Decisions made by the partnership need to be communicated and justified to the public, officials, and other stakeholders. It is anticipated that active participation of partnership members will result in outreach that is effective across all jurisdictional boundaries.

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New Mexico 20 Communities Initiative— Protecting Communities in the Wild Land/Urban Interface

by *New Mexico Energy, Mineral and Natural Resources Department*, presented by Fred Rossbach, Forestry Division

According to a 1999 General Accounting Office (GAO) Report to Congress, "the most extensive and serious problem related to the health of national forests in the interior West is the over accumulation of vegetation, which has caused an increasing number of large, intense, uncontrollable, and catastrophically destructive wildfires."

Scientists believe this increased number of fires is due primarily to the decades-old policy of putting out wildfires on federal lands. The policy has caused the disruption of frequent, low-intensity fires, which had removed accumulated vegetation and prevented fires from becoming larger. Unfortunately, these intense fires now pose a grave threat to human health, safety, property, and infrastructure along boundaries between forests and urban communities. This policy has been costly. Federal Forest Service fire suppression costs rose 150% between 1986 and 1994, and the number of fires in national forests, burning more than 1,000 acres, grew from an average of 25 to 80 per year.

The situation in New Mexico is no different. Costs of suppressing wildfires have escalated to an all time high during the fiscal year 2000, and the number of acres burned almost tripled compared to the 10-year average (Fig. 1). This trend will continue until the threat of large, catastrophic wildfires is diminished.

What is the threat in New Mexico? (1) 15,202,080 acres in New Mexico are considered forested and woodland. (2) 4,800,000 of those forested and woodland acres are under the state's fire suppression jurisdiction. (3) 540,447 of the forested acres administered by the state are located in a wild land/urban interface, estimated using a 2-mi radius around communities with a population greater than 5,000.

A primary goal of New Mexico Energy, Minerals, and Natural Resources Department (EMNRD) Forestry Division is to determine which communities are most vulnerable to fire and provide them with the necessary tools to make needed changes. The Forestry Division's approach will emphasize the importance of protecting homes within these communities; developing fuel breaks, or areas of limited vegetation, from which firefighters can build a line of defense against an approaching fire; and thinning of forested areas to reduce the possibility of catastrophic fires.

In order to evaluate which New Mexico communities are most vulnerable to fire, an objective rating system was developed that assesses a number of factors contributing to a community's fire risk. The criteria include: type of vegetation and proximity to homes, availability of water, effective evacuation route, topography (ridge, valley, slope, and exposure), type of fuels (forest type) and fuel accumulation, number and size of previous fires, direction of prevailing and local winds, and the ability of community or subdivision to protect homes.

Based on an evaluation of these criteria, the 20 New Mexico communities most vulnerable to fire (Fig. 2) are: Angel Fire/Black Lake, Capitan/Lincoln, Catron County, Cloudcroft, East Mountains, Española Bosque, Gallinas watershed, Jemez/La Cueva, Los Alamos, Manzano Mountains, Mayhill/Timberon, middle Rio Grande bosque, Mora County interface, Pecos, Red River, Ruidoso, Santa Fe watershed, Silver City area, Taos Canyon/Shadybrook, and upper Brazos.

In order to proceed with EMNRD Forestry Division's goal to provide at-risk communities with tools to effect needed changes, an implementation plan is being developed. The plan requires cooperation among all stakeholders (federal, state, tribal, and community leaders) and could take from 2 to 5 years to complete. The implementation plan includes two stages: (1) assessment of at-risk communities and (2) development and implementation of damage prevention and restoration projects. Stage I of the plan, assessment, includes the following elements:

- Identify sites that need treatment, immediate and long term, and for each site identify a funding source;
- Ensure that individuals, tribes, municipalities, and counties understand the threat posed by wildfire;
- Establish community-based teams to plan projects and set priorities;

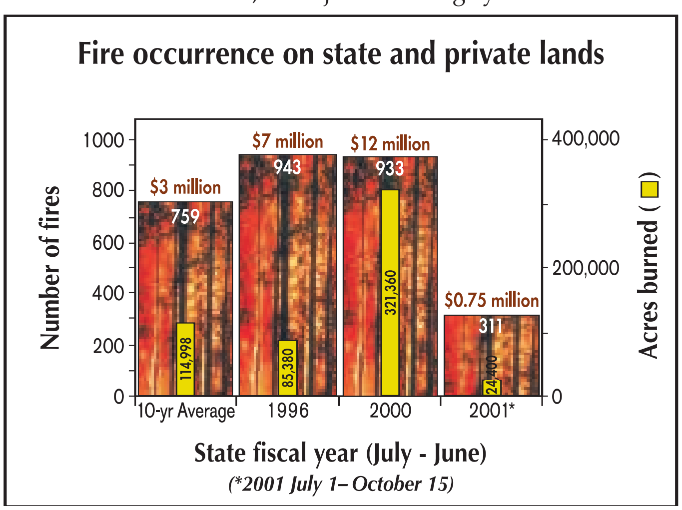

FIGURE 1—Fire occurrence on state and private lands.

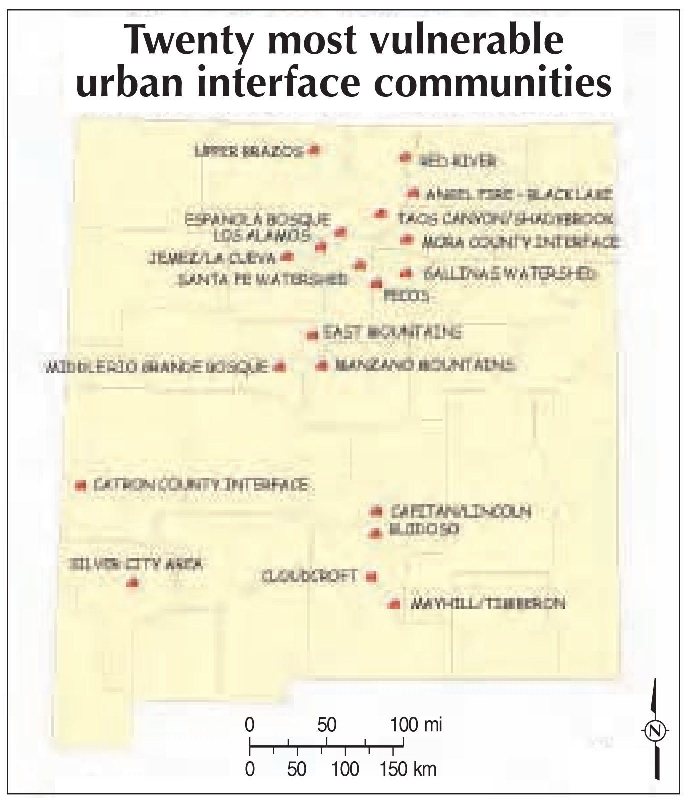

FIGURE 2—The 20 most vulnerable urban-interface communities.

- Involve community leaders in identifying damage prevention and restoration projects;
- Assess suppression infrastructure, fire-fighting capability, and ability to complete projects; and
- Develop information and education programs.

Stage II of the plan, damage prevention and restoration, includes the following elements:

- Identify, define, and complete projects that improve the health of identified sites; for example, estimate that 2,000 acres/community needs an immediate treatment such as thinning, harvesting, prescribed fire, etc.;
- Establish priorities for long-range projects and establish a funding regime;
- Maintain and/or increase local ability to suppress fires while they are small;
- Develop and improve evacuation plans, geographic information system (GIS) mapping, and fire detection;
- Inform landowners and municipalities of specific actions which will help prevent erosion and other after-effects of fires;
- Help individuals understand appropriate treatments to safeguard their homes;
- Work with stakeholders to find commercial markets for material removed during projects;
- Restore burned lands; and
- Enact local ordinances where and when appropriate.

Cooperation among stakeholders is a critical element for success of the assessment, prevention, and restoration plan. First, stakeholders need to be identified and their functions defined. Four stakeholders, or categories of stakeholders, are readily identifiable: (1) federal agencies and tribes, (2) State Forestry Division of EMNRD, (3) local and tribal entities, and (4) individuals. These entities will focus efforts from the backwoods to the urban/wild land interface, and in some cases to individual backyards. Federal agencies and tribes will be required to obtain significant increases in the National Environmental Policy Act (NEPA) and other environmental clearances to complete thinning projects, conduct burning, and create fire breaks, and they will be required to provide education and technical advice. The EMNRD State Forestry Division will provide flow through funding for projects, provide leadership, education and technical advice, and work with landowners on projects to treat their lands according to sound scientific principles. Local and tribal entities will actually implement and complete identified projects, enact relevant ordinances, and enhance fire protection. Individuals can also have a significant impact in protecting their own homes and neighborhoods by making changes to home exteriors to improve fireproofing, clearing vegetation, reducing flammables around homes, and improving access for fire engines.

No one can be excluded from this critical process. According to the GAO (2000), "the window of opportunity for taking corrective action is estimated to be only about 10 to 25 years before widespread, unstoppable wildfires with severe immediate and long-term consequences occur on an unprecedented scale."

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The Potential for Rainfall-Triggered Debris Flows Following the Cerro Grande Fire

by *Susan H. Cannon*, Landslide Hazards Program, U.S. Geological Survey

Debris flows generated from recently burned areas can pose a significant hazard to lives and property. The term *debris flow* refers to the rapid downslope movement of a viscous slurry consisting of up to boulder-sized material and mud. Debris flows usually occur during periods of intense rainfall or rapid snowmelt. They can occur with little warning, are capable of transporting large material over relatively gentle slopes, and develop momentum and impact forces that can cause considerable destruction. As a result of these characteristics, mitigation of debris-flow hazards can be more difficult than mitigation of flood hazards. On September 1, 1994, at approximately 10:30 pm, debris flows were generated in response to a torrential rainstorm from the recently burned hillslopes of Storm King Mountain in Colorado. The debris flows poured down onto I–70 from every basin burned by the wildfire. Thirty cars traveling on the highway at the time of the debris flows were engulfed or trapped by the mud, and at least two people were swept into the Colorado River. Although some travelers, including those swept into the river, were seriously injured, fortunately no deaths resulted from this event. I–70 was closed for 3 days to allow crews to remove the tons of rocks, mud, and burned vegetation that inundated the highway.

Factors Controlling Debris-Flow Occurrence in Recently Burned Basins

In a study of 96 recently burned basins in southern California, New Mexico, and Colorado, Cannon (1999) and Cannon and Reneau (2000) compared conditions in basins that produced debris flows with conditions that resulted in sediment-laden streamflow to determine the factors that best indicate a susceptibility specifically to debris flow. This work demonstrated that the factors that best separate debris-flow-producing basins from those that produce primarily streamflow are the basin and the geologic materials that mantle the hillslopes. Although debris flows were produced from basins with a broad range of areas and gradients, a basin area/channel gradient threshold could define debris-flow susceptibility. Cannon (1999) and Cannon and Reneau (2000) also evaluated the effect of the areal extent of the burn and the presence of water-repellent soils on debris-flow generation and found that debris flows can be generated from even partially burned basins and that the presence of a water-repellent soil does not indicate a propensity specifically for debris flow. They also suggested that a spatially extensive burn and the presence of water-repellent soils may affect the magnitude of erosive events following wildfire, but do not distinguish debris-flow-producing basins from those that produced streamflow.

The Cerro Grande Study

In a recent study, I qualitatively evaluated the potential for fire-related debris flows by comparing conditions in eight basins burned by the Cerro Grande fire with the conditions identified by Cannon (1999) and Cannon and Reneau (2000) as likely to produce debris flow (Fig. 1). For each basin, the likelihood of debris-flow activity is assessed upstream from the first point within the channel where debris flows could potentially impact man-made structures. Debris-flow susceptibility of Water Canyon, Cañon de Valle, South Fork of Pajarito Canyon, Pajarito Canyon, and Two Mile Canyon is assessed upstream from where each canyon crosses NM–501/502. Los Alamos Canyon is evaluated for debris-flow susceptibility upstream from Los Alamos Reservoir. Pueblo Canyon is evaluated upstream from the Diamond Drive crossing, and Rendija Canyon is evaluated upstream from the first crossing behind Guaje Pines Cemetery.

Cannon (1999) found debris-flow susceptible basins could be distinguished from streamflow-dominated basins by a basin area/channel gradient threshold (Fig. 2). The basin area and gradients of all the canyons evaluated in this study, with the exception of Los Alamos Canyon, fall above this threshold (Fig. 2). The data suggest that, given sufficient rainfall, the remaining seven basins can potentially produce debris flows. Data from Los Alamos Canyon fall outside the range of conditions known to have produced debris flows; comparison with the threshold is inconclusive in this case.

Cannon (1999) and Cannon and Reneau (2000) found that the geologic materials that mantle the hillslopes could also identify debris-flow susceptible basins. For example, in nearby Bandelier National Monument, fire-related debris flows were generated from colluvium and soil weathered from the dacite-rich Paliza Canyon Formation (a fine-grained volcanic rock). Geologic mapping (Smith et al., 1970) shows that the basins evaluated in this study are primarily underlain by similar dacites of the Tschicoma Formation and in lower reaches by the Bandelier Tuff. This suggests that, based on the type of geologic materials forming the basins' hillslopes, the basins burned by the Cerro Grande fire are also susceptible to debris-flow activity. In addition, the abundance of loose, easily erodible soil and ash mantling steep hillslopes, extensive areas of up to boulder-sized material mantling some steep hillslopes, and the considerable volume of material stored in the channels are all elements that can potentially contribute to debris-flow production from these burned hillslopes.

How long will the debris-flow potential persist? The debris-

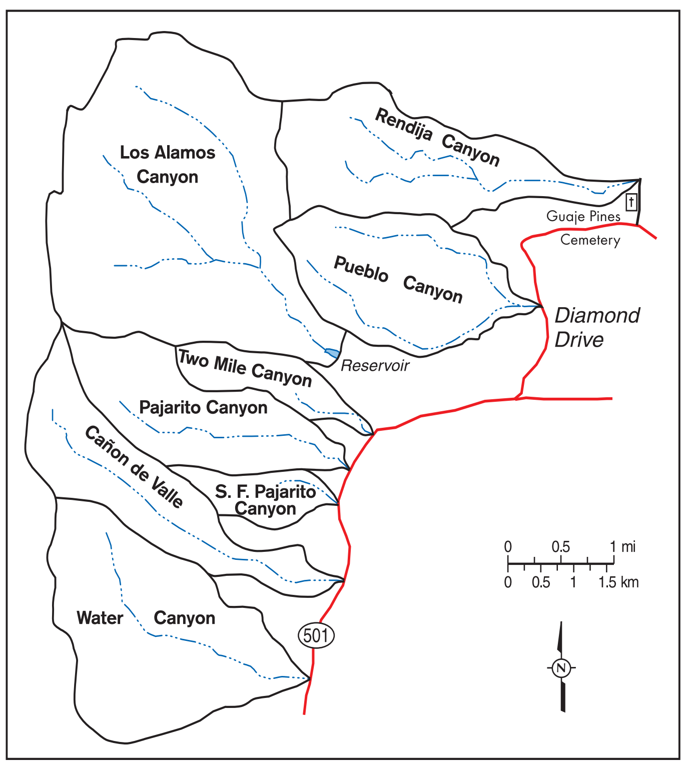

FIGURE 1—Map showing locations and extent of basins burned by Cerro Grande fire that are evaluated in this study.

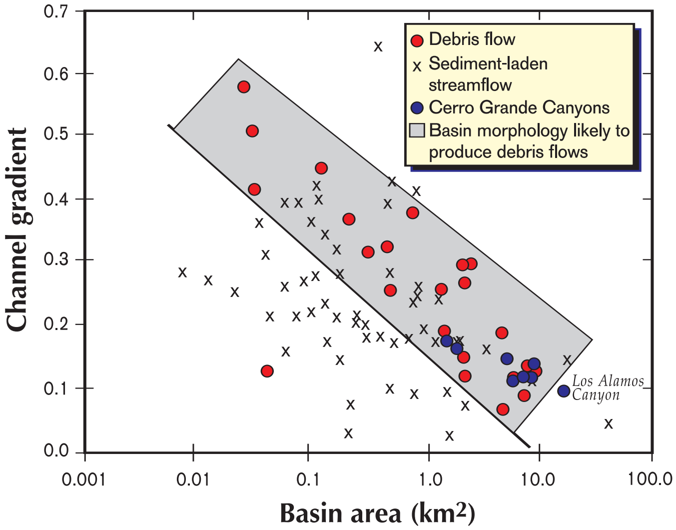

FIGURE 2—Data from Cerro Grande basins compared with basin area/channel gradient threshold for debris-flow-producing basins defined by Cannon (1999). Channel gradient is calculated as the maximum relief from basin mouth to the divide, divided by the length of the longest stream channel extended to the drainage divide. Open circles represent measurements from basins known to have produced debris flows; x's show measurements from basins that produced sediment-laden streamflow. Solid circles show data from the eight basins burned in the Cerro Grande fire evaluated in this study. Shading highlights the field occupied by data from debris-flow producing basins.

flow producing basins studied by Cannon (1999) and Cannon and Reneau (2000) all experienced significant rainfall events within a few months of the wildfires. The evaluation presented here is thus based on the assumption that the burned basins will be exposed to heavy rainfall in the near future. Streamflow measurements following two wildfires in nearby Bandelier National Monument demonstrated that rainfall-triggered runoff events returned to near pre-fire conditions approximately 4 years after the fire (Veenhuis, in press). Based on this work, we conclude that debris-flow hazards will exist in the basins evaluated in this study for approximately 4 years.

Conclusions

This preliminary evaluation suggests that in the next 4 years debris flows can potentially be produced from the basins burned by the Cerro Grande fire, given sufficient but as yet unspecified amounts of rainfall. Hillslope materials are similar to those that produced debris flows following the Dome fire in nearby Bandelier National Monument in 1996, and seven of the eight basins are above the basin area/channel gradient threshold defined by Cannon (1999) for debris-flow susceptibility. Although the materials mantling hillslopes in Los Alamos Canyon can produce debris flows, the basin area and channel gradient of this canyon are beyond the range defined by Cannon (1999).

This method for debris-flow hazard assessment allows for only a qualitative estimation of susceptibility to rainfall-triggered events. Depending on the triggering event, the scale of the debris-flow response from these basins could vary considerably. Extensive areas of high-severity burn and water-repellent soils may also increase the magnitude of potential erosive events following wildfire. Accordingly, the scope and scale of appropriate and effective mitigation approaches must also vary considerably. In addition, although debris flows have been generated from burned areas by snowmelt, this study does not address this issue due to a lack of data.

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Cerro Grande Ash as a Source of Elevated Radionuclides and Metals

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The Cerro Grande fire in 2000 burned a large area in the eastern Jemez Mountains, Los Alamos townsite, and on Los Alamos National Laboratory (LANL) land (BAER, 2000). Because of the potential for large floods generated in the upper portions of burned watersheds to erode and transport contaminated sediments in the canyons, the laboratory is implementing a comprehensive sampling and monitoring effort to characterize the impacts of flooding. The main purpose of the sampling is to obtain data to evaluate the impacts of post-fire floods on sediments, soils, surface and storm water, alluvial ground water, and biota. This information will be used to assess human health and ecological risk for areas that are affected by the floods. Data will also be used to document changes in the spatial distribution of existing contaminant inventories and concentrations (e.g., Reneau et al., 1998; Katzman et al., 1999) as a function of erosion and deposition of sediments and changing hydrology within affected watersheds.

The initial sampling effort focused on the collection of ash and muck (post-fire sediments that are dominated by reworked ash) from locations west of the laboratory. The locations were selected to be representative of background conditions upstream of known laboratory releases and predominantly upwind from airborne releases from stacks at the laboratory facilities. Ash and muck samples were also collected in the Viveash fire area (near Pecos, New Mexico) for comparison. The ash is composed of the concentrated remains of burned vegetation and forest litter (pine, fir, spruce needles, and leaves), and non-flammable, non-volatile constituents like minerals and metals (including radioactive elements). Some researchers have used tree-ring analysis to quantify the timing and magnitude of radionuclide uptake from locations around the world (e.g., Garrec et al., 1995). Thus, it was expected that detectable radionuclide concentrations associated with global fallout from aboveground nuclear testing conducted primarily in the 1950s and 1960s would be present and likely concentrated in the ash. The data from the ash and muck samples are important for interpreting concentrations of radionuclides that may be present in storm runoff and sediment deposits, and are necessary for distinguishing fire-related constituents in storm water and sediments from legacy-contamination in canyons on the laboratory. The ash and muck data provide a necessary post-fire baseline to support the assessment of potential impacts to the laboratory and offsite (e.g., the Rio Grande and Cochiti Reservoirs) from fire-related contaminants found in storm runoff.

An Interagency Flood Risk Assessment Team (IFRAT) consisting primarily of representatives of the New Mexico Environment Department, Los Alamos National Laboratory, the New Mexico Department of Health, the Environmental Protection Agency, the University of New Mexico Center for Population Health, and the Department of Energy are organized to evaluate the data in the context of risk and communicate that information to the public via press releases, the internet, and public meetings.

Expected Hydrologic and Geomorphic Effects

The Cerro Grande fire produced significant hydrologic changes to large portions of several watersheds above the laboratory (BAER, 2000). These hydrologic changes are primarily due to altered soil conditions in the burned areas. Loss of plant cover and forest litter, development of ash covers, and locally extreme water-repellent (hydrophobic) soil conditions have greatly reduced infiltration rates on hillslopes. Under these conditions, reduced infiltration rates produce extremely rapid surface runoff especially during thunderstorms, mobilizing ash, eroding surface soils, and repeatedly generating large floods in the canyons. The 1977 La Mesa fire and the 1996 Dome fire, which burned large parts of the Frijoles Canyon and Capulin Canyon watersheds, respectively, provide examples of expected hydrologic and geomorphic responses of watersheds to the Cerro Grande fire. Peak post-fire flood discharges in these canyons were up to 100 times higher than before the fires, and the most extreme effects occurred in the first 2 years after the fires (Veenhuis, 1999). The effects of flooding can include extensive bank erosion and/or vertical incision, consequently remobilizing large volumes of canyon floor sediment, some containing contamination (Fig. 1). It is expected that contaminants in any remobilized sediment would be mixed with large volumes of uncontaminated sediment derived from the upper watersheds and from downstream reaches, resulting in lower contaminant concentrations than in the original deposits.

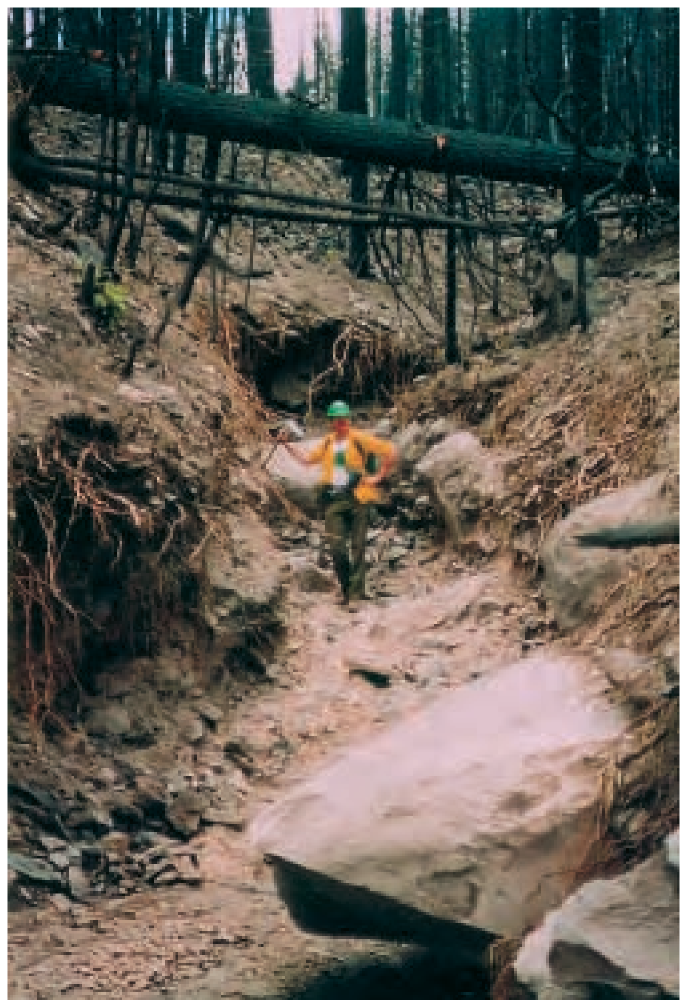

FIGURE 1—Photo showing the vertical incision and channel widening in upper South Fork of Pajarito Canyon following several recent, moderate-intensity storms.

Results

The box plots in Fig. 2 show that concentrations of representative radionuclides in ash and muck are greater than pre-fire background concentrations in soil and sediment determined for the laboratory area (Ryti et al., 1998). The concentrations of

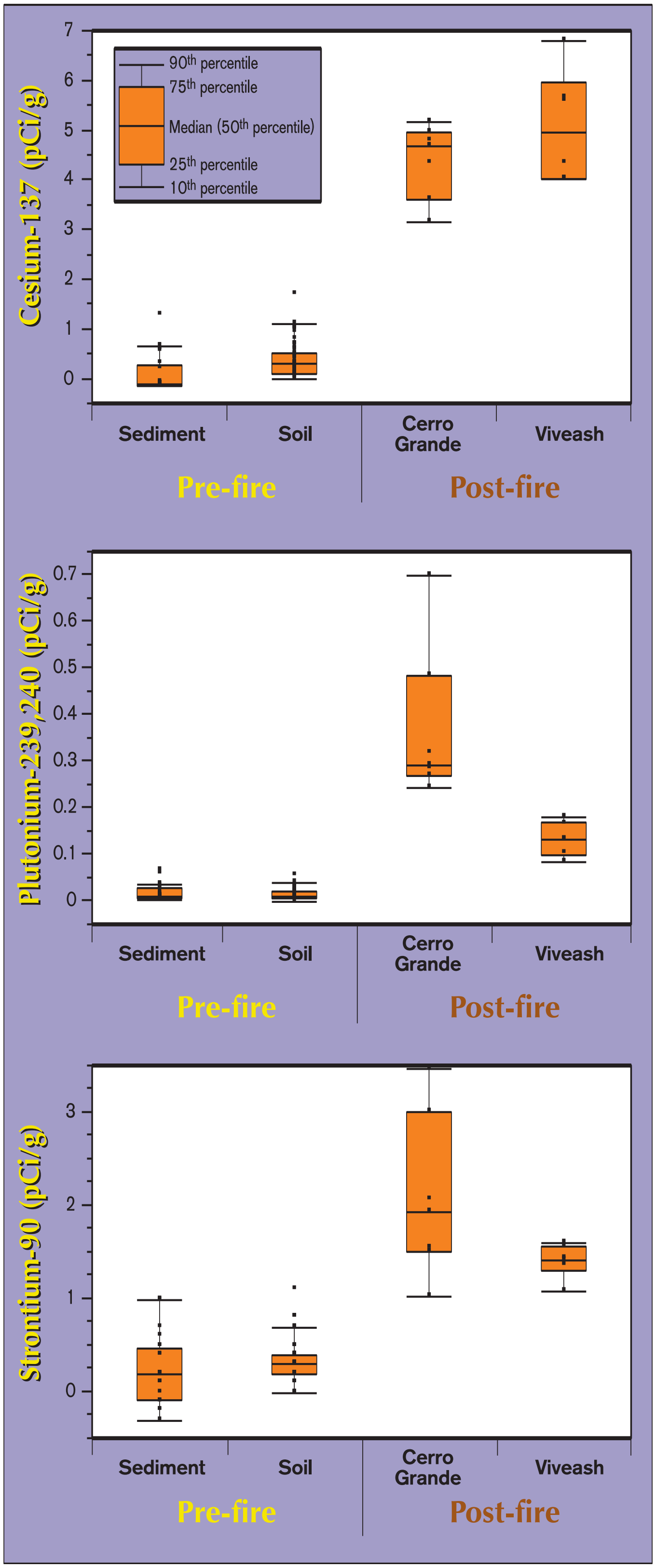

FIGURE 2—Box plot comparison of concentrations of three radionuclides (cesium-137, plutonium-239, 240, and strontium-90). Plots show pre-fire background concentrations in soil and sediment at LANL and post-fire ash and muck samples from the Cerro Grande and Viveash areas.

cesium-137 and strontium-90 in Viveash area ash and muck are similar to concentrations found in the Cerro Grande fire area, supporting the hypothesis that the source of these elevated constituents is atmospheric fallout. The concentrations of cesium-137 are also comparable to the values reported by Ferber and Hodgdon (1991) for samples of ash from wood collected across the United States. It is worth noting, however, that concentrations of plutonium-239, 240 are greater in the Cerro Grande fire samples. Thus, it is possible that some of the plutonium-239, 240 measured in Cerro Grande ash had its source as stack emissions from laboratory facilities, which would explain a slightly greater concentration near Los Alamos. Data previously reported by the laboratory's Environmental Surveillance Group support this interpretation by showing that laboratory perimeter locations have 3–4 times the regional average for plutonium-239, 240 (Fresquez et al., 1996).

Similar patterns are observed for metals, and the ash and muck samples contain greater concentrations of several metals than measured in pre-fire background soil and sediment samples. The metals most elevated in the ash are those that are readily taken up into plant tissue, including barium, manganese, and calcium. These relationships further confirm that the source for the elevated concentrations of most ash constituents is from the natural process of uptake into plants and concentration of non-flammable, non-volatile constituents during the fire.

Conclusions

These findings are important for understanding the effect of large, post-fire floods on the transport and deposition of metals and radionuclides that are present as contaminants in canyons draining the laboratory. Concentrations of fallout radionuclides and metals transported in floods should decrease over time as ash is stripped from the slopes in the upper watersheds. In some canyons, deposition of muck during flooding will leave a radionuclide and metal inventory higher than existed before the fire, and much of the "contamination" transported to the Rio Grande may be unrelated to the laboratory. Risk assessors should not, however, discriminate between sources of contamination in their assessments because the potential effects of exposure to radionuclides and metals are irrespective of their source. Knowledge of the source of contamination primarily guides the nature and location of potential mitigation measures.

Acknowledgments

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Runoff Following the Cerro Grande Fire

by *Bruce Gallaher* LA-UR-01-148, *Ken I. Mullen*, and *Michael Alexander*, Water Quality and Hydrology Group, Los Alamos National Laboratory

The Cerro Grande fire of May 2000 burned almost 48,000 acres of forested land near Los Alamos, New Mexico. The fire burned nearly 7,400 acres on the Los Alamos National Laboratory (LANL) and major portions of watersheds draining onto LANL from adjacent Santa Fe National Forest lands. In these forest service watersheds above the laboratory, from 20% to 80% of acreage burned was considered high-severity burn. On LANL, most of the area burned was considered low-severity burn, but many small structures burned and some inactive waste sites had cover vegetation at least partially burned.

It has been well established through studies around the world that runoff and sediment yields can dramatically increase following wildfires. Accompanying these physical changes are changes in the composition or quality of runoff water. At Los Alamos, these changes may be severe due to the steepness of the burned terrain and the high severity of the burn, creating water-shedding hydrophobic soils (BAER, 2000).

Immediately after the fire, these increases in predicted runoff and sediment yields raised concerns about erosion of contaminants that exist in soils on LANL and about movement of these contaminants to offsite lands and potentially to the Rio Grande.

To understand the possible impact to downstream water bodies, runoff events after the fire were monitored and sampled by the laboratory. An extensive network of automated samplers and stream gages served as the cornerstone of this effort (Fig. 1). By the end of the year 2000 runoff season, over 90 separate runoff samples had been collected and submitted to outside commercial analytical laboratories. Additional complementary monitoring of the Rio Grande by the U.S. Geological Survey during flood events will provide considerable information to scientists about the contaminant risks from the runoff.

Due to a general lack of intense "monsoon" type rainfall during the summer of 2000, severe runoff passing across the laboratory was limited to a single event on June 28. Record peak discharges were recorded for several drainages leading onto LANL during that event. For example, in Water Canyon above NM–501, the estimated peak of 840 cubic ft per second (cfs) dwarfed the pre-fire maximum of 0.3 cfs. Fortunately, downstream property damage from this storm was minimized due to precautionary engineering. It remains to be seen what impacts will be felt during wetter rainy periods in later years.

Based on our review of the early results, the most significant aspects of the chemical quality of the runoff water appears to be in the contaminants being carried by the runoff, as opposed to those that are dissolved in the water. Samples of the sediment and ash being carried onto the laboratory by the runoff contain higher levels of radionuclides and metals than those measured in local background soils and sediments before the fire (Katzman et al., this volume). The radionuclides appear to be from decades of accumulation of radioactive fallout in trees, other plants, and in forest ground litter. The metals include mineral nutrients (like calcium and potassium) and trace concentrations of other metals that are naturally in soils. Several of these materials are 10 times higher than before the fire. Also, approximately one-half of the turbid water samples contained cyanide. Fortunately, we have detected little of the most biologically harmful form of cyanide.

Concentrations of most metals dissolved in storm water are below the Environmental Protection Agency or New Mexico drinking water standards; however, a few (for example, aluminum, barium, and manganese) are above the standards in many samples. Dissolved manganese concentrations increased by about 50 times above pre-fire levels and barium by 20. Concentrations of radionuclides dissolved in storm water are slightly elevated or comparable to pre-fire levels.

Two separate scientific panels are working to formally evaluate the health risks, if any, posed by these contaminants. They hope to have some early results available to the public before the start of the second season of post-fire runoff. This is a considerable challenge. The health experts must not only review the concentrations of the many hundreds of chemicals tested for, but they also must determine the likelihood that some person or organism would come in contact with the chemicals. Then they face a difficult task of communicating the results of their studies to a public that may be very fearful of contacting any chemicals or pollutants at any level.

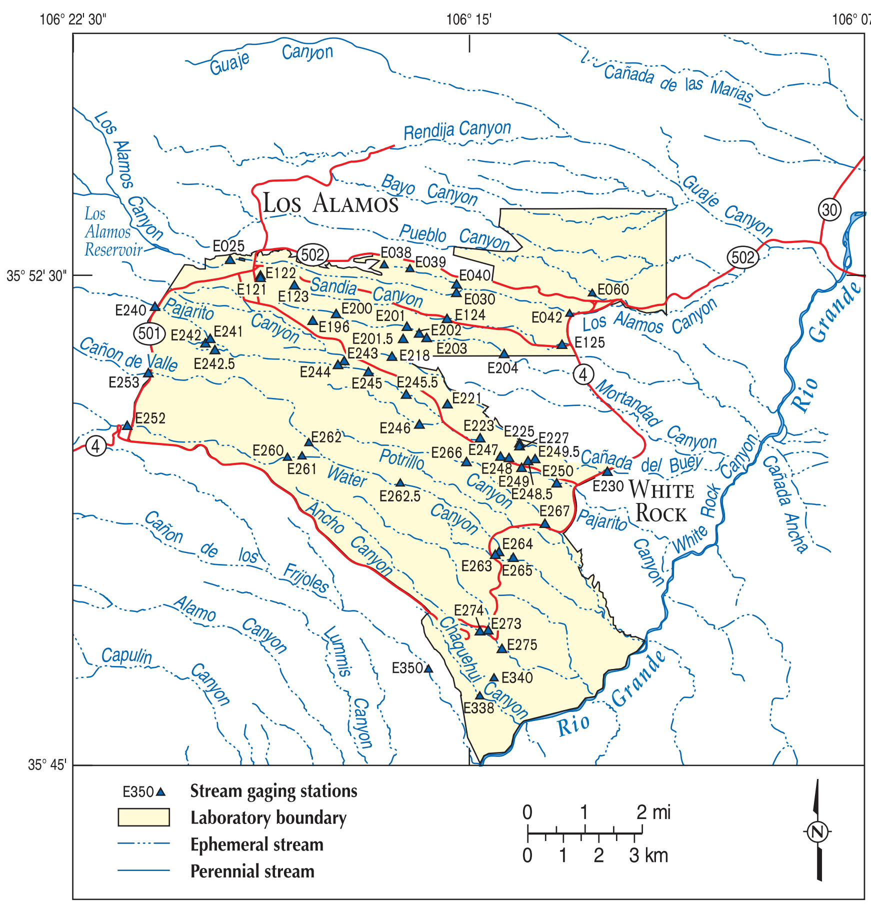

FIGURE 1—Location of Los Alamos National Laboratory automated water quality sampling stations and stream gages.

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Ground-Water Monitoring Program at Los Alamos National Laboratory

by *Charles L. Nylander*, LA-UR-01-2054, Water Quality and Hydrology Group, Los Alamos National Laboratory

Before 1990, Los Alamos National Laboratory (LANL) believed that its facilities and operations could not impact the drinking water in the regional aquifer. This belief was held because its facilities were located 600–1,000 ft above the regional aquifer and were separated from it by dry volcanic rock. Historically, 13 water-supply wells, 8 deep-test wells, and many springs were used to monitor the quality of the ground water in the regional aquifer. However, over the past 10 years of monitoring, the appearance of very low levels of specific contaminants in some of the test wells led laboratory hydrologists to suspect that the dry volcanic rock barrier was not as impervious as originally thought. The laboratory realized that the movement of water from the land surface down to the regional aquifer was not understood well enough to know how contaminants were moving downward. In 1994, the laboratory initiated a project to install additional ground-water monitoring wells.

Because of the laboratory's desire to gain a better understanding of the hydrogeologic setting and the need to satisfy a 1995 request from the New Mexico Environment Department (NMED), the laboratory developed a site-wide hydrogeologic characterization workplan, which was approved by NMED in March 1998. The plan describes data collection, data analysis, and data management activities that are being employed to improve the understanding of the hydrogeologic setting beneath the Pajarito Plateau. Data collection includes the drilling and installation of 32 deep wells into the regional aquifer, installation of 51 shallow alluvial wells, and quarterly sampling of the ground water in those wells. Data are analyzed using numerical modeling tools to synthesize, analyze, and visualize the previously existing and newly collected data. All data collected and used in the hydrogeologic characterization program are managed through a water quality database that will be available to the public via the Internet.

The characterization program described in the workplan represents a 7-year program, estimated in 1996 to cost approximately $50 million, which began with the drilling of the first regional aquifer well in 1998. Through fiscal year 2000, the program has completed 7 wells in the regional aquifer and developed flow and transport models for the unsaturated zone (the dry rock between the ground surface and the regional aquifer) and for the regional aquifer. Wells are prioritized for drilling based on hydrogeologic characterization data needs and on an assessment of which laboratory areas are more likely to have contaminants. Several of the seven wells installed thus far encountered contaminants including nitrate, high explosives, tritium, uranium, and perchlorate, although most contaminants were at levels below health standards. However, well R-25 in the southwest area of the laboratory, where high explosives were manufactured and machined, encountered high explosives in the ground water at concentrations above Environmental Protection Agency (EPA) health advisory limits.

When contaminants are detected in ground water by the hydrogeologic characterization program, the laboratory's Environmental Restoration (ER) Project steps in to further characterize the areas of contamination. To date, the ER Project has installed one deep well in the high explosives area to further delineate the extent of high explosives detected in R-25. The ER Project has also installed one well in the intermediate perched ground-water zone (a zone of saturated rock between the land surface and the regional aquifer) along the northeastern boundary of the laboratory where uranium was detected (at concentrations above a proposed EPA standard) in regional aquifer well R-9.

The data thus far support the conceptual model that ground water is found in three distinct zones beneath the Pajarito Plateau, namely shallow alluvial zones, intermediate perched zones, and the regional aquifer beneath. The characterization wells indicate that the alluvial and intermediate perched zones are typically found beneath the canyons that have large surface-water flows but are typically absent beneath the mesas and dryer canyon bottoms. Deep ground water in the regional aquifer generally moves from west to east-southeast beneath the plateau at velocities estimated to be between 50 and 250 ft/yr. Further characterization and improved mapping of the

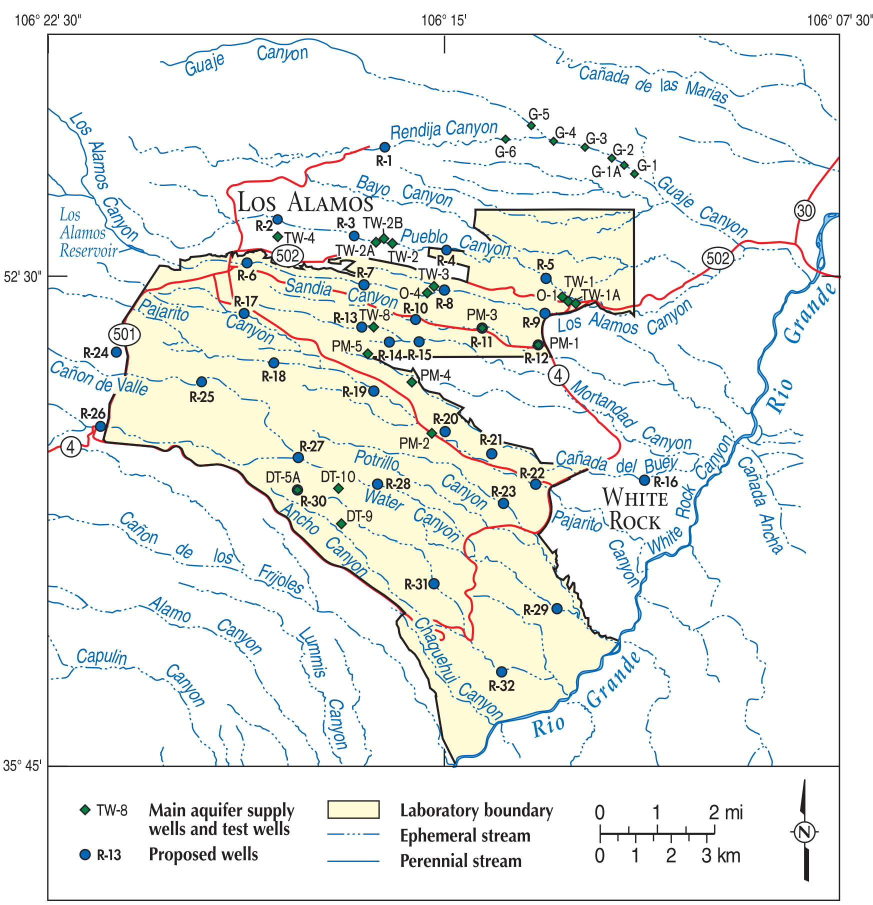

FIGURE 1—Regional aquifer supply and existing test-well locations and locations of proposed characterization and monitoring wells.

ground-water surface(s) will enhance the laboratory's ability to monitor contaminants and locate future monitoring wells as needed.

Due to the complexity of the hydrogeology beneath the Pajarito Plateau, hydrogeologic characterization data quality objectives, laboratory security requirements, data collection, and well installation are costly compared to other regulated facilities nationwide. High costs are primarily attributable to the significant depth to the regional aquifer; the drilling methods required to keep the borehole open while drilling without tainting samples; drilling in areas requiring special site procedures; extensive laboratory health and safety (HS) requirements requiring HS plans and HS personnel at the drill sites; and comprehensive analyses for samples. Although the costs are high, the ultimate value of the characterization data will be worth the costs. The data will assure the laboratory, Department of Energy, NMED stakeholders, and the public that future ground-water monitoring is adequate to protect public health and the environment.

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The Role of Risk Assessment in Ground-Water Protection

by *Diana J. Hollis*, LA-UR-01-2052, University of California/Los Alamos National Laboratory

Studying a hydrogeologic system as complex as the Pajarito Plateau is an earth scientist's dream. Here, water flows from the surface into and through the subsurface geologic units in what reveals itself as a three-dimensional maze of paths, some through-going, others dead-ending; some direct, others circuitous; some fast, and others slow. Because of this complexity, our understanding of the processes governing the hydrologic system is still incomplete, even after decades of productive investigation by hosts of dedicated scientists. While this circumstance is acceptable and even desirable to earth-science researchers, it can frustrate decision makers charged with ensuring that ground-water quality and quantity are adequately preserved and protected for present and future generations. This situation affects both proactive planning to ensure that future activities do not adversely impact surface and/or ground water, and retroactive cleanup to ensure that impacts from past or present activities do not harm the biological systems so integrally dependent on water.

We know with certainty that people's activities have impacted water quality in the Pajarito Plateau watershed. We will likely make decisions about how to minimize that impact before we have the same degree of certainty about exactly how impacted water moves through the geosphere into the biosphere and exactly how living organisms may be affected. We will know absolutely that something must be done only if we find incontrovertible evidence of impacts exceeding a specific regulatory threshold (such as a maximum concentration limit in a drinking-water supply well). However, as responsible stewards of the environment, we would like to be able to control impacts so that they never reach that threshold. Thus, we are compelled to make decisions about ground-water protection (and potential cleanup) in the face of great uncertainties about the detailed hydrogeology that affects, and is affected by, such decisions. One way that we can make those decisions in the face of great uncertainty is through risk assessment.

Risk assessment uses mathematics to describe the physical forces that control the movement of man-made constituents in ground water, and the chemical and biological reactions that such constituents undergo in the environment and in living systems. The solutions to these mathematical equations are used to estimate the risk to living organisms that may come into contact with impacted ground water. By using additional mathematical methods, the uncertainties in the physical, chemical, and biological relationships can be analyzed to understand which uncertainties are most important to the risk estimate. This gives us a way to focus our investigations of the complex hydrogeologic system on the collection of information that is most relevant. Thus, risk assessment and information gathering are iterative (Fig. 1), and the final iteration is that which provides sufficient information to decision makers so that they can make a logical and scientifically sound judgment about the need for and scope of protective measures or cleanup. In a situation where a regulatory threshold is reached, decision makers may need no additional information to know that something must be done to control the situation. However, they may still need additional information to know what would be the most cost-effective solution.

The goal of risk-based decisions is to identify (even in the face of uncertainties) the conditions that pose the highest risk and to focus (limited) corrective-action resources on those highest-risk conditions. Ideally, risk assessment in support of resource protection and cleanup decisions would use exact information about the type, amount, and location of a potential contaminant; the direction and rate of movement of a contaminant; the (eventual) amount of contaminant at a location where living organisms may be exposed; and the biological effect of that amount of contaminant on an exposed organism. Realistically, this information is always uncertain. The objective is to balance the science of information gathering (uncertainty reduction) and interpretation with the risk-management decision at hand. The Los Alamos National Laboratory's investigation of the ground water within the Los Alamos/Pueblo watershed elucidates this process.

The Environmental Restoration Project has identified several sources of potential ground-water contamination in the Los Alamos/Pueblo watershed. These include the decommissioned Omega West research reactor in upper Los Alamos Canyon (a source of radioactive tritium), the decommissioned uranium processing facility on DP Mesa (a source of radioactive uranium isotopes), and the sewage-treatment facility in Pueblo Canyon (a source of nitrates). From the open literature we know certain things about these contaminants needed for risk assessment, including their solubility in water, their physical and biological half-lives, and their regulatory thresholds. This information is supplemented with site-specific information, such as the ground-water travel times and measured contaminant concentrations in alluvial water, in unsaturated rock, in intermediate ground water, and in the regional aquifer. We are in the process of assimilating all of this information by means of a risk assessment to guide our future investigations in a way that reduces the most significant uncertainties in the context of ensuring ground-water (and ground-water receptor) protection. To date, our risk-assessment results indicate very little likelihood of exceeding a regulatory or risk threshold for tritium in a water supply well, now or in the future. We are in the process of calculating the transport of uranium in ground water to support an assessment of risk associated with uranium transport to water-supply wells.

It is the challenge of regulators to make good decisions about ground-water protection and cleanup despite inexact scientific information regarding the current and future impacts of man-made constituents on human health and the environment. We must understand natural ground-water processes to the extent that we can apply the laws of nature to effectively protect and preserve water quality. To this end, risk assessment provides a means of understanding available scientific information and inherent uncertainties. This information can be evaluated by the constituency of affected stakeholders, who

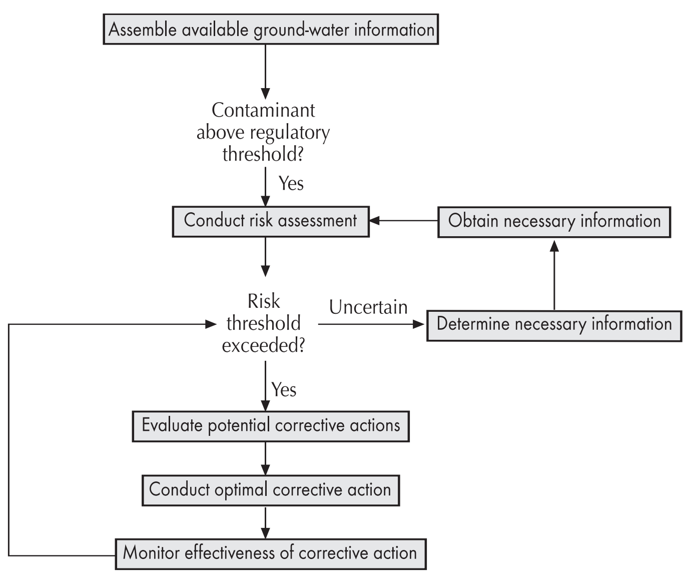

FIGURE 1—Iteration of data collection and decision making.

will provide additional information for decision makers to consider in their task of balancing scientific uncertainty, technological practicability, fiscal accountability, local socioeconomic impacts, and human values.

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Day One

Independent Analysis of Exposures and Risks to the Public from the Cerro Grande Fire

by *John Parker*, New Mexico Environment Department

On May 4, 2000, a prescribed burn at Bandelier National Monument grew out of control and was declared a wildfire on the following day. By June 6, when the Cerro Grande fire was finally declared contained, nearly 50,000 acres of forest in and around Los Alamos, New Mexico, were burned, including over 7,000 acres of Los Alamos National Laboratory (LANL). In recognition of the need for an independent assessment of exposures and risks to the public from the fire, the New Mexico Environment Department has contracted with Risk Assessment Corporation[1] (RAC) to evaluate potential health risks to the communities of northern New Mexico.

During the fire, high winds carried huge smoke clouds in a north-northeasterly direction over Los Alamos, Española, and the many small communities north to Taos. The smoke clouds could even be seen from southern Colorado and western Oklahoma. Ash deposits blanketed cars, homes, and the ground surface in these areas. In response to concerns over possible elevated levels of radionuclides and chemicals from LANL, an aggressive air-monitoring program was conducted by LANL, the U.S. Environmental Protection Agency (U.S. EPA), and the New Mexico Environment Department (NMED; Fig. 1). Radionuclide concentrations were found to be elevated above background concentrations—although the elevated readings quickly tailed off when repeated measures were taken, indicating a predominance of short-lived, naturally occurring radionuclides.

In addition to the potential for exposures from the air pathway, another concern from the fire involves the potential for enhanced transport of contaminants via the surface-water pathway. The fire burned along the eastern flank of the Jemez Mountains and portions of the Pajarito Plateau, particularly the heavily forested areas of the western margin and canyons. The loss of vegetation within these watersheds and the reduced infiltration due to the effects of the intense heat on the ground surface are likely to result in much larger-than-normal surface-water flow in the canyons leading to the Rio Grande and the potential for large amounts of surface erosion and flooding.

Whereas the structural damage at LANL from the fire was minimal and major facilities containing chemicals and radioactive materials were not significantly impacted, environmental contamination from over 50 years of operations at LANL was now at increased risk of being transported beyond laboratory boundaries. Historically, facilities at LANL disposed of effluents and debris containing radionuclide and chemical wastes into the many steep-sided canyons traversing the Pajarito Plateau. Areas containing these "legacy wastes" are termed "potential release sites" or PRSs. Over 600 PRSs are located within the fire perimeter[3]. Contaminated materials from these sites could be transported by surface-water runoff, which could impact the water quality and sediments of the Rio Grande.

The independent risk assessment is intended to address public concerns over potential health risks due to the transport of contaminants by air and surface water. The risk assessment will analyze the effects and longer-term impacts of the Cerro Grande fire in terms of increased public exposures to radionuclides and chemical toxins and the corresponding health risks. Specifically, the work will address the following issues:

(1) The magnitude and associated risks of public exposure from the Cerro Grande fire created by the transport of radionuclides and chemicals through the air pathway;
(2) The magnitude and associated risks of public exposure to radionuclides and chemicals resulting from potential surface-water pathways;
(3) The lessons that should be documented with regard to monitoring, analyzing, estimating, and reporting risks to the public from radionuclides and chemicals released during and following the Cerro Grande fire; and
(4) Close interaction with the public to report progress and findings and respond to questions from local communities.

The RAC Team will need to access an extensive amount of information before it can begin to perform any assessment of risk. Much of this information exists at LANL where years of environmental monitoring and an extensive post-fire monitoring effort will provide the primary source of data. In addition, both the U.S. EPA and the NMED have monitoring data on select pathways that will be used in the assessment. Data quality will be assessed to assure that outliers or otherwise questionable results don't influence results of the risk modeling.

The risk-assessment is slated to begin in early 2001 and expected to conclude in approximately a year. Results and conclusions will be presented to the public in a report as well as in public meetings. The assessment is funded under an Agreement-in-Principle[4] between the state of New Mexico and the Department of Energy.

FIGURE 1—New Mexico Environment Department staff collect air samples during the Cerro Grande fire.

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[3] http://erproject.lanl.gov/Fire/firehome.html (accessed April 11,2001)
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Watersheds, Los Alamos National Laboratory, and the Pueblo of San Ildefonso

by *Neil S. Weber*, Director, Department of Environmental and Cultural Preservation, Pueblo of San Ildefonso

The Pueblo of San Ildefonso is the only Native American community that shares a common boundary with a nuclear weapons research facility—Los Alamos National Laboratory (LANL). Additionally, LANL occupies land that is within the ancestral domain of our people and contains culturally sensitive sites. The impact of past and present activities at LANL has a dramatic influence upon the pueblo's traditional way of life.

Four major watersheds or canyon systems are shared by LANL and the pueblo: Guaje, Pueblo/Los Alamos, Sandia, and Mortandad. Radioactive and chemical legacy wastes were often disposed of on mesa tops and in canyon bottoms. Contaminants from ongoing operations have the potential to be released into the environment. It has been shown that both chemical and radioactive contaminants have invaded the surface and ground water. Such contaminants are potentially harmful to human health and natural resources. Regulatory and action levels are based upon the anticipated effect upon a population that is exposed to contaminants through a generalized use of resources, foodstuffs, and anticipated contact with contaminants in daily life. Past and current studies are based upon a generalized population's utilization of environmental resources and risk assessment.

The people of the Pueblo of San Ildefonso live a traditional lifestyle, and their culture is intimately associated with the natural environment. Resources are utilized in a manner much different than that of the outside world. Therefore any risk assessment studies based upon the outside world's exposure is not relevant to the pueblo population. It is the intent of the pueblo's Environment Department to develop a Tribal Risk Assessment study based upon the unique exposure pathways experienced by tribal members. One of the difficulties in designing a Tribal Risk Assessment is that the particular utilization of resources by tribal members is proprietary, not only to the outside world, but also between various groups within the pueblo. The Environment Department of the pueblo is attempting to design a study that will gather the necessary information and at the same time protect its proprietary nature—a difficult endeavor. However, unless a true Tribal Risk Assessment is developed, the exact risks to chemical and radioactive contaminant release from LANL will never be determined.

The pueblo's residential, agricultural, religious, cultural, and sacred areas are situated directly downstream from LANL in four major canyons and watersheds. The potential for radiological and chemical contaminant transport from past and present LANL operations into pueblo lands, air, surface water, and ground water has always existed. However, as a result of the Cerro Grande fire this potential has increased. Soils in severely burned areas in the watersheds above LANL have become hydrophobic, and runoff from rains and snowmelt will be increased up to 100 fold. Many of these watersheds and canyon systems drain directly over and through LANL property on which exist "potential release sites" (PRSs) and activities that utilize radiological and chemical substances that are a threat to the environment. Thus, the likelihood of contaminant transport onto pueblo lands and into waters is now increased.

Our people hold our lands and waters dear to our existence. Our cultural and religious activities are closely intertwined with the natural environment. Any insult to the environment is an insult to our culture and the heart of our existence. It is imperative that our people be assured that our land, air, and water have not received the insults of chemical and radiological contamination from LANL activities. Such insults are tantamount to desecration of our culture and religion.

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Santa Clara Pueblo and the Cerro Grande Fire—Burned Area Emergency Rehabilitation Projects and Fire Restoration Program

by *Jerome Jenkin*s, Santa Clara Pueblo

Post-fire rehabilitation can reduce hazards such as falling snags and prevent property damage and resource degradation from flooding and erosion. After a major fire, a Burned Area Emergency Rehabilitation (BAER) Team is formed to assess fire damage and to implement a rehabilitation plan. BAER teams include specialists from many disciplines such as biology, archaeology, ecology, and geology.

The Cerro Grande BAER Team, formed in May 2000 following the Cerro Grande fire, was the largest BAER effort in the history of the nation. The team included dozens of representatives from federal and state agencies throughout the West.

On June 17, 2000, a BAER project leader was assigned to Santa Clara Pueblo to assist with the Cerro Grande fire BAER projects and to implement emergency treatments specific to Santa Clara.

On July 7, 2000, a contract was signed between the Department of Interior-Bureau of Indian Affairs and Santa Clara Pueblo. The purpose was to expedite transfer of emergency fire rehabilitation funds for immediate emergency treatment implementation.

The 23 projects below are specific to this contract. A brief narrative follows each line item explaining how these projects affect Santa Clara Pueblo. However, it is not all encompassing and should not be taken as such. Also, it does not apply to implemented or planned rehabilitation work within Santa Clara ancestral lands but outside reservation boundaries.

(1) Rehabilitate roads—This project is for the rehabilitation of roads that may have been damaged during the fire. Santa Clara Pueblo has approximately 20 mi of roads that were affected. Additionally, the maintenance and re-grading of roads within the burned area has been complicated by post-fire soil erosion and flooding, and our crew has responded to many mudslides and debris flows in the canyon (south side area included) following summer rainstorms.

(2) Rehabilitate parking, Puye Cliffs—Fire suppression significantly altered the parking lot at the Puye Cliff Dwellings historical visitor center. Approximately 15 acres were bulldozed flat as part of fire operations during the wind-driven Cerro Grande fire. A landscape designer has been hired to rehabilitate the area through transplanting trees, re-grading the parking lot, and implementing soil erosion treatments.

(3) Protect power poles—Sandbags and large boulders have been strategically placed around streamside power poles for protection from potentially damaging floodwaters.

(4) Protect wellhead—Sandbags were filled and placed around a small concrete building that houses an open well. The sandbags divert water around the structure, thereby protecting the building and preventing floodwater from entering an exposed well hole. Balance of funds remains for anticipated rebuilding of damaged or destroyed barriers.

(5) Monitor water quality—Santa Clara Pueblo Environmental Department obtains water-quality samples from Santa Clara Creek six times a year. Our Office of Environmental Affairs uses an ISCO automated surface-water sampler on loan from the State of New Mexico. The samples, analyzed in Albuquerque, include primary organics and primary inorganics.

(6) Monitor grass-seeding effectiveness—The Santa Clara Pueblo Environmental Department contracted Terry Foxx, an independent contractor, to accomplish this activity. Transects have been placed across Santa Clara Pueblo lands, and these sites will be revisited periodically to determine seeding effectiveness.

(7) Monitor invasive plant species—The Santa Clara Pueblo Environmental Department contracted Terry Foxx, an independent contractor, to accomplish this activity. Transects have been placed across Santa Clara Pueblo lands to determine if any invasive plant species have germinated. If monitoring indicates invasive plant species exist, a recommendation for funding to eradicate these species shall be made.

(8) Install safety-hazard signs—Flood warning and safety signs have been paid for and received. The signs are needed for road-danger areas; several signs also measure the depth of rising waters.

(9) Install range fence—The fence runs from north to south, on the east side of Puye. The purpose of the fence is to keep cows and other livestock away from artificial regeneration or planted seedlings. Funds have been obligated for materials, supplies, and wages associated with this activity.

(10) Repair permanent range and boundary fence—A Santa Clara Pueblo hand crew is in the process of rebuilding this fence. This is a very slow and costly procedure because the area is remote and roadless and the materials must be hand carried. Approximately 1 mi of a 5-mi fence has been completed. Snow has delayed this project.

(11) Inventory trails and trail reconstruction—A majority of trails on the south rim of the canyon have been burned out and are inaccessible due to soil erosion and fallen trees. A short hand crew will dedicate itself to cutting new trails, reopening existing trails, and implementing soil-erosion treatments for cultural and fire-suppression purposes.

(12) Clean and replace culverts—Runoff from rainstorms, slope failure, and mudslides clog culverts, which must be cleaned to prevent added deterioration of the culvert and roadbed. Our crew has responded many times to clean clogged culverts immediately after significant rainfall.

(13) Control tree hazard—Periodically, trees become a public safety threat; they are either cut down or bucked up. Our fire rehabilitation crew completes this as needed.

(14) Assess and protect structures—The Sawyer Dam outlet was constructed in accordance with Corps directions. Clearing for the laying of riprap and tree removal from both dikes has been completed. Jersey barriers from the Corps have not yet been received; they are to be placed in front of streamside trailers by tribal crews.

(15) Armor catchment basins—There are several earth dikes that now function as catchment basins for soils and debris. The earth dikes must be reinforced with rock because the amount of water subsequent to the Cerro Grande fire has the potential to erode the dikes.

(16) Install stream control structures—Rock dams are placed inside drainages where water cuts into the banks. Crews have installed many rock dams as weather permits. Heavy rainstorms and day-to-day operations of stream and culvert cleaning have prevented our crew from concentrating on this very effective flood-control measure. Rock dams within Santa Clara Canyon were destroyed by heavy flooding and were rebuilt. We are currently concentrating on drainages negatively affecting the south side canyon road in the hope of mitigating recurring road damage.

(17) Clear stream debris—Many hours have been spent clearing shrubs, rocks, and downed logs from the stream. This prevents debris from forming dams, which can burst, creat-

ing more damage downstream. Clearing the stream also keeps debris from plugging culverts. Rains push debris into the stream from the burned hillsides above, and the stream must be cleaned again. For example, the rains on September 8, 2000, moved large logs down hill and caused huge culverts at the checking gate to become plugged. The plugged culverts then forced the water to flow over the blacktop and erode the downside road bank. Our crew, using a tribal backhoe, cleaned the culverts after the rain ended.

(18) Re-establish CFI plots—Work has started on the re-establishment of CFI plots. Trees are renumbered, stakes are replanted, and reference trees are re-established. Data sheets are used to assist the crew in plot location, and photo points are established.

(19) Assess cultural-resources damage—We will conduct a cultural-resources field inventory of all places disturbed by the fire-suppression activities to identify cultural-resource sites (cultural, historic, and prehistoric) directly affected by the fire. We will inventory previously documented cultural resources within the burned areas to determine damage and site-stabilization needs.

(20) Stabilize archaeological site LA 12700—Prehistoric archaeological site LA 12700 is listed on the National Register of Historic Places. This site must be protected through erosion-control measures to maintain its integrity. We conduct periodic law-enforcement and site-stewardship patrols to evaluate the effectiveness of treatments and to implement needed changes or additional stabilization measures through plan amendments.

(21) Monitor rehabilitation—We monitor implementation of the cultural-resource prescriptions of the BAER plan, as well as implementation of other ground-disturbing BAER plan treatments to ensure cultural-resource compliance and coordination with other agencies.

(22) Coordinate volunteer workers—We provide a Volunteer Coordinator/Public Affairs Officer to coordinate and oversee volunteer, public involvement, and information exchange for the Cerro Grande Fire Rehabilitation Program in cooperation with other agencies.

(23) Clean catchment—We clean out debris and sediment from catchment basins after each storm-flow event. For seven basins, we estimate four storm-flow events per year for 3 years.

The above treatments, specific to the Pueblo of Santa Clara, were identified in the June 2000 Cerro Grande fire BAER plan prepared by the Interagency BAER Team.

Acequia Communities on the Upper Rio Grande: Acequia de Chamita Case

by *José A. Rivera*, Professor of Public Administration, University of New Mexico

The summer of 1998 marked the cuartocentenario (400th year anniversary) of the first Spanish colony in La Provincia del Nuevo México. On July 11, 1598, Capitán General Juan de Oñate arrived in present-day San Juan Pueblo and established the first European settlement in the northern frontiers of New Spain, calling it San Juan de los Caballeros. This initial headquarters for Oñate and his party was probably located on the east bank of the Rio del Norte (now the Rio Grande), near its confluence with the Rio Chama, all in keeping with the requirement of colonial ordinances that settlements should be located in areas with "good and plentiful water supply for drinking and irrigation."

The Oñate colony was located within lands and dwellings already occupied by Tewa Pueblo Indians. For long term occupation, however, Governor Oñate intended to build a Spanish municipality to be named "San Francisco de los Españoles" somewhere near the vicinity of San Juan Pueblo. On August 11, one month after his arrival, Oñate gathered 1,500 Tewa laborers from the area to construct the first Spanish acequia, presumably to irrigate crops that would be needed to sustain the planned city and permanent capital. In most instances, building of a local ditch was the first public works project for any settlement during the colonial period; construction of a church, government buildings, and other structures all awaited the completion of the critical irrigation system.

The acequia that was initiated for use in the town site of San Francisco appears to have been the first Spanish ditch in the New Mexico province. However, there is no historical record as to its ultimate fate or whether it was ever completed. A more certain development was the fact that Oñate soon abandoned plans to build the new town of San Francisco. Instead, he chose the more practical alternative of relocating his colony across the Rio Grande, on the western bank, at the confluence with the Rio Chama. Here he laid out plans (c. 1599–1600) for the villa of San Gabriel, now Chamita, at the location of a smaller and partially abandoned Tewa Pueblo, Yunque. At this second site for a capital city, Governor Oñate simply had to remodel and expand the existing Tewa structures at Yunque. According to historian Marc Simmons (1991), this location was already advantaged with a plaza and some 400 dwellings, a configuration suitable for expansion into a U-shaped village to also accommodate a new church and an attached convento or friary.

While completing these additions at San Gabriel, the colonists also built an irrigation canal, diverted from the Rio Chama, sufficient to irrigate the fields to be cultivated in the fertile valley between the two rivers. Scholars agree that San Gabriel was located in the area now known as Chamita, and most agree that the San Gabriel ditch is the present-day Acequia de Chamita. This recognition probably establishes the Acequia de Chamita as the oldest, still functioning community ditch of Iberian origin in New Mexico, dating to around 1600. For evidence of its early use, scholars often cite a report by Juan de Torquemada, a Franciscan historian who visited the colony in 1612–13, where he observed the practice of irrigated agriculture:

"San Gabriel…is situated at 37° latitude, and its sides consist of two rivers, one of which has less water than the other. This small one [the Rio Chama] irrigates all the varieties of wheat, barley, and corn, in cultivated fields, and other items that are planted in gardens, because those lands produce cabbage, onions, lettuce and beets, and other small vegetables than in this one: producing many and good melons and watermelons. The other river is very large; they call it [Rio] del Norte, which provides a lot of fish…" (Monarquía Indiana por Fray Juan de Torquemada, published in 1615).

San Gabriel remained the capital city of the fledgling province until 1609–1610 when a subsequent governor moved it to its present location at Santa Fe. In 1968, the archaeological site of San Gabriel del Yunque was declared a National Historic Landmark by the United States Department of the Interior. Today, the Acequia de Chamita runs for 3 or 4 mi, and at its upper and middle sections, the acequia irrigates about 485 acres of farmland, serving 83 Hispanic parciante families, many of them descended from the first Oñate settlers. At its lower end, this ancient canal irrigates hundreds of additional acres farmed by the Pueblo of San Juan. Other large ditch systems on the lower Rio Chama include the Hernández and the Salazar Acequias, themselves of colonial origin and historical significance. The Hernández and the Chamita ditches share the same diversion dam, with their head gates on each bank of the Rio Chama (Baxter, n.d.).

Throughout New Mexico, there exist about 1,000 acequias, the majority of them dating to the colonial or early territorial periods. Many acequias enjoy vested rights, meaning that their historic uses of water predate the New Mexico Water Code of 1907 and are among the oldest non-Indian water rights in the state. Acequia associations have become increasingly expert in gathering and presenting a wide array of evidence to defend the antiquity of their customary irrigation practices, making a case for the protection of the historic acequias in the modern era of population growth and the emergence of active water markets (Rivera, 1998). The contributions and significance of acequia agriculture are many:

(1) Following Spanish and Mexican laws, the acequia appropriators evolved customary rules for the administration and equitable distribution of water resources, traditions that continue in effect but that differ in some respects with the hierarchical system of priority calls;
(2) The technology to construct the irrigation systems was a melding of Iberian–Islamic traditions, transplanted from the Mediterranean provinces of Spain to the Americas, with the irrigation practices observed by early Spanish explorers at many Pueblo Indian villages;
(3) The acequia associations of New Mexico are the oldest European-derived water management institutions in the United States, and their autonomous governance establishes them as the oldest grassroots democracies in the U.S.;
(4) The first water laws of the modern state of New Mexico were in fact the "Acequia Laws" of the territorial period, 1851–1852, a codification of customs and traditions that evolved from the Spanish colonial and Mexican periods;
(5) The acequia associations function as "water democracies" at the local level, and they also enjoy a unique standing as political subdivisions of the state of New Mexico, unlike their counterparts in the other western states;
(6) Located upstream in the major rivers and tributaries, acequias often are the first points of diversion of headwaters' streams, underscoring their stewardship role in protecting forest ecosystems and pristine waters for use by other stakeholders downstream;
(7) As earthen irrigation canals, the acequias extend the riparian zones, preserve hydraulic landscapes, and increase ecological biodiversity for plant and wildlife species (including the willow flycatcher);
(8) After 400 years of successful adaptation, the acequias of the upper Rio Grande are model institutions worthy of further

research as to their historic, cultural, economic, and ecological value to the state as a whole;

(9) The acequia villages perpetuate cultural continuity, a sense of place, and participatory democracy, values that need to be considered when weighing and comparing their contributions against other uses; and

(10) The acequia culture of the region promotes tourism and economic development in the state of New Mexico by way of the quaint village architecture, the greenbelts, and open space that define the landscapes of the river valleys, and the production of renowned arts and crafts marketed worldwide.

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What Decision Makers Should Know About Collapsible Soils in New Mexico

by *David W. Love*, New Mexico Bureau of Mines and Mineral Resources

FIGURE 1—Ground subsidence of 2.2 ft affecting an area of 600 ft^2 after injecting nearly 17,000 gallons of water into the soil at a depth of 10 ft over 16 days (water equivalent to septic tank use by a family of four for 1 month). Collapse was initiated within 1 week.

Collapsible soils are soils that compact and collapse after they get wet. The soil particles are originally loosely packed and barely touch each other before moisture soaks into the ground. As water is added to the soil in quantity and moves downward, the water wets the contacts between soil particles and allows them to slip past each other to become more tightly packed. Water also affects clay between other soil particles so that it first expands, and then collapses like a house of cards. Another term for collapsible soils is "hydrocompactive soils" because they compact after water is added. The amount of collapse depends on how loosely the particles are packed originally and the thickness of the soil that becomes wetted. In one area of El Llano on the east side of Española, one collapse-crater feature was 150 ft across and 5 ft deep in the center. The loose soil originally was more than 50 ft thick. Its collapse literally split and tilted the foundations of two homes and threatened two more. The addition of water to the naturally dry soil was caused by a septic tank, a leaky municipal water line, runoff from roads, and runoff from the roofs of the houses nearby. Several other houses and other facilities in the same neighborhood were affected by addition of water near their foundations.

Collapsible soils are common in New Mexico. They have caused millions of dollars of damage to public facilities such as schools, highway maintenance buildings, jail facilities, water tanks, roads, and other infrastructure. Housing developments from Velarde to Las Cruces and from Alamogordo to Socorro have been subject to collapsible soils. Collapsible soils are likely to continue to plague unsuspecting homeowners. They have damaged some homes to the point of condemnation. Several would-be homeowners have had their houses condemned and have had to continue paying mortgages on houses that they can not live in nor repair. Developers have had to buy houses back from would-be homeowners after foundations were ruined by collapsible soils.

Collapsible soils develop on valley margins where soil particles move from the foothills toward the valleys. They commonly accumulate to tens of feet thick. As New Mexico's population has moved out of the well-watered and irrigated valleys with compact soils to develop the valley margins and foothills, the collapsible soils have made their presence known as the newcomers add water to the drier soils.

What Can Property Owners Do?

In areas that have not been developed, soils should be tested for collapsibility as well as other problems (shrink-swell potential, corrosiveness, and depth to bedrock). If collapsible soils are found, thin amounts may be removed and compacted with heavy machinery. If collapsible soils are thick, large tracts may be settled by prewetting the soils to depth before development takes place. Road right-of-ways may be compacted by repeatedly dropping heavy weights from a large crane along the route.

In areas that have already been developed and then are discovered to have collapsible soils, property owners should try to keep as much water as possible from seeping into the ground. This means xeriscaping rather than watering lawns and shrubbery, particularly near building foundations; installing municipal water and sewer lines rather than individual wells and septic tanks; and installing downspouts and storm-sewer lines to remove rainfall runoff from the area as quickly as possible. New foundations should follow construction guidelines of the Building Research Advisory Board (BRAB), developers of the BRAB slab, a reinforced "waffle-like" foundation that also prevents damage from shrink-swell soils. Pylons not on solid subsurface materials and "slurry jacking" do not work in collapsible soils.

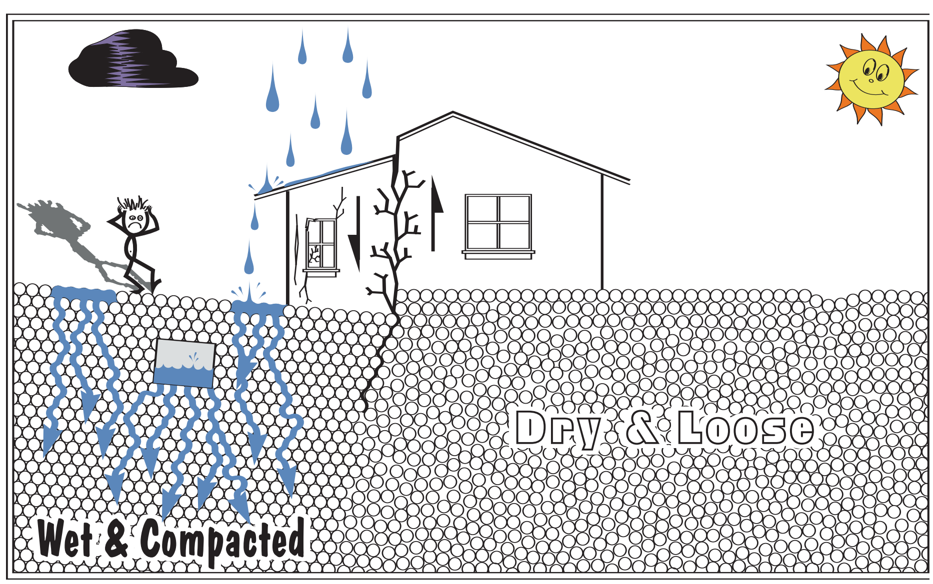

FIGURE 2—Cartoon of loose, dry soil supporting a house versus soil collapse due to the addition of water by runoff, septic tank, and irrigation.

What Can Geologists, Engineers, and Soil Scientists Do?

Collapsible soils may be suspected in undeveloped areas that have young, accumulating sandy and silty soils in dry areas. The soils may be confirmed to be collapsible through engineering testing. These tests include study of seismic waves through the soils, rates of drilling through the soils (blow counts), and testing undisturbed soil samples obtained by careful drilling for compaction after wetting. Unfortunately, these tests are expensive for individual property owners. Scientists need to develop better, less expensive ways of determining the extent of collapsible soils in the subsurface. Developers are required to file soil-engineering reports before development, but often tests for collapsible soils are not performed, and homebuyers rarely look at soil-engineering reports. More publicity about the presence of collapsible soils in New Mexico would help make the public more aware of the problem and make property sellers more apt to test and treat problem soils before they become a problem. It should be noted that collapsible soils are not the sole cause of surface subsidence in New Mexico; several other natural and human-caused processes may also cause the ground to collapse.

What Can Decision Makers Do?

The dilemma for decision makers is how to balance the protection of would-be buyers and users of property from the devastation of problem soils against the undue burden of expensive testing of soils regardless of the property's location. Some municipalities and counties have zoning restrictions that may aid in limiting some uses of some property or in requiring xeriscaping in developed areas that have experienced collapsible soils. All construction of public facilities should have proper subsurface testing and evaluation done before bidding takes place, and supervision of the site during the building phase. Xeriscaping makes sense for foundation safety regardless of the availability of water and rainfall runoff. Decision makers should insist on non-leaky waterlines and better municipal sewer and drainage systems to remove rainfall runoff from problem neighborhoods.

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The Rio Grande Compact in New Mexico and the San Juan–Chama Project

New Mexico Interstate Stream Commission, presented by Rolf Schmidt-Petersen, Hydrologist

The Rio Grande Compact was signed in Santa Fe, New Mexico, in 1938, following more than a decade of negotiations and four decades of controversy over the relative shares of three states (Colorado, New Mexico, and Texas) and two countries to this desert river.

The compact was developed for the purposes described in its introduction: "to remove all causes of present and future controversy among these States and between the citizens of one of these States and citizens of another State with respect to the use of the waters of the Rio Grande above Ft. Quitman, Texas"; "for the purpose of effecting an equitable apportionment of such waters"; "for interstate comity."

The apportionment of water under the Rio Grande Compact reflects uses at the time it was being negotiated. Large-scale irrigation systems were developed in the San Luis Valley in Colorado in the late 1800s. The Rio Grande Project, including Elephant Butte Reservoir, was developed by the Bureau of Reclamation to serve more than 155,000 acres of irrigated land in New Mexico and Texas. Most of this irrigated land (57%) is in New Mexico. In contrast, acequias in the middle Rio Grande in New Mexico were irrigating approximately 40,000 acres, far less than Colorado and the Rio Grande Project. The Rio Grande Compact does not affect the obligations of the United States to Indian Tribes nor impair their rights.

The obligation of New Mexico to deliver water to Texas under the Rio Grande Compact is based on flow conditions measured at the Otowi gage located near Otowi Bridge. New Mexico's maximum annual allocation of the native water that passes Otowi gage is 405,000 acre-ft (Fig. 1). New Mexico is obligated to deliver the remaining portion of the annual Otowi gage inflow to the base of Elephant Butte Dam. Under the compact delivery schedule, the percentage of Otowi flow that must be delivered at Elephant Butte increases with increasing water supply, ranging from 57% in low-water years to 86% in high-supply years. Thus, when the annual flow of the Rio Grande at Otowi gage is very low, New Mexico may consume 43% of that water and must deliver the remaining 57% to below Elephant Butte Dam. When the annual flow of the Rio Grande at Otowi gage is very high, New Mexico may consume only 13% of that water and must deliver the remaining 87% to below Elephant Butte Dam. In an average year, when 1.1 million acre-ft of Rio Grande water flow past the Otowi gage, New Mexico is entitled to consume 393,000 acre-ft of that amount (Fig. 2). If depletion of Rio Grande flows in New Mexico above the Otowi gage changes, the Otowi "index" flow must be adjusted accordingly. However, no adjustments of this nature have been needed.

New Mexico is also allowed to consume all tributary inflows to the Rio Grande between Otowi gage and Elephant Butte Dam. This includes flows from the Rio Jemez, the Rio Salado, the Rio Puerco, Galisteo Creek, and the Santa Fe River. Tributary inflows are highly variable, but in an average year total about 100,000 acre-ft plus an unknown, small amount from minor ungaged tributaries (Fig. 3). Water imported from the Colorado River basin, including the San Juan–Chama Project supply, is not subject to Rio Grande Compact apportionment (Fig. 3).

New Mexico's deliveries are measured as the releases from Elephant Butte Dam plus the change in storage in Elephant Butte Reservoir. Evaporation from Elephant Butte Reservoir is accounted against New Mexico's compact allocation of Rio Grande water.

The compact requires annual water accounting and provides for a system of annual debits and credits. Figure 4 presents New Mexico's historical compliance with its Rio Grande Compact delivery obligations. During the 1990s New Mexico had a net credit and that situation continues today. However, as you can see from the figure, it is not the usual historical situation. New Mexico may accumulate up to 200,000 acre-ft of debits in its deliveries to Elephant Butte Dam. Water must be retained in storage in reservoirs constructed after 1929 to the extent of each state's respective debits and cannot be used. It must be released upon demand by the downstream states under conditions specified in the compact. Reservoirs constructed after 1929 in New Mexico include El Vado Reservoir (owned by the Middle Rio Grande Conservancy District) and Nichols and McClure Reservoirs, which provide a large portion of the Santa Fe municipal water supply. If storage in Elephant Butte Reservoir is less than 400,000 acre-ft, neither Colorado nor New Mexico may increase the amount of water stored in reservoirs constructed after 1929.

Spills from Elephant Butte and Caballo Reservoirs are an important element of the compact. Credit water spills first. Debits are reduced as the reservoirs approach full capacity to the point of elimination when the reservoirs are completely full. Normal total releases from Elephant Butte and Caballo Dams are defined as 790,000 acre-ft/yr. Releases in excess of that amount affect the calculation of spills.

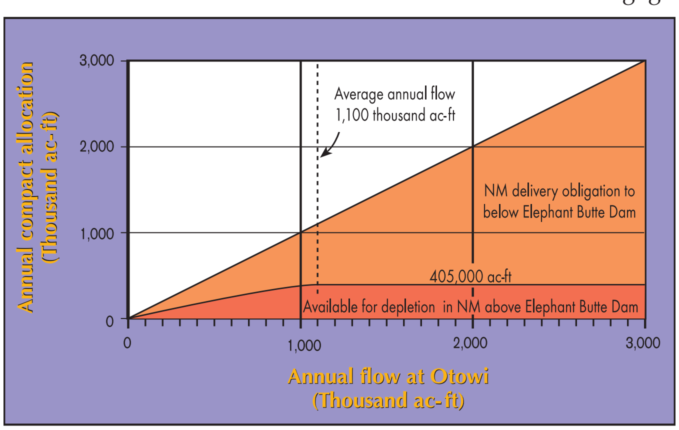

FIGURE 1—The Rio Grande Compact, signed in 1983 in Santa Fe, New Mexico, apportions the Rio Grande water supply between Colorado, New Mexico, and Texas based on flow conditions at Otowi gage.

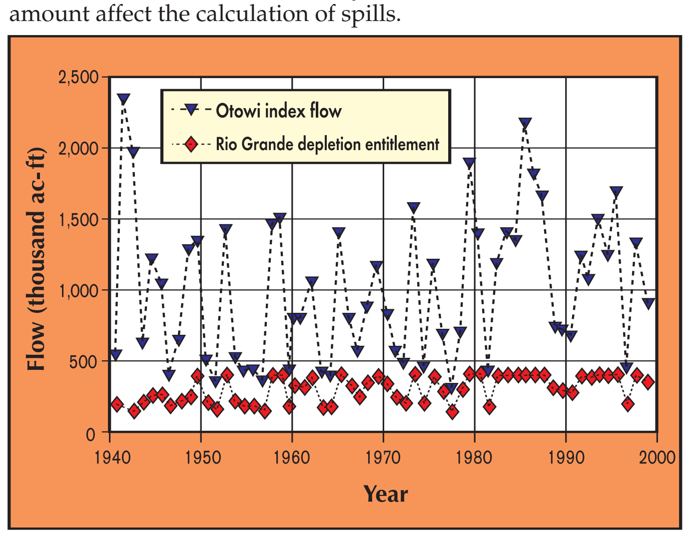

FIGURE 2—New Mexico's share of the native flow of the Rio Grande at Otowi gage.

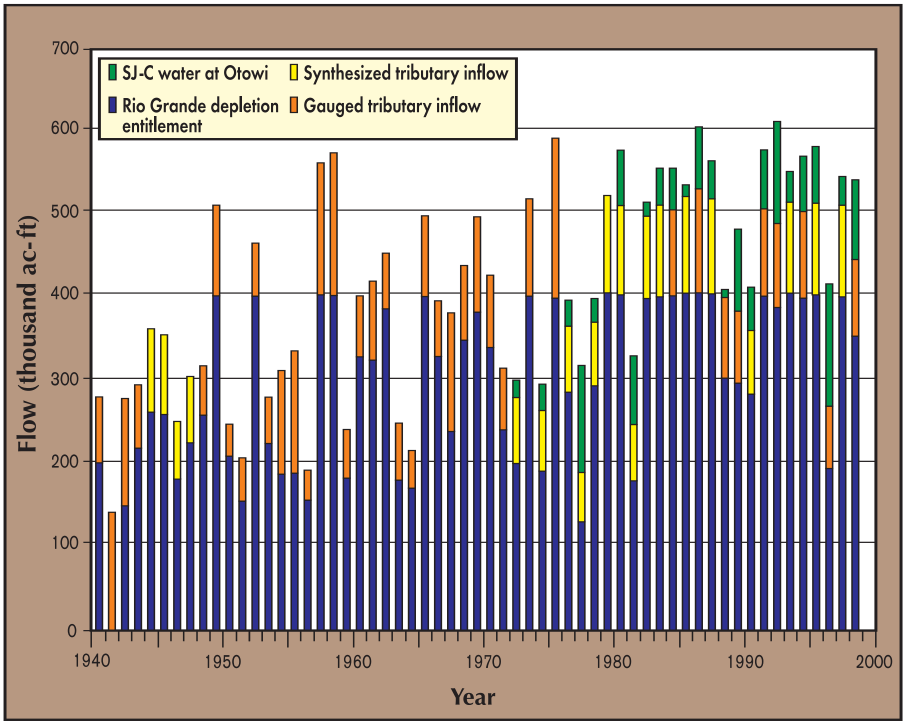

FIGURE 3—New Mexico's total available water supply (1940–1998) from the Rio Grande, tributary inflow, and San Juan–Chama Project supply.

San Juan–Chama Project

The San Juan–Chama Project is a transbasin diversion that was authorized in 1962 by Public Law 87-483 to divert an annual average of 135,000 acre-ft/yr of Upper Colorado River basin water allocated to New Mexico under the Upper Colorado Basin Compact into the Rio Grande basin for use in New Mexico. The water is diverted from tributaries to the San Juan River and brought through a tunnel across the continental divide to the Rio Chama drainage, where it is stored in Heron Reservoir until it is released to its New Mexico contractors. Further storage of San Juan–Chama Project water in Abiquiu and Elephant Butte Reservoirs was authorized in 1981 by Public Law 97-140.

Diversions from the San Juan River basin by the San Juan–Chama Project in any given year are limited by the available water supply. The project has three diversion points, all in Colorado, one each on the Blanco River, the Little Navajo River, and the Navajo River. The diversions are administered so as not to deplete minimum bypass flows required for the preservation of fish and aquatic life in the Blanco and Navajo Rivers.

San Juan–Chama Project water is contracted by the U.S. Bureau of Reclamation (USBOR) based on allocations recommended by the New Mexico Interstate Stream Commission. San Juan–Chama Project water has been allocated and contracted to the following entities in the amounts shown in Table 1.

In addition, 2,990 acre-ft of water has been reserved for the Taos area for possible settlement of water rights claims of Taos Pueblo and 2,000 acre-ft for San Juan Pueblo. An additional 5,000 acre-ft is used to offset annual evaporative losses to the Cochiti Lake recreational pool, as authorized by Public Law 88-293. These allocations represent the entire firm yield of the San Juan–Chama Project of 96,200 acre-ft.

Each year's allocation of San Juan–Chama Project water must be released from Heron Reservoir within the calendar year unless a waiver is requested from and granted by the USBOR. The project water can only be released from the reservoir upon request of the above contractors, and the water must be beneficially used in New Mexico.

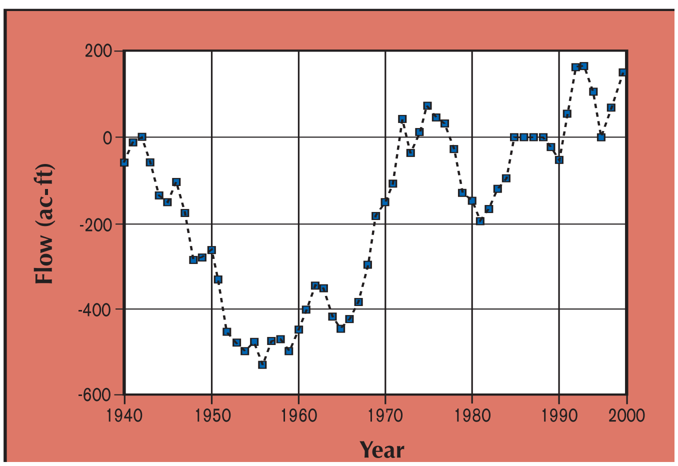

FIGURE 4—New Mexico's Rio Grande cumulative compact delivery (1940–1998).

TABLE 1—Water allocated and contracted by the San Juan–Chama Project.

Entity	Allocation (acre-feet)
City of Albuquerque	48,200
Middle Rio Grande Conservnacy District	20,900
Jicarilla Apache Tribe	6,500
City of Santa Fe	5,605
County of Los Alamos	1,200
Pojoaque Valley Irrigation District	1,030
City of Española	1,000
City of Belen	500
Town of Bernalillo	400
Village of Los Lunas	400
Town of Taos	400
Town of Red River	60
Twining Water and Sanitation District	15

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Rolf Schmidt-Petersen is the Albuquerque Office Manager for the New Mexico Interstate Stream Commission (NMISC), New Mexico's water planning and development agency. His responsibilities on the Rio Grande include investigation, development, conservation, and protection of Rio Grande water resources, interstate stream compact administration and compliance, and resolution of interstate and federal water resource issues affecting Rio Grande water resources. Before joining the NMISC staff, Mr. Schmidt-Petersen worked in New Mexico as a consulting hydrologist on many projects ranging from the investigation and remediation of groundwater contamination, characterization of landfill seepage, and development of mine land closure plans. His current interests include developing a better understanding of surface water/ground-water interactions and riparian and open-water evapotranspiration along the Rio Grande.

The San Ildefonso Pueblo Collector Well Pilot Project

by *Jack Frost*, Santa Fe County Hydrologist, 1996–2000; and
Estevan Lopez, Santa Fe County Land Use Administrator

San Ildefonso Pueblo and the city and county of Santa Fe are partners in an experimental collector well to divert water from the Rio Grande. This is one of two projects to access surface water. The city and the county are also evaluating a surface diversion from the river at Buckman Springs well field, about 4 mi south of Otowi Bridge. The collector well site lies approximately 1,000 ft north of the bridge (NM–502) on the east side of the Rio Grande (Fig. 1). First evaluated in 1984 by Public Service Company of New Mexico (PNM) and the Bureau of Indian Affairs (BIA), collector well feasibility to access the Rio Grande is finally being tested.

Collector wells (also known by the proprietary name “Ranney wells”) are large diameter caissons containing horizontal wells beneath the level of and aimed toward the river (Fig. 2). About 25 ft of permeable channel sediment lies beneath the river at the test site. Rio Grande water quality is poor and varies seasonally. Collector wells are an alternative to expensive surface-water diversion and treatment structures. Pumping at the collector well induces flow from the river through the streambed, using the filter function of the sediment to enhance water quality. Well yield is sensitive to stream flow, water temperature, and turbidity. Hopefully, the resulting water quality will be stable and clean enough that only disinfecting will be necessary.

Direct diversion of surface water from the Rio Grande could help relieve part of the demand on local ground water, currently the primary source of water in the region. Available water rights to Rio Grande water include the city and county joint contract for San Juan–Chama water, Native American rights, and potential rights transferred to the wells. Coincidentally, the project lies north of the Otowi stream gage, whose measurements determine New Mexico water deliveries to Texas and Mexico under the Rio Grande Compact. Pre-compact water rights, including pueblo rights, consumed above the gage decrease New Mexico’s delivery requirements south of Elephant Butte. The site also lies upstream of watersheds draining Los Alamos and is thus isolated from associated water-quality concerns.

Environmental studies have been completed, and plans for the test project appear acceptable. The environmental, visual, and noise impacts of construction and the resulting structure can be mitigated. All phases of the project are subject to oversight by the San Ildefonso Pueblo Environment Department.

Test drilling on the project was conducted in 1999, and a yield of 1 million gal/day is expected. The next phase will construct a pilot collector well and conduct testing over a variety of conditions for several seasons. Stored city San Juan–Chama water will be used for testing.

The current agreement between the parties only covers the pilot well. The city, county, and pueblo will each retain an ownership interest in the completed pilot well. The pueblo has its own water supply needs, as the shallow valley-aquifer-water quality has degraded over the years. Santa Fe County has expressed an interest in taking a share of water to serve the greater Pojoaque Valley and to address water-quality concerns at several traditional communities and pueblos. This possibility might resolve some of the sticky issues of the Aamodt federal water rights lawsuit, which has clouded water rights and development in the Pojoaque, Nambe, and Tesuque River basins for many years.

If the pilot confirms feasibility, new negotiations with San Ildefonso Pueblo are necessary to develop subsequent collector wells. The city of Santa Fe plans require the ultimate development of multiple collector wells, each producing 1,000+ acre ft/yr. Water would be transported 6 mi to the south to link up with Buckman Springs well field and the existing 16-mi pipeline to the city. If successful, this project, coupled with a return flow pipeline at Buckman Springs, could help satisfy water needs for the greater Santa Fe metropolitan area for 40 years.

References (not cited)

Environmental Assessment, 1984, Proposed Ranney Collector Project at San Ildefonso, New Mexico: BIA.

Feasibility Study for Rio Grande Diversion System, 1997: Boyle Engineering.

Environmental Assessment for the Rio Grande Infiltration Collector Well

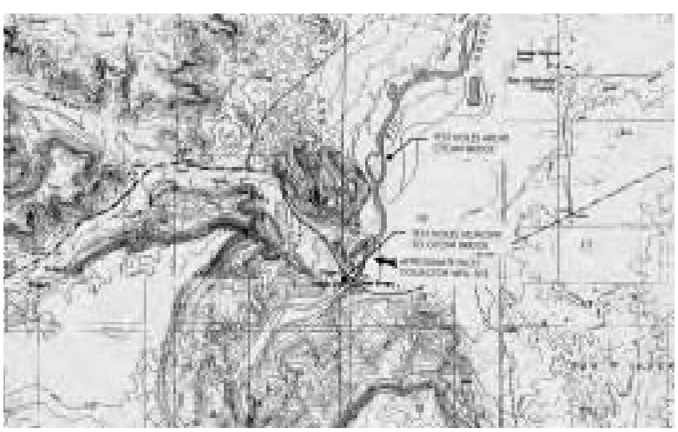

FIGURE 1—Site of San Ildefonso Pueblo collector well pilot project.

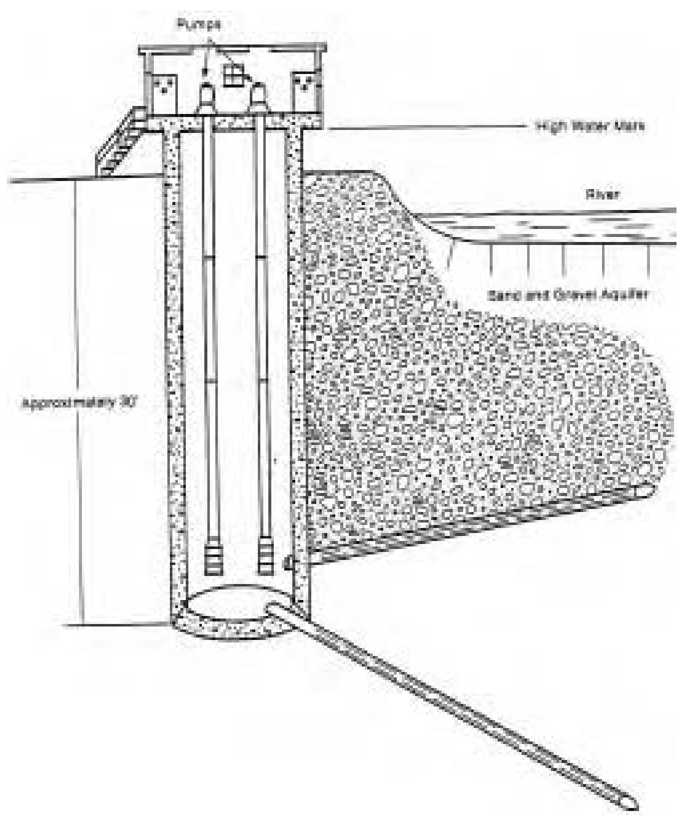

FIGURE 2—Collector well schematic diagram.

Day One

Demonstration Project at San Ildefonso Pueblo, 2000: BIA.

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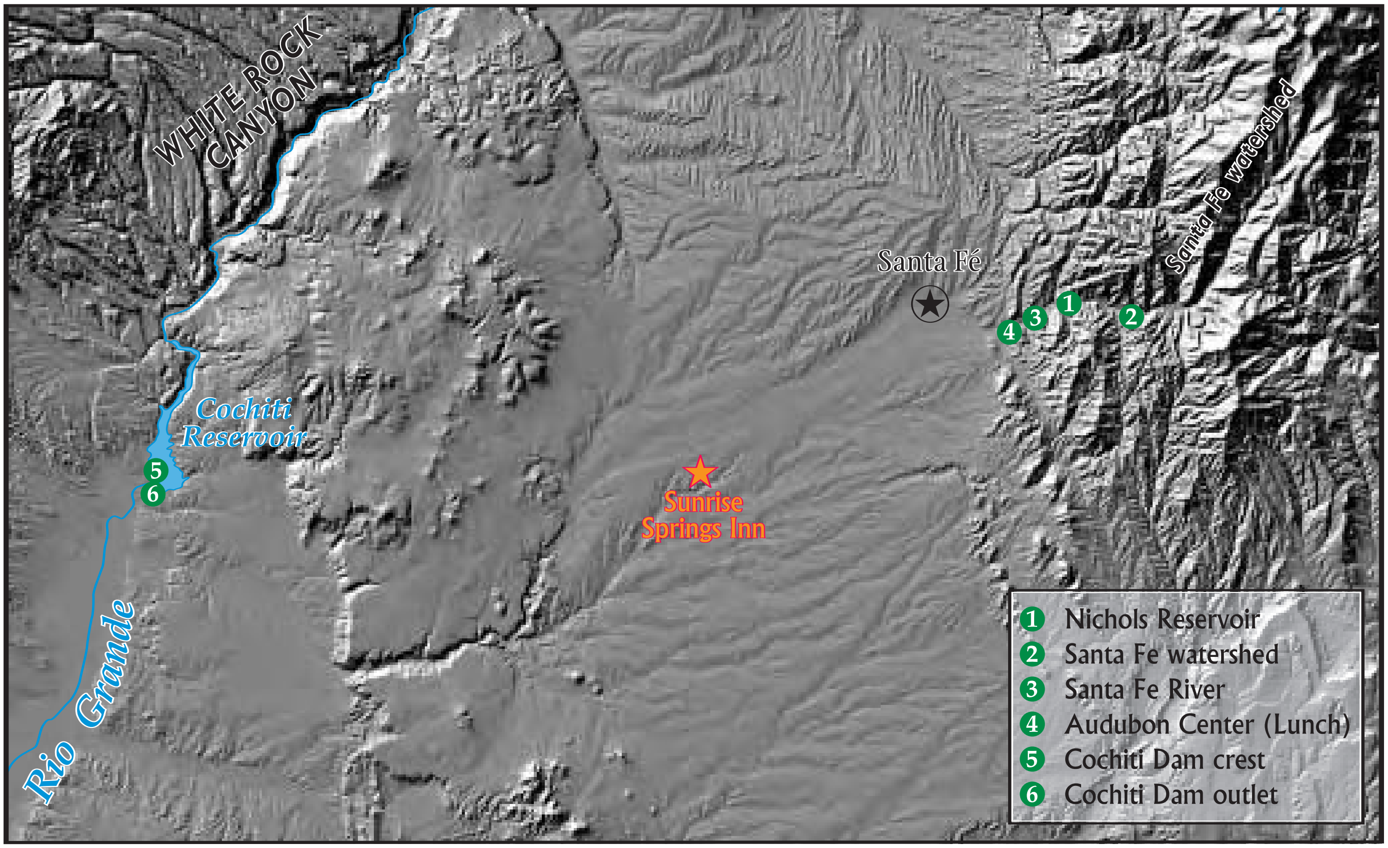
DAY TWO, MAY 10, 2001

The Santa Fe River—Headwaters to the Rio Grande



Thursday, May 10, 2001

Stop 1 **Nicholas Reservoir**
The Santa Fe Municipal Watershed

Stop 2 **Santa Fe Watershed**
Fire-vegetation relationships on the Santa Fe National Forest
Potential for crown fire in the watershed
Management alternatives for the watershed

Stop 3 **Santa Fe River**
Arroyo formation
The TMDL Program in New Mexico

Stop 4 **Audubon Center**
History of water planning in New Mexico
Statewide water planning—a progress report
Water planning in Jemez y Sangre
Regional water and wastewater

Stop 5 **Cochiti Dam Crest**
Volcanism in northern New Mexico
A study of plutonium in Cochiti Reservoir
Earthquake hazards, Rio Grande valley

Stop 6 **Cochiti Dam Outlet**
Downstream effects of dams
Santa Ana River Rehabilitation Project
URGWOM, a management tool
Water budget for middle Rio Grande
Water operations review and EIS

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.

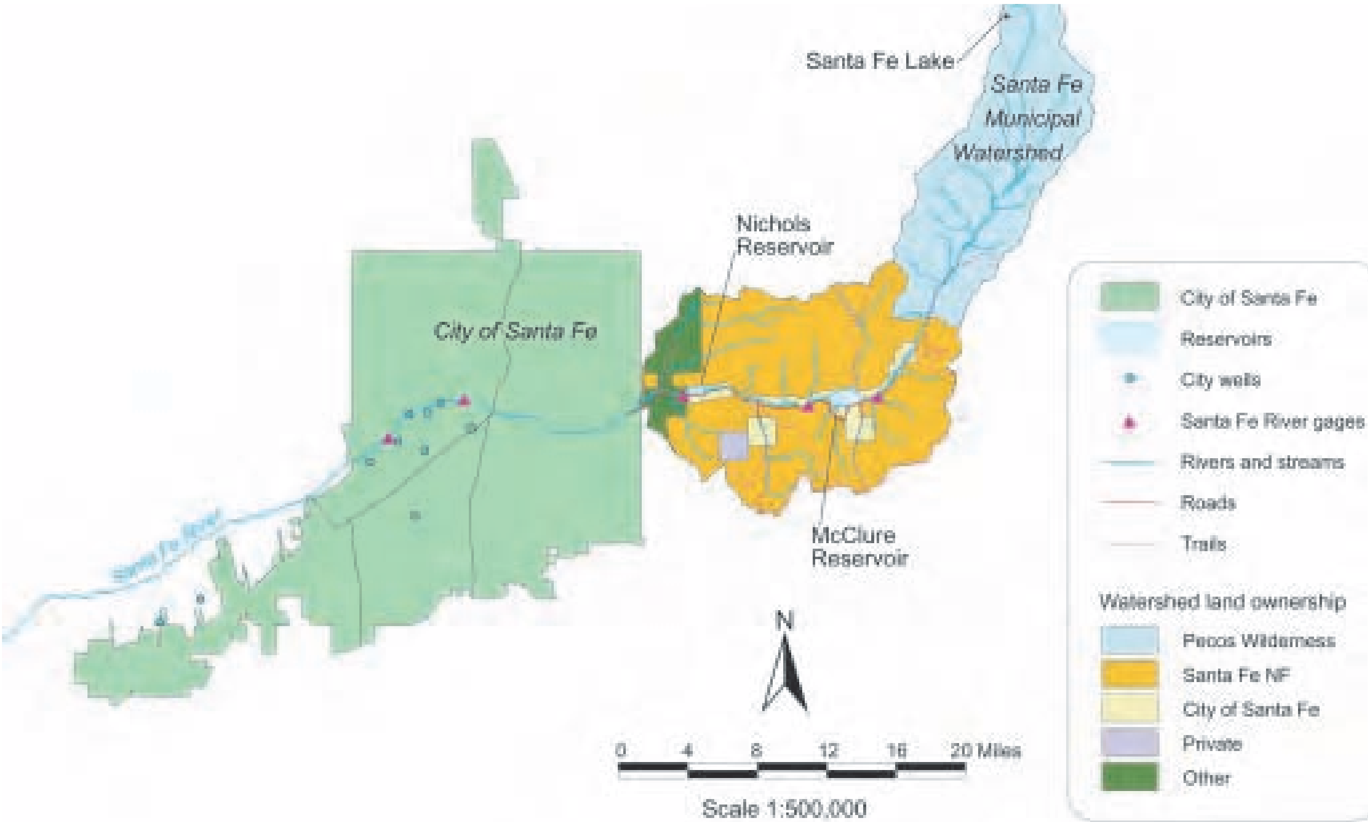

FIGURE 1—Santa Fe Municipal Watershed.

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, understory 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.

Reference

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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.

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

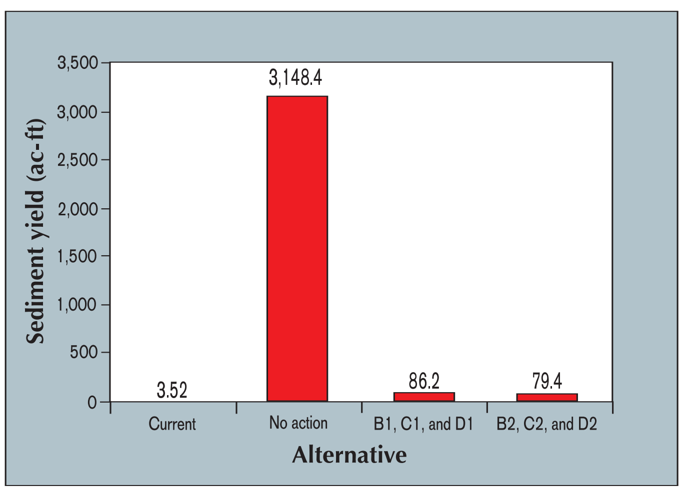

FIGURE 1—Erosion analysis showing sediment yield in the Santa Fe River area and reservoirs under current conditions.

[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

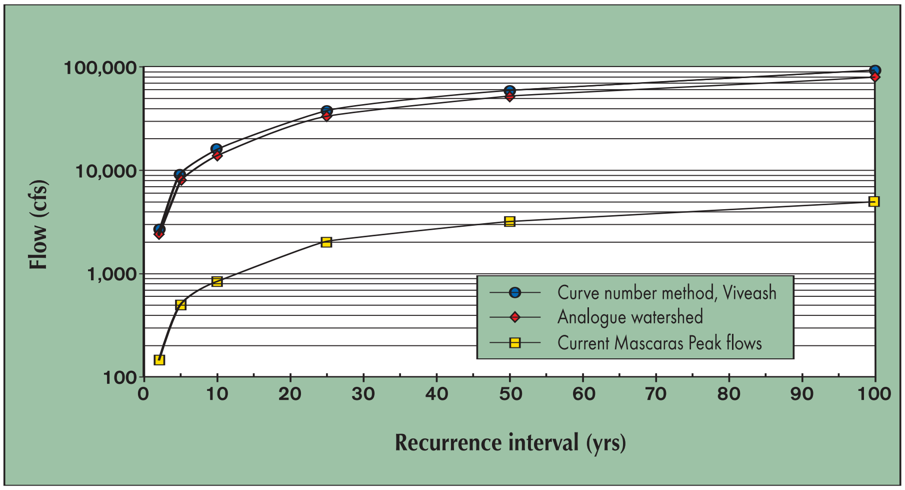

FIGURE 2—Peak flow (flood) frequency curves under current conditions.

(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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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

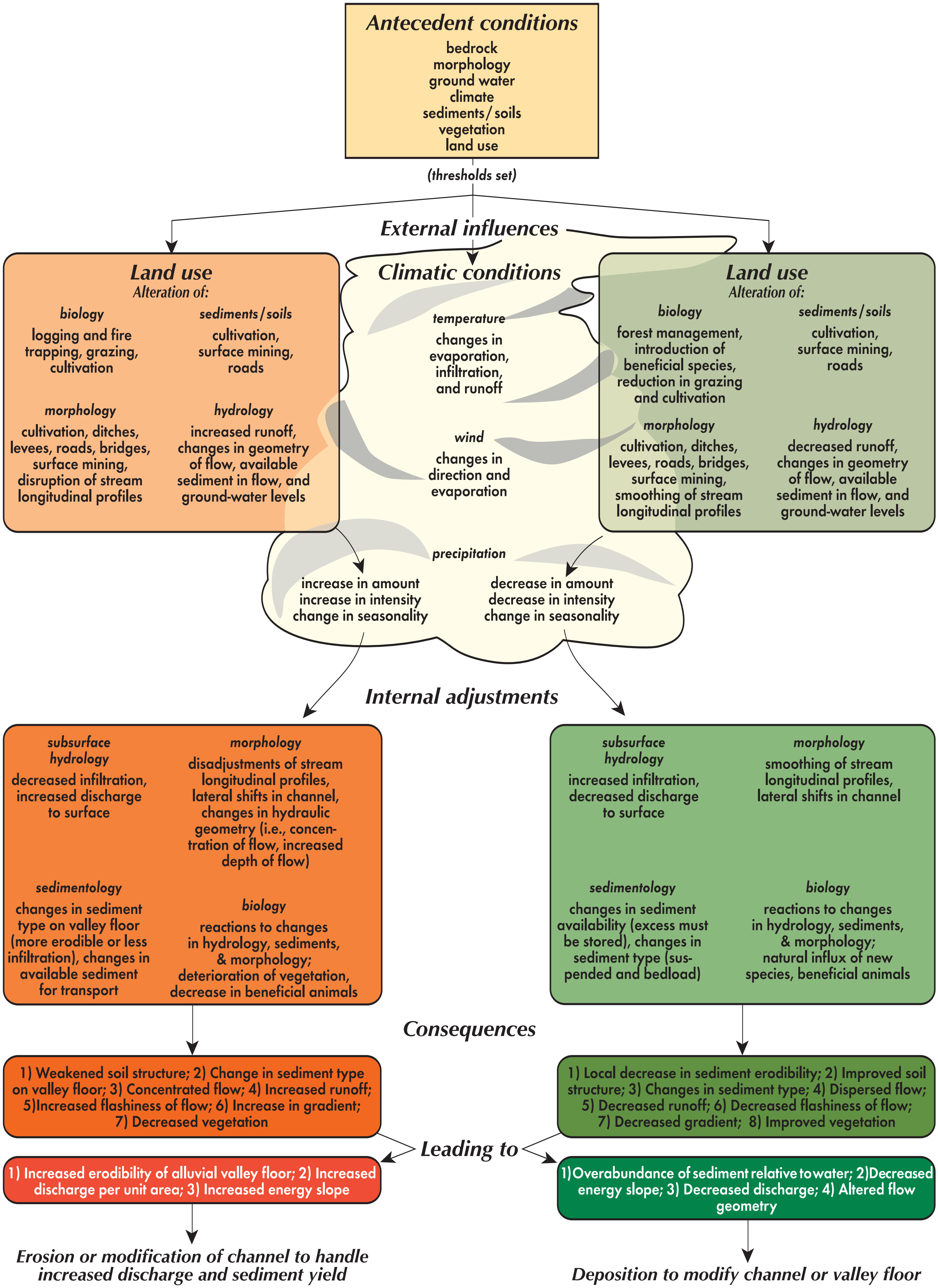
Antecedent conditions
bedrock
morphology
ground water
climate
sediments/soils
vegetation
land use
(thresholds set)
External influences
Land use
Alteration of:
biology
logging and fire trapping, grazing, cultivation
sediments/soils
cultivation, surface mining, roads
morphology
cultivation, ditches, levees, 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

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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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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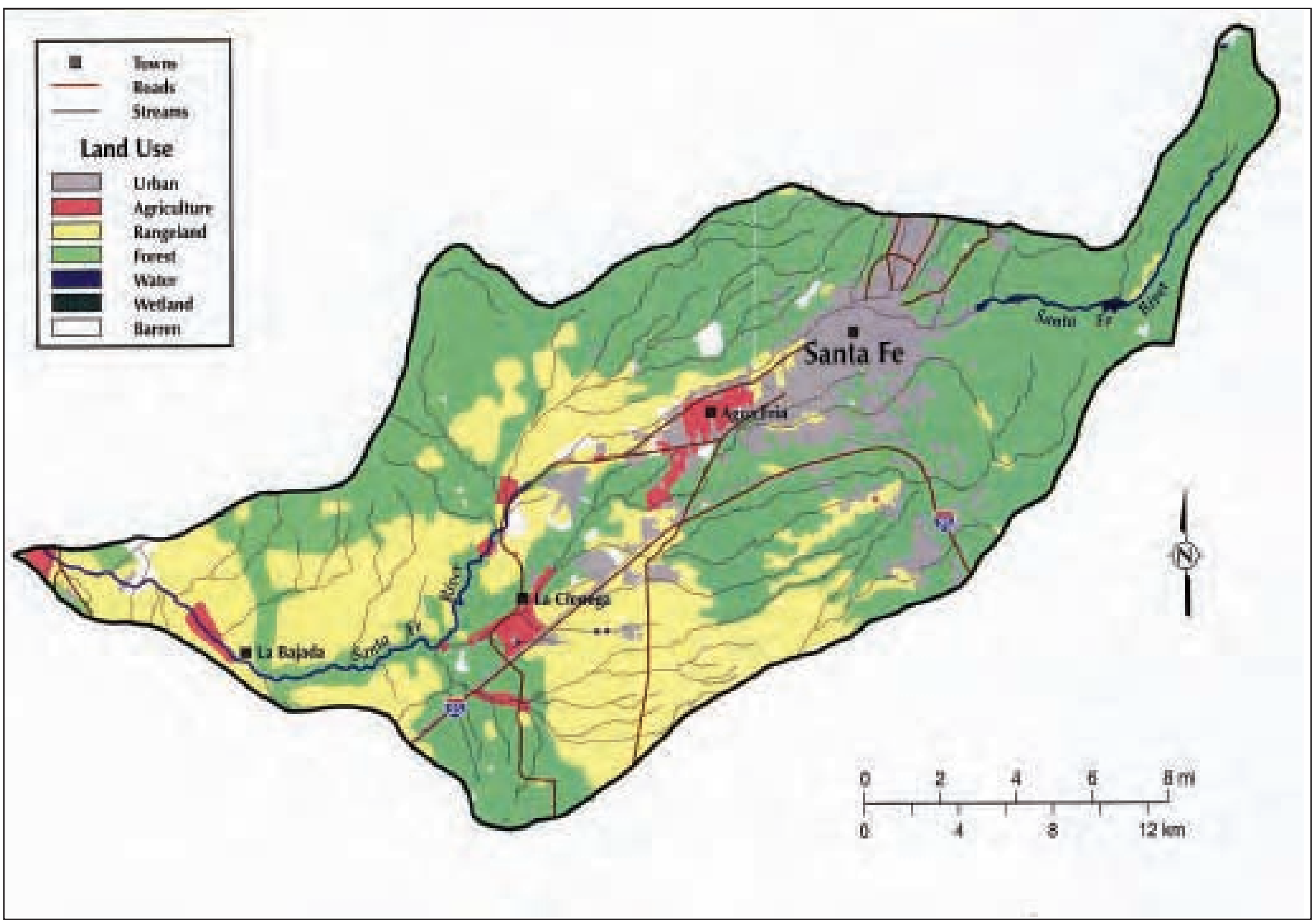

FIGURE 1—Watershed map of the Santa Fe River study area.

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.

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

New Mexico water planning regions

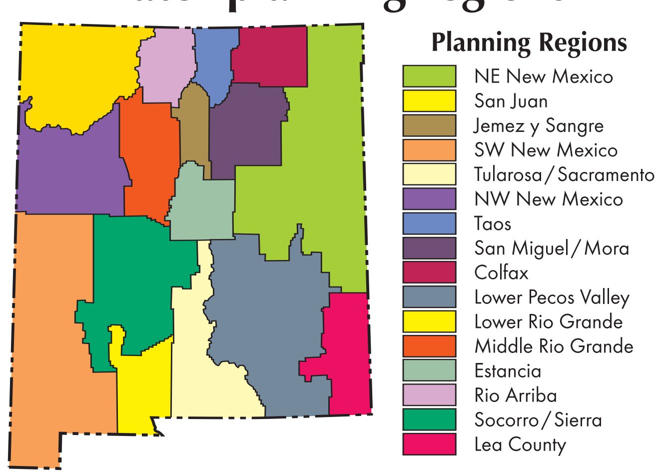

TABLE 2—Regional water planning awards, November 2000.

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

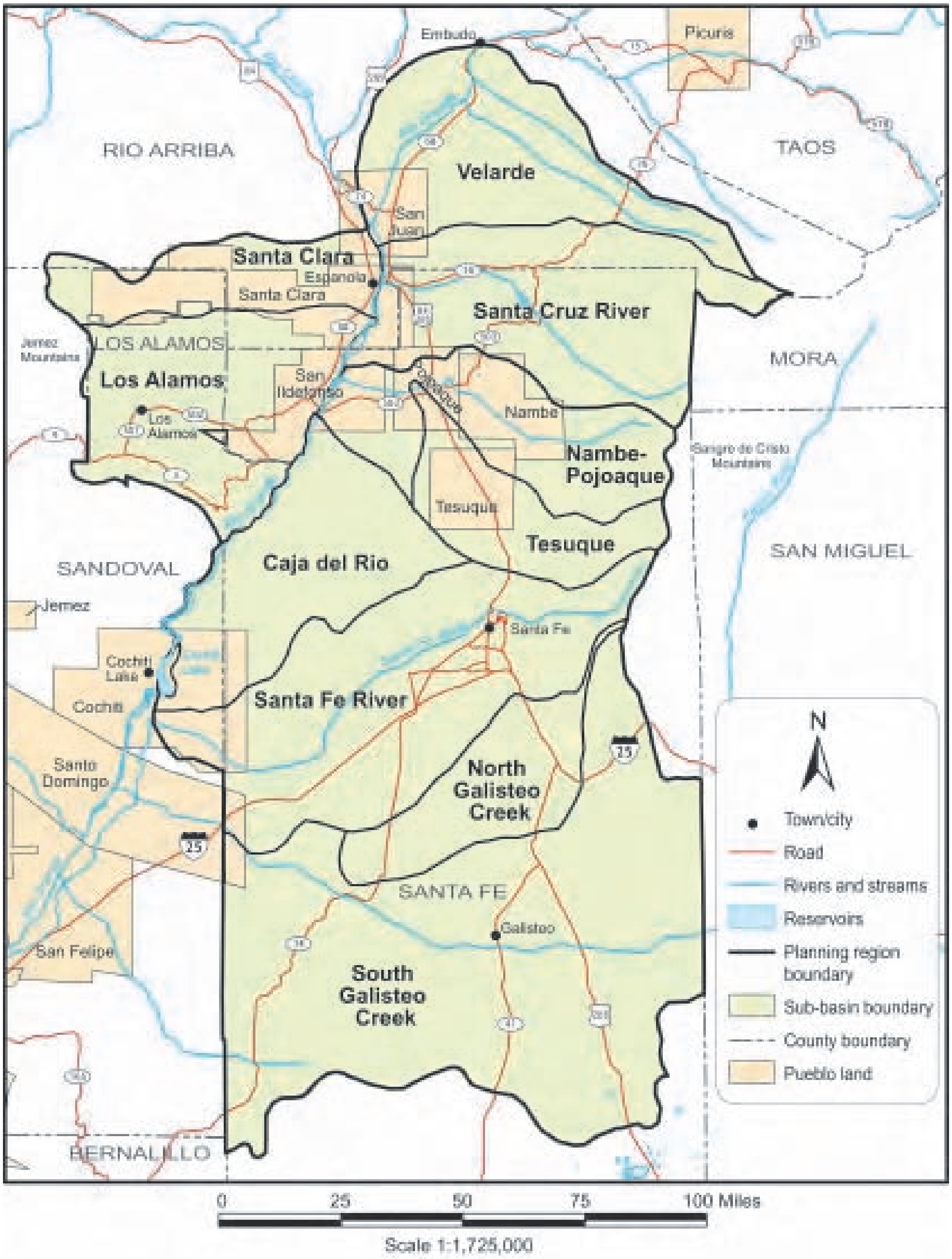

FIGURE 1—Jemez y Sangre Water Planning Region and sub-basins.

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

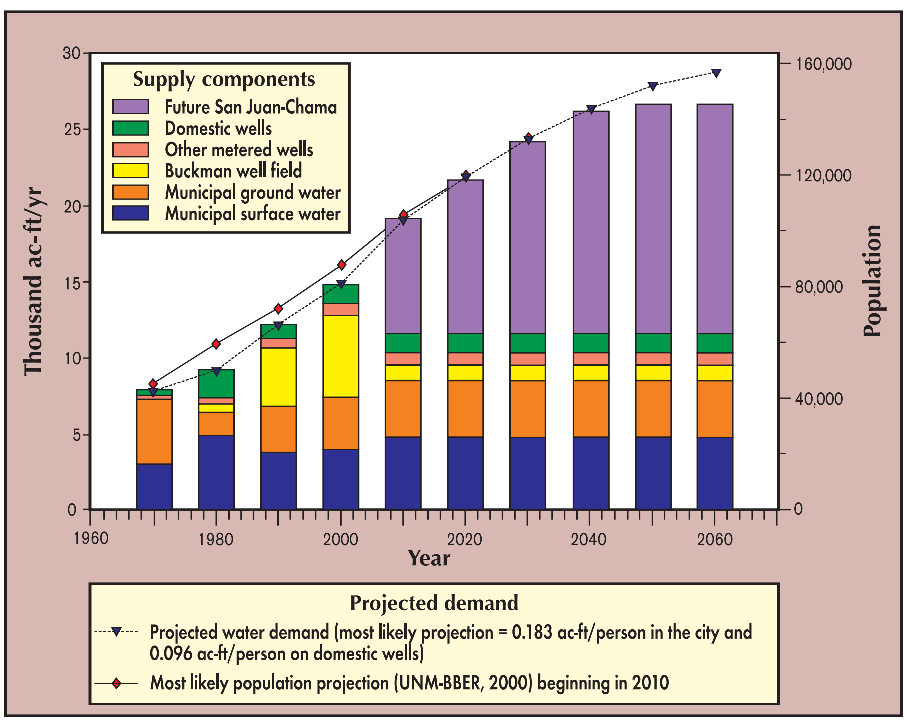

FIGURE 2—Water availability and future water demand in the Santa Fe sub-basin.

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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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.

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.

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 longstanding 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

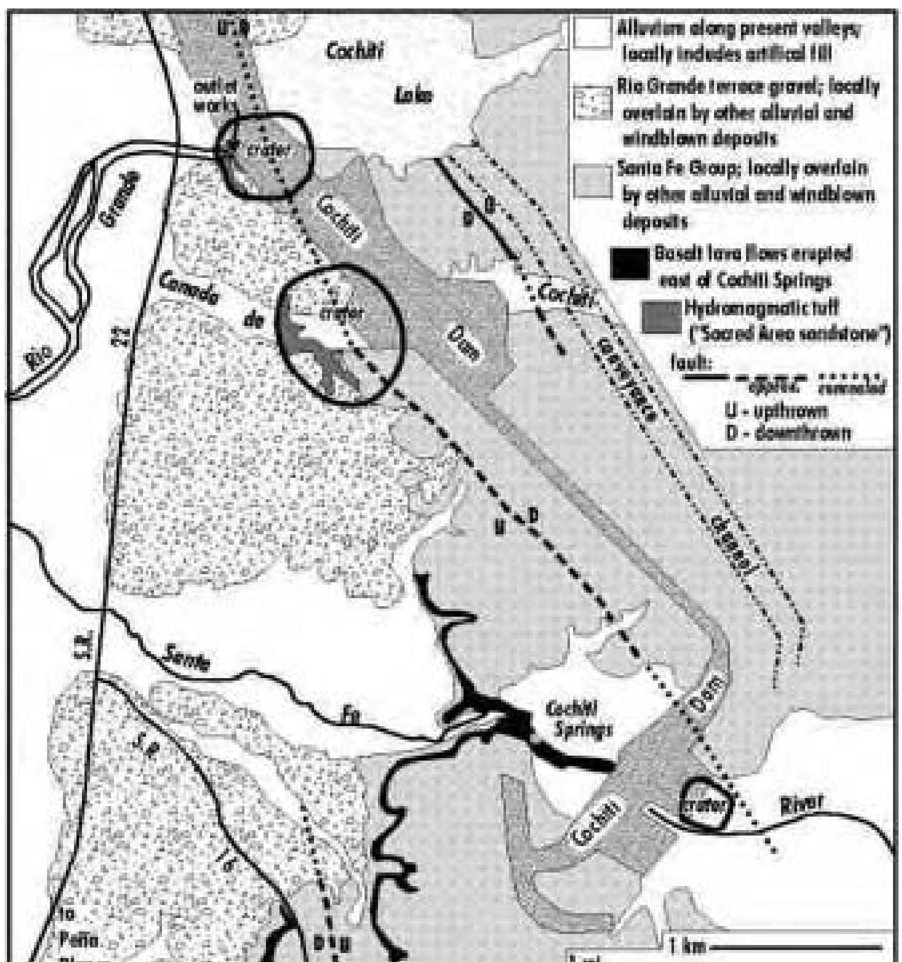

FIGURE 1—Geologic map (generalized from Smith and Kuhle, 1998) of the Cochiti Dam area emphasizing the distribution of basaltic lava flows and hydromagmatic tuff erupted from three known volcanic craters closely coincident with the dam.

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.

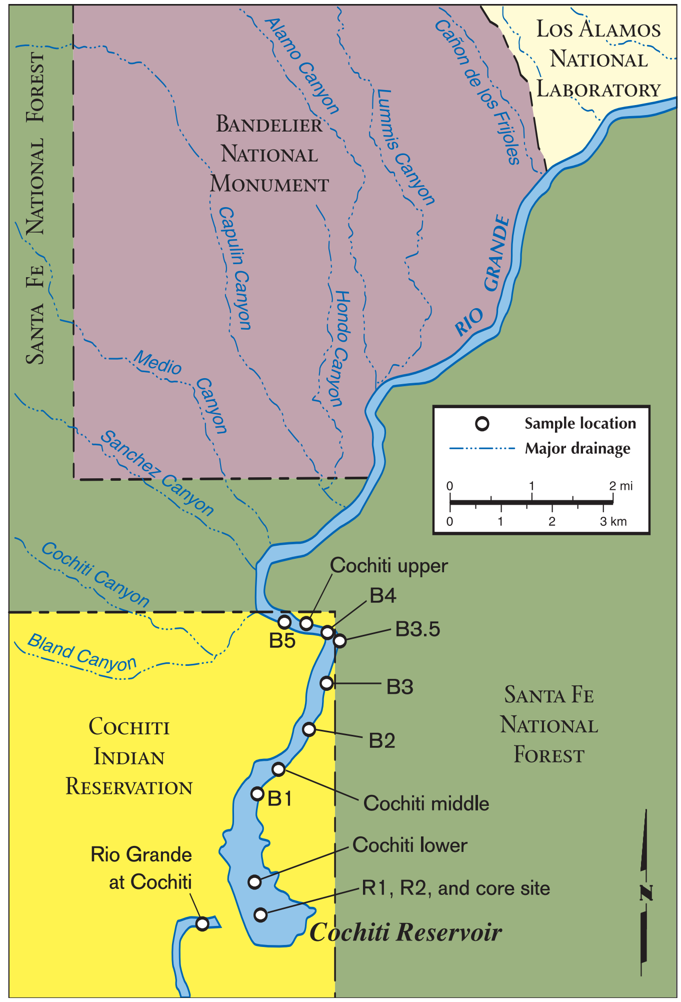

FIGURE 1—Sample locations for bottom sediments in Cochiti Reservoir.

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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
David W. Love, New Mexico Bureau of Mines and Mineral Resources

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-

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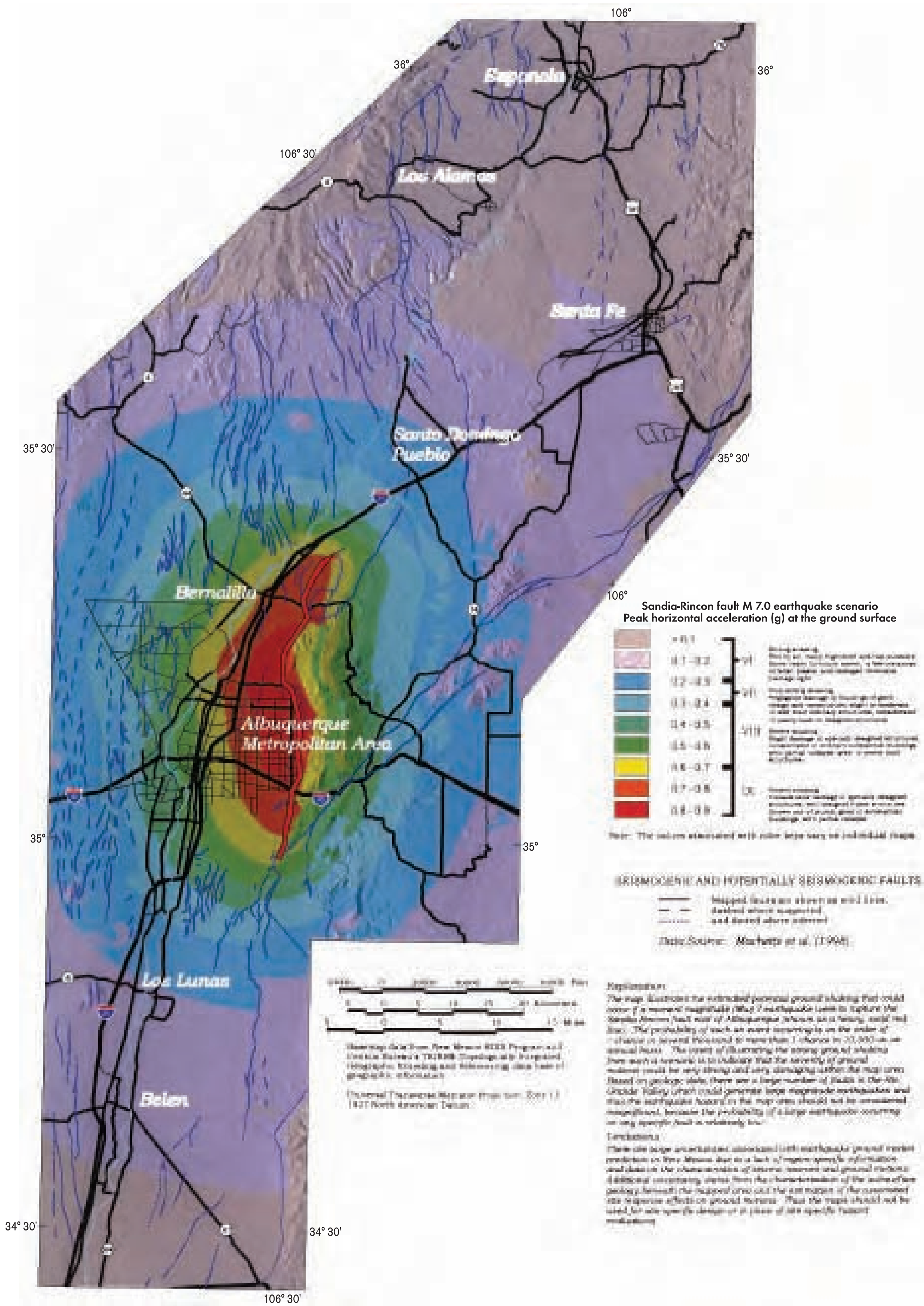
FIGURE 1—Earthquake scenario and probabilistic ground-shaking maps for the Albuquerque–Belen–Santa Fe, New Mexico, corridor.

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



Day Two

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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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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For the past 24 years at URS, Mr. Wong has directed and participated in the seismic hazard evaluations of more than 200 critical and important facilities worldwide. This includes more than 100 dams, several of which are in New Mexico, and major U.S. Department of Energy facilities such as the Los Alamos National Laboratory. Currently he is the Principal Investigator for the seismic design of the proposed underground nuclear waste repository at Yucca Mountain, Nevada. Mr. Wong has performed extensive research on the seismicity and active faulting of the Intermountain U.S., including New Mexico. Some of his research has been supported by grants from the U.S. Geological Survey through the National Earthquake Hazard Reduction Program. Mr. Wong is the author or co-author of more than 170 professional publications. He is also a Research Associate at the Arizona Earthquake Information Center at Northern Arizona University and an instructor at the California Academy of Sciences.

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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.

Hydrologic History of the Middle Rio Grande Basin

by *Dan Scurlock*, Wingswept Research,
and *Peggy S. Johnson*, New Mexico Bureau of Mines and Mineral Resources

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

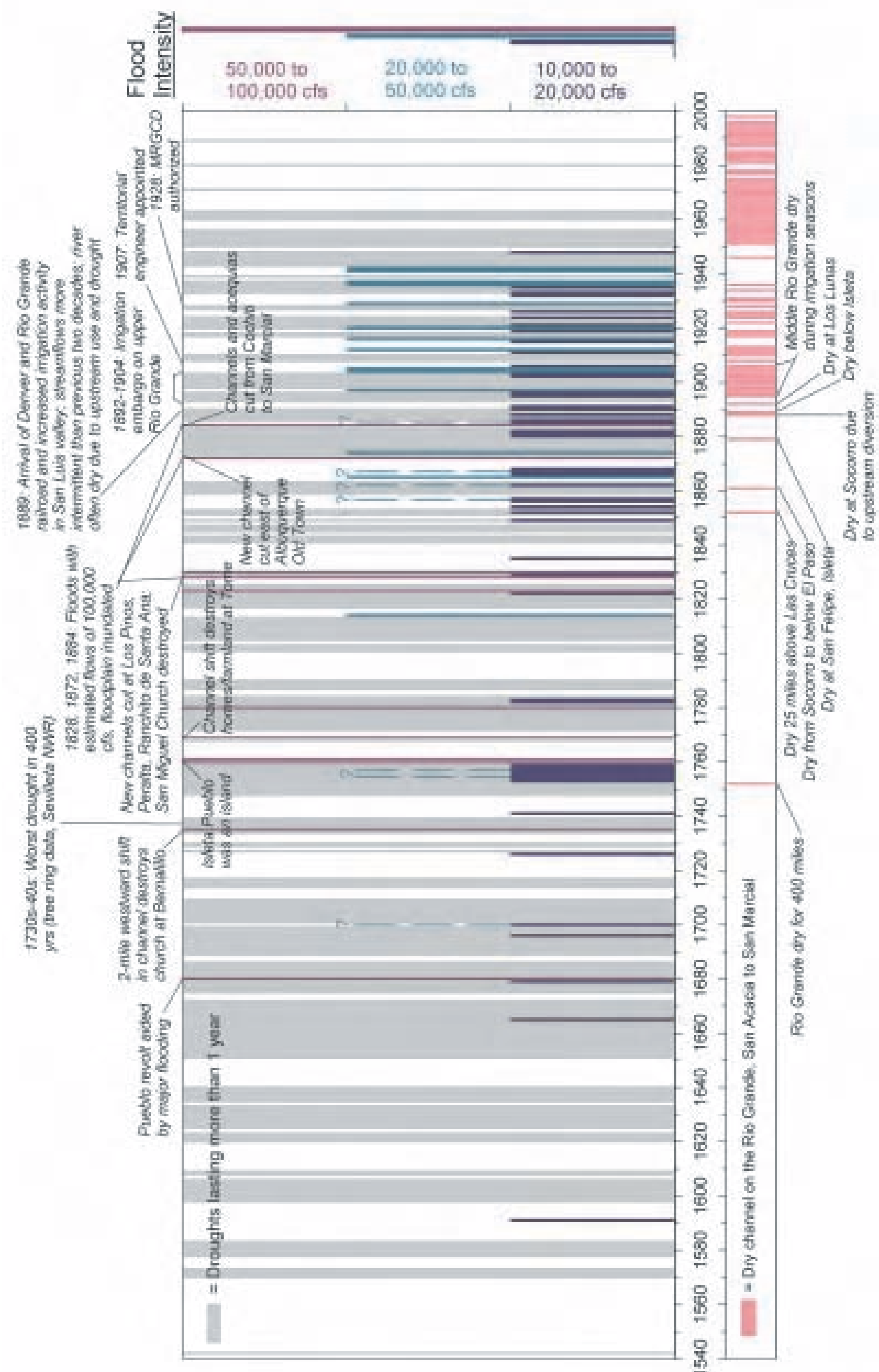

FIGURE 1—Historic floods and droughts on the middle Rio Grande, 1542–1990.

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 Angostura	1918	850	
	1962	400	
	1992	250	29%
Angostura to Bernalillo	1972	1,150	
	1995	400	35%
Rio Puerco to San Acacia	1918	1,750	
	1962	700	
	1992	400	23%
San Acacia to San Marcial	1918	1,600	
	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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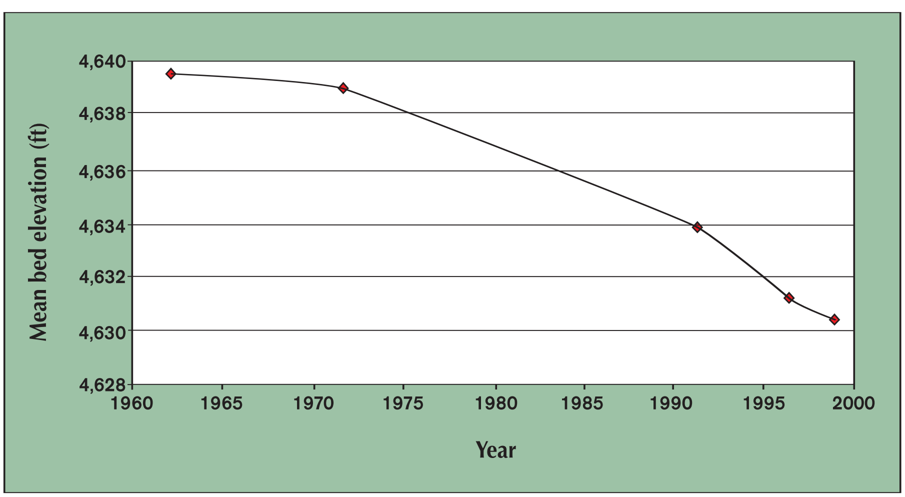

FIGURE 1—Lowering of the river bed elevation between San Acacia and Escondida on the middle Rio Grande, a total of 9.6 ft since 1962, has been most dramatic following upstream reservoir construction in the early 1970s.

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)*

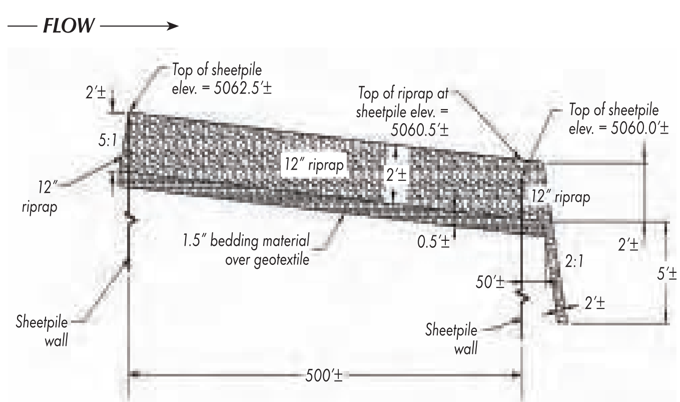

FIGURE 1—Profile of the gradient restoration facility.

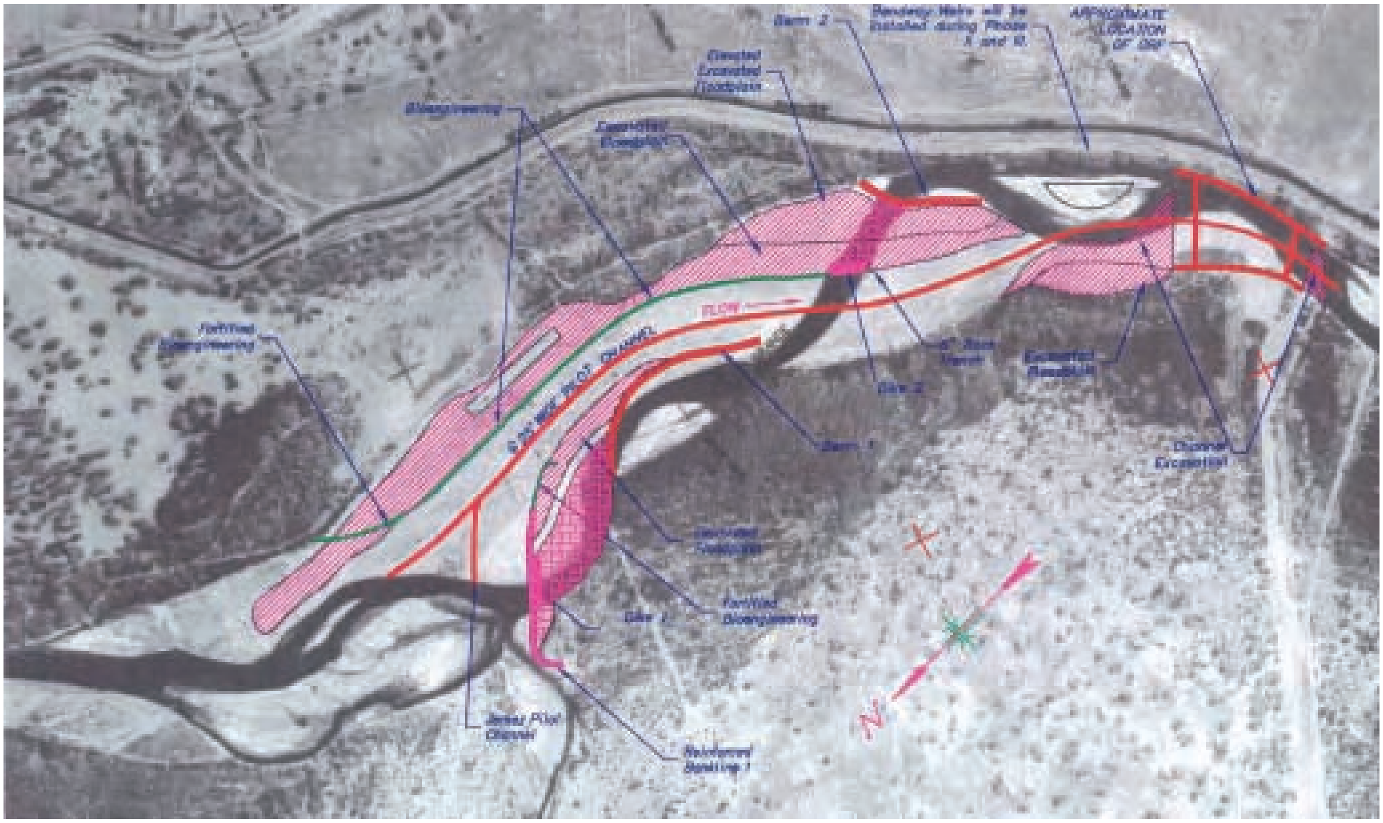

FIGURE 2—Realigned channel design.

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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Day Two

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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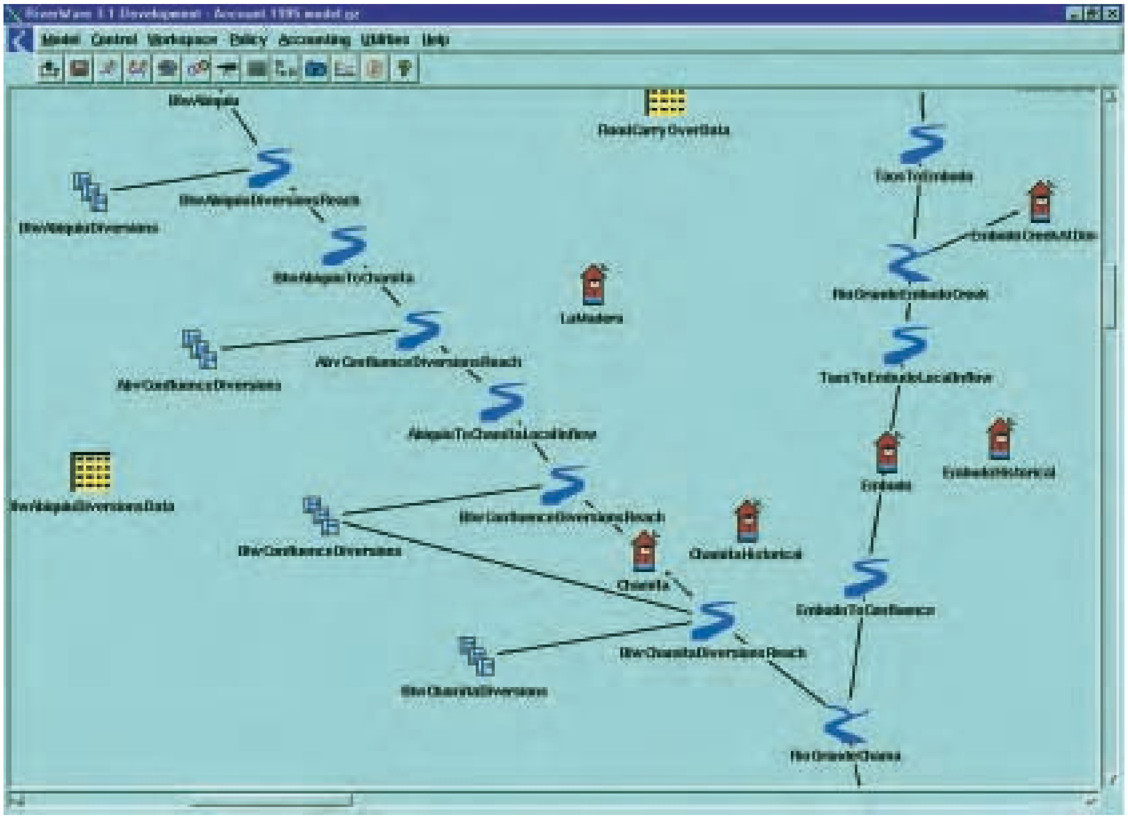


FIGURE 1—Example of RiverWare layout for the confluence of the Rio Chama with the Rio Grande.

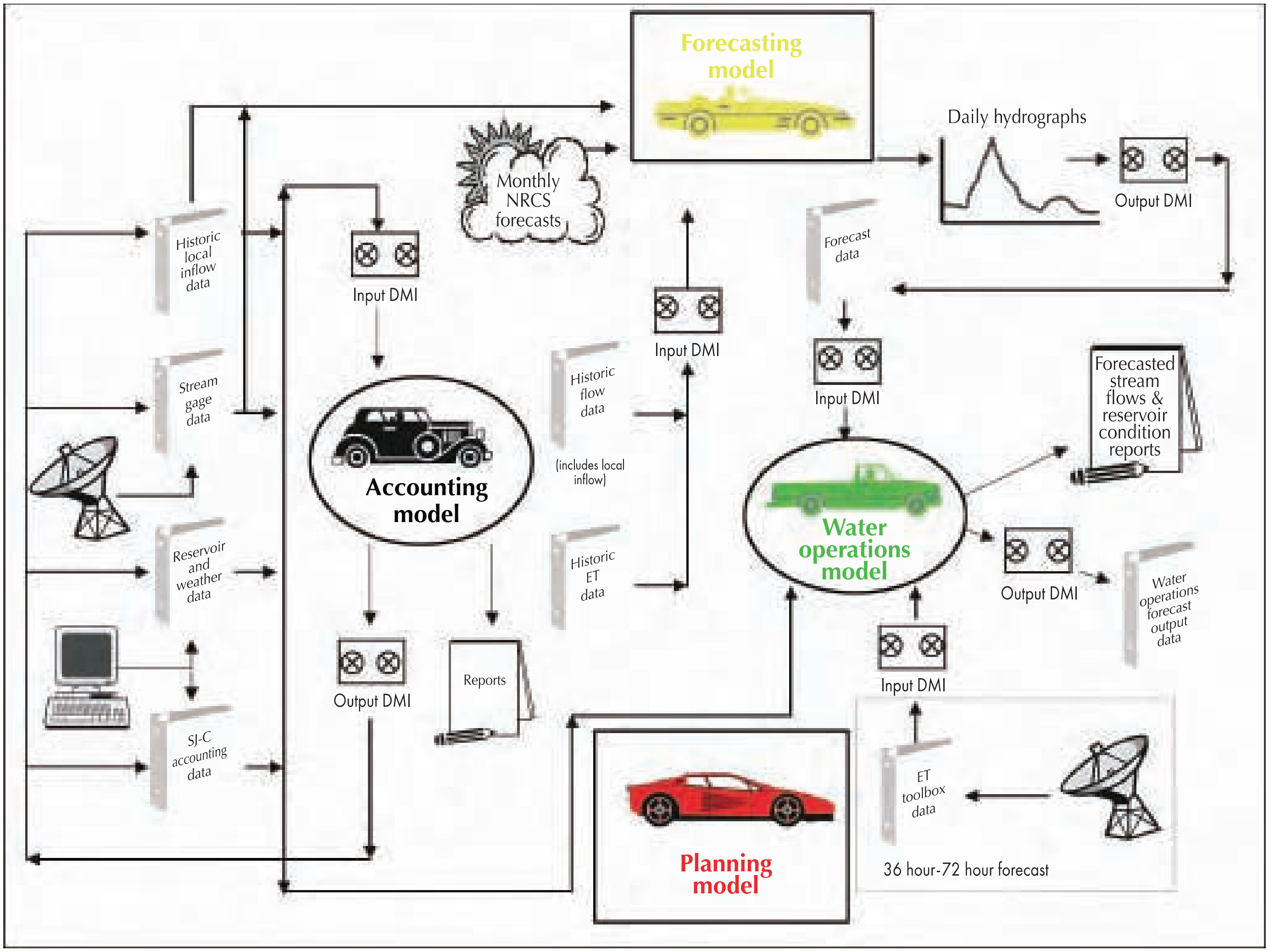


FIGURE 2—The set of four models that make up URGWOM, their input, and output.

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

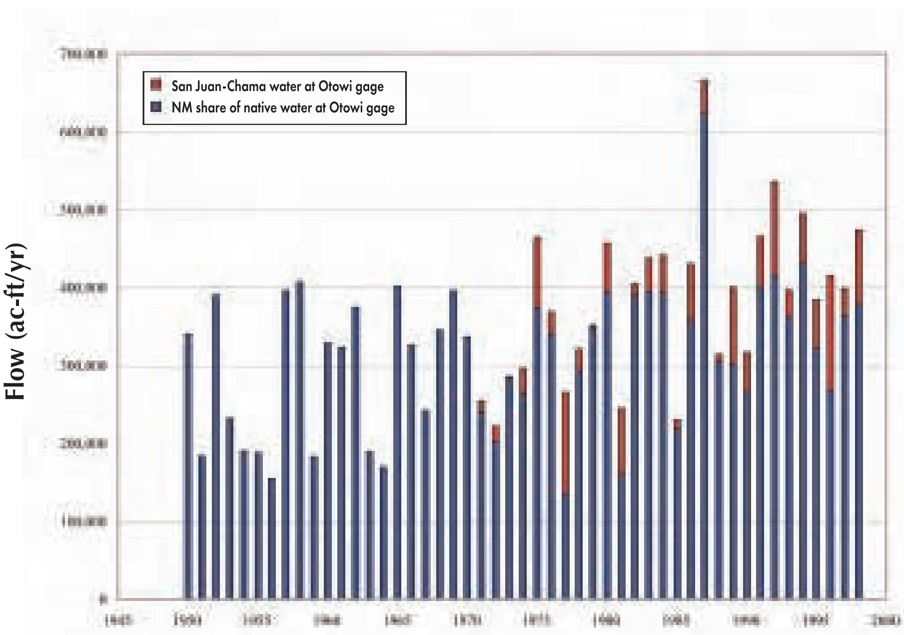


FIGURE 1—New Mexico's share of water supply at Otowi gage, 1950–1998.

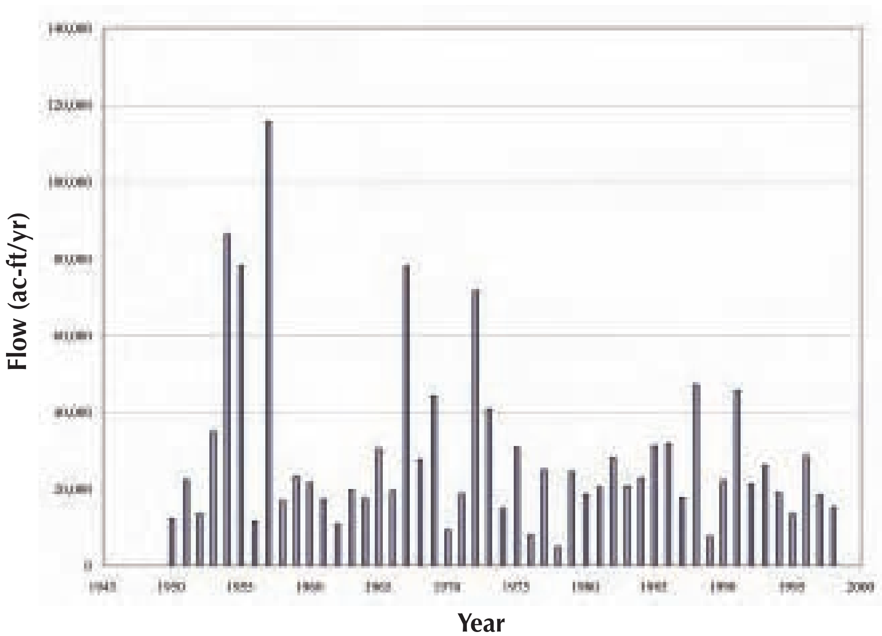


FIGURE 2—Rio Puerco tributary inflow, 1950–1998.

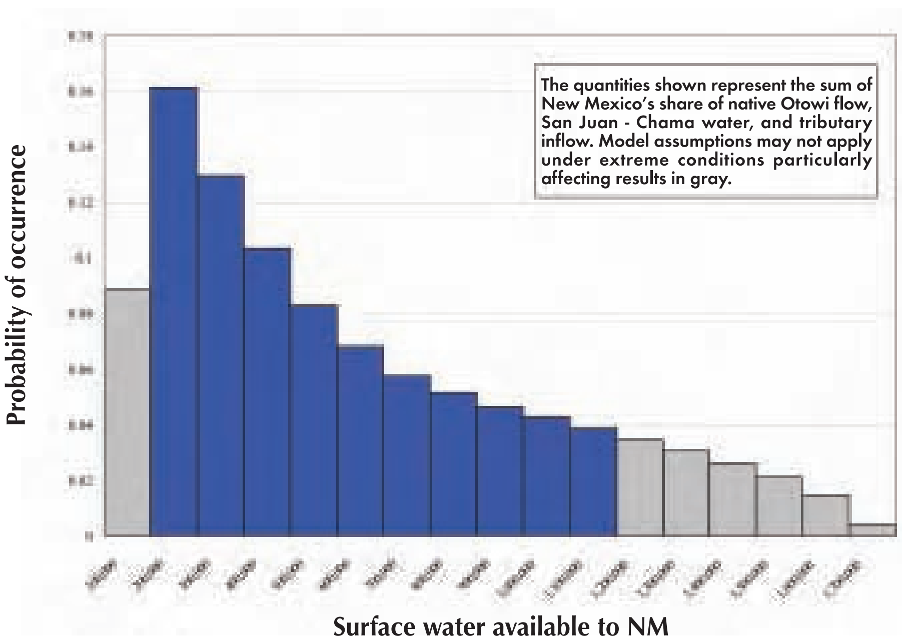


FIGURE 3—The middle Rio Grande share of surface water supply: probability distribution.

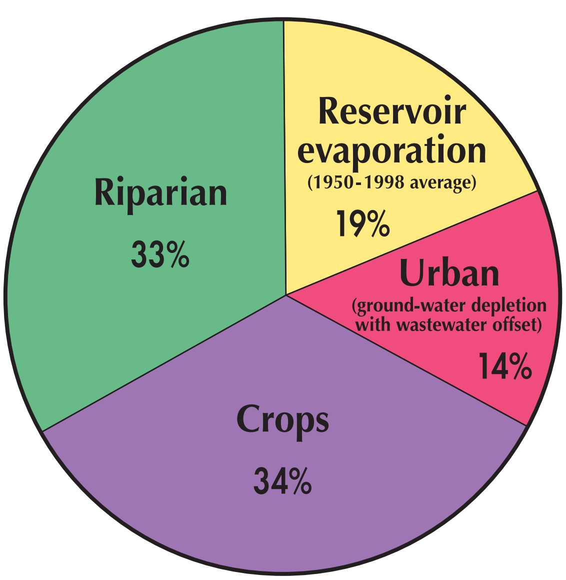
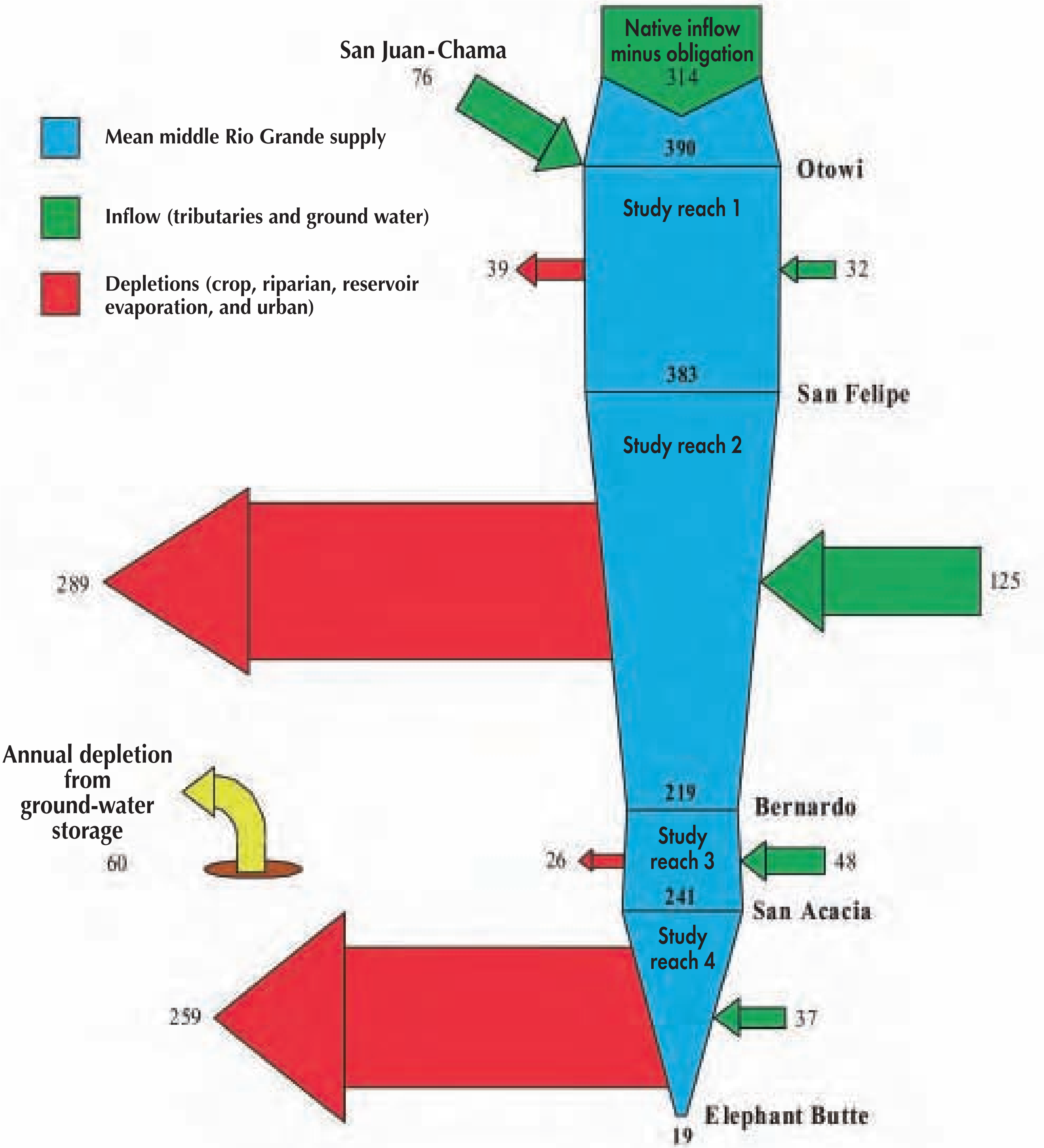


FIGURE 4—Summary of mean depletions.



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.

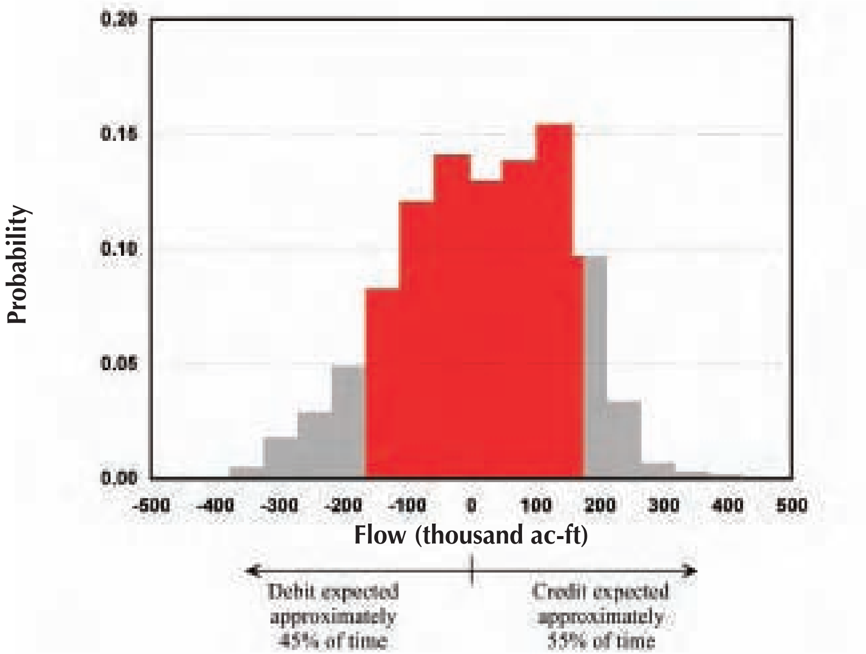


FIGURE 6—Rio Grande Compact credit-debit probability distribution, present development conditions, year 2000.

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.

Reference

Papadopulos, S. S., & Associates, Inc., 2000, Middle Rio Grande water supply: Prepared for the U.S. Army Corps of Engineers and New Mexico Interstate Stream Commission.

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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

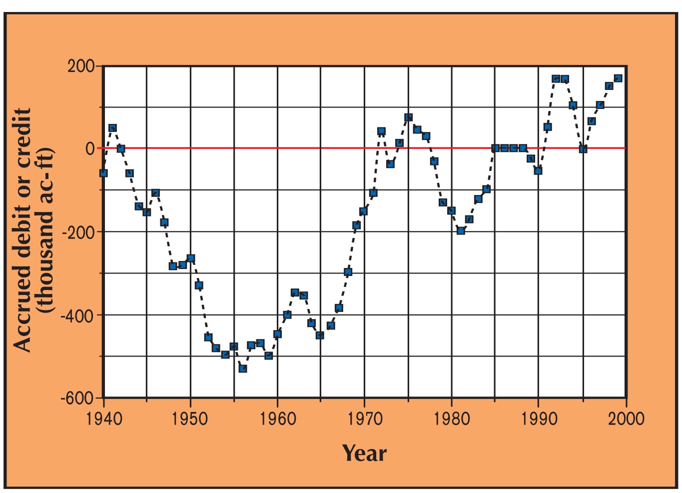

FIGURE 1—The cumulative deficit in Rio Grande Compact deliveries that accrued in the 1940s and 1950s, and the reversal of the deficits in the 1960s and 1970s.

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.

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;

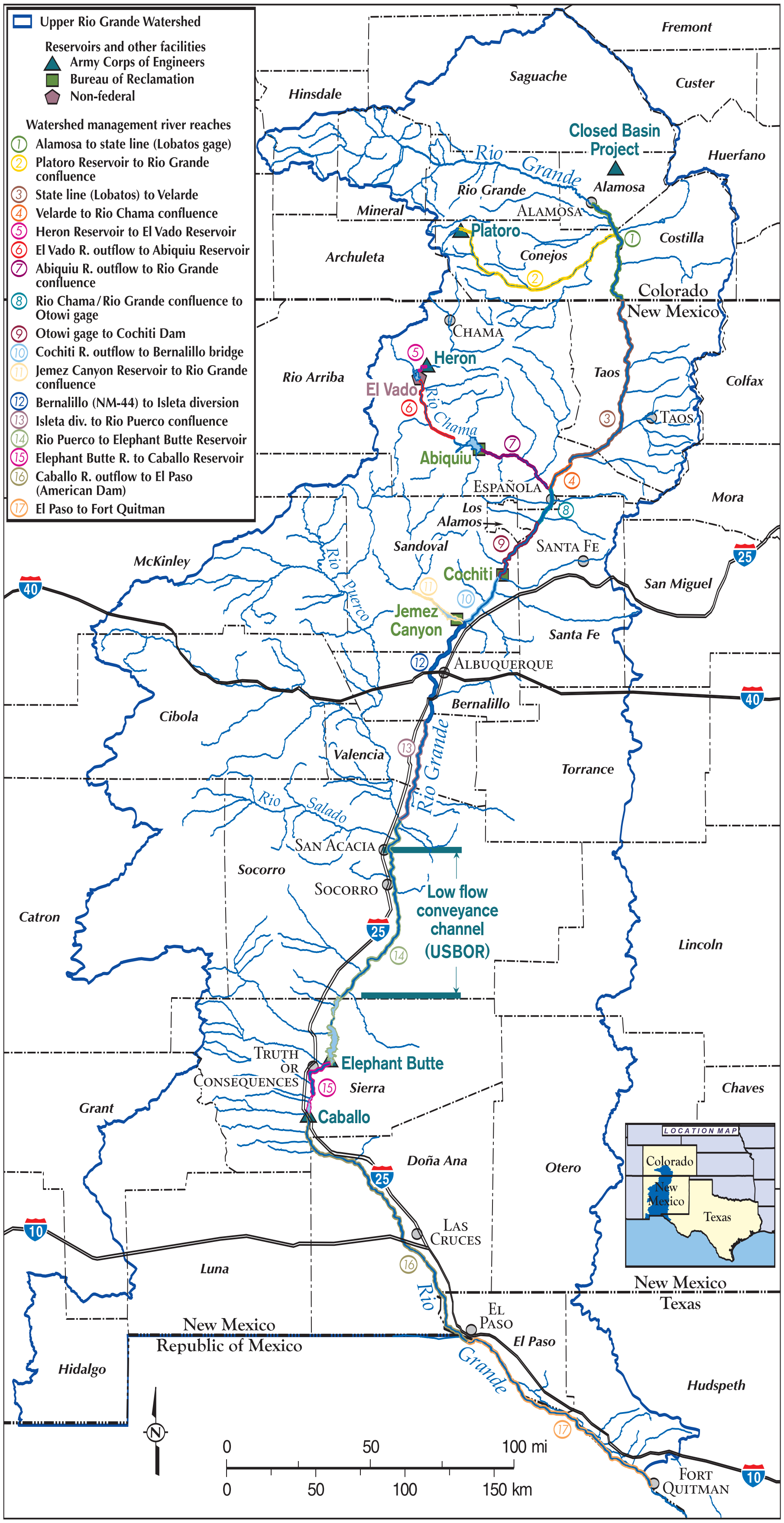

FIGURE 2—Location of rservoirs and other facilities in the upper Rio Grande basin and the 17 river reaches framing the Water Operations Review and EIS.

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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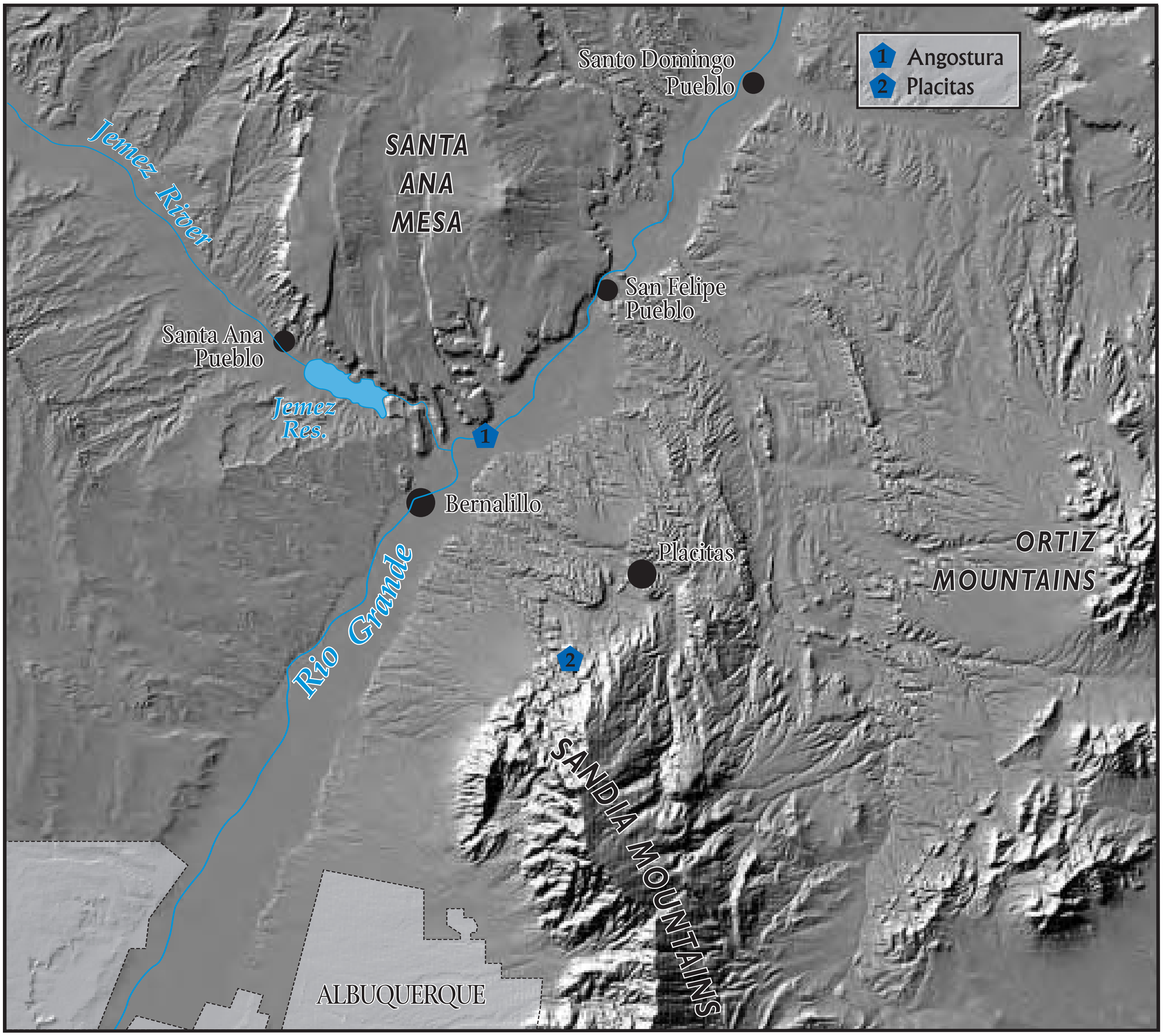
Gaume has served as Director of the New Mexico Interstate Stream Commission, New Mexico's water planning and development agency, since 1997. The commission's responsibilities include investigation, development, conservation, and protection of New Mexico's water resources and stream systems; interstate 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.

Day Three, May 11, 2001

The Middle Rio Grande—Impacts of Growth on Water Resources



Friday, May 11, 2001

Stop 1 **Angostura**
Middle Rio Grande Conservancy District
Pueblo concerns in the Rio Grande basin
Endangered species and water management
Source-to-sea protection for the Rio Grande
Value of water in the middle Rio Grande

Stop 2 **Placitas**
Water planning on a developmental scale
Subdivision regulations for Placitas
Ground-water administration
Geology of the Placitas area
Limitations on ground-water availability
Sustainable ground-water development

The Middle Rio Grande Conservancy District

by *Subhas K. Shah*, Chief Engineer, and *Sterling Grogan*, Biologist/Planner, Middle Rio Grande Conservancy District

This paper summarizes the history of 20th century water problems in the middle Rio Grande valley and describes how the Middle Rio Grande Conservancy District, which was created to respond to those difficulties, has evolved to support endangered species and help sustain agriculture in central New Mexico.

In the 1920s much of the once-irrigable land within the middle Rio Grande valley was saturated and unusable due to aggradation of the river and a corresponding rise in the water table. Irrigation works were in disrepair and needed much work and the valley was subjected to periodic flooding, often with devastating effects.

Efforts to solve these and other problems led to the creation of the Middle Rio Grande Conservancy District in 1925 to provide flood control, drainage, and irrigation for the middle Rio Grande valley. The conservancy brought 70 acequias into one unified entity designed to make all suitable lands in the middle valley irrigable.

During the 1940s the conservancy was financially unstable, and the canals, drains, levees, and other works were deteriorating. Consequently, the conservancy asked the U.S. Department of the Interior Bureau of Reclamation to take over the operation of the district temporarily and retire its outstanding bonds. In 1951 the conservancy entered into a 50-year, interest-free repayment contract in the amount of $15,708,567 with the Bureau of Reclamation for the benefit of the district. In 1975 the Bureau returned operation of the system to the conservancy, and in late 1999 the conservancy paid off the debt. Because of the successful efforts of the conservancy, the middle Rio Grande valley and its citizens are now protected from flooding; the once-saturated soils have been drained and restored to a condition suitable for farming, development, and other uses; and the old irrigation works have been rehabilitated or replaced.

The Middle Rio Grande Conservancy District today extends from Cochiti Dam south for approximately 150 mi to the Bosque del Apache National Wildlife Refuge (Fig. 1). The conservancy encompasses approximately 278,000 acres in four counties, of which 128,787 acres are irrigable lands. At present, approximately 70,000 acres are using irrigation water. Within the district's boundaries are thousands of property owners and many towns and villages, six Indian pueblos, and much of the city of Albuquerque. Over one-quarter of the population of New Mexico resides within the conservancy, much of it in some of the most rapidly urbanizing areas in the state. The conservancy maintains and manages four diversion dams, 834 mi of canals and ditches, and 404 mi of riverside drains that are capable of delivering water for irrigation and a variety of other purposes.

As guardian and advocate of the waters of the middle Rio Grande for its constituency, the conservancy is adapting its water policies and methodologies to meet changing needs. The conservancy meets those needs through its water bank, through planning efforts for protecting endangered species, and through an ongoing program to upgrade the technology and management of the water conveyance system.

Because of the varied history and make up of the conservancy, seven categories of legally recognized water rights are found within the district boundaries. In total, the amount of consumptive use allowed by state Engineer permits within the boundaries of the conservancy from surface flows of the Rio Grande is approximately 298,339.4 acre-ft. Total net diversions from the Rio Grande average 350,000 acre-ft annually, of which about 238,000 acre-ft are consumptively used. The acreage under permits held by the conservancy may be greater than land actually irrigated today because the permits have not been fully developed. Determining the total perfected amount of the conservancy right is a complex process that is currently under way.

To meet the changing needs of its constituents, the conservancy's board of directors established a water bank in 1995. The water bank is essentially a water management system and a method by which the district manages the distribution of water within the conservancy by moving water from areas where it is not being used to areas of need. In this way, the district can maximize the beneficial use of water within the conservancy. Holders of current water rights within the conservancy who are not using their rights can place those rights in the water bank. Persons or entities that need water can "borrow" water from the bank. Thus, water use can be maximized by delivering it to where it can continue to be put to beneficial use.

There is some irony in the fact that, as a direct result of the measures taken to solve the problems of the early 20th century, the conservancy district today faces new challenges. Primarily as a result of the dams, levees, and channel-narrowing devices built from the 1930s through the 1960s, much of the habitat for endangered species in the middle Rio Grande has deteriorated. As the human population has grown along with awareness of the environmental consequences of what we consider today essential human infrastructure, the conservancy district finds itself fighting new assaults on the district's attempts to support and sustain that infrastructure for agriculture in the middle Rio Grande valley. Foremost among the new challenges is the Endangered Species Act.

The Rio Grande silvery minnow, a small fish that today appears to survive only in the middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir, was listed as an endangered species in 1994. The conservancy district is working closely with the Bureau of Reclamation and other federal and state agencies to protect the minnow and plan for its recovery in ways that allow legally authorized water use and development to proceed in compliance with state water law and interstate compacts.

There is widespread recognition that the potential for dewatering a segment of silvery minnow habitat in the middle Rio Grande is very high, due to multiple use of the water throughout the river system, conveyance losses that depend largely on weather conditions, and other river conditions outside the control of human water users. These uses and conveyance losses from the Rio Grande occur from its headwaters in Colorado to Elephant Butte Reservoir. Therefore, to maintain the viability of agriculture and to benefit endangered species, the conservancy district operates its water conveyance system in close coordination with state and federal agencies. With financial and logistical support from some of those agencies, the conservancy also continues to improve the efficiency of the water conveyance system through automated metering of river diversions and return flows, and other system improvements.

In conclusion, it is important to note that the increase in the urban population of the middle Rio Grande valley has brought with it new demands on our water resources, and the complexity of water management in the middle Rio Grande valley has increased significantly. To respond to the new physical and regulatory challenges, the conservancy is improving operations and increasing its ability to meet changing demands. As demonstrated by the extensive list of ecosystem rehabilitation projects contemplated for improvement of habitat for endangered species along the middle Rio Grande, the conservancy recognizes the need to find balanced solutions to environmental challenges, so that the centuries-old culture of irrigated agriculture can be sustained for our children, who will inherit this magnificent valley.

Reference (not cited)

Middle Rio Grande Conservancy District Water Policies Plan, April, 1993.

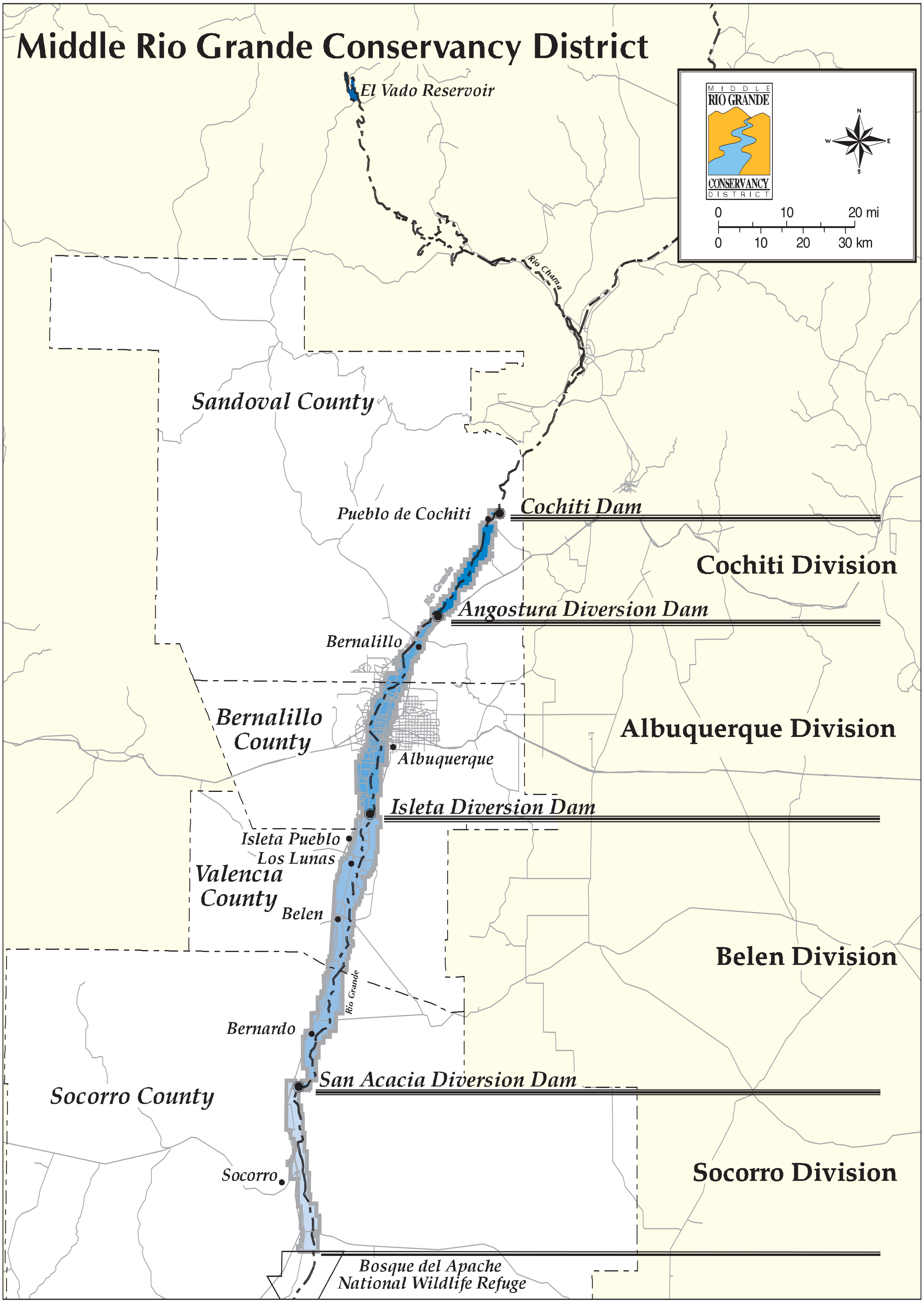


FIGURE 1—Map of the Middle Rio Grande Conservancy District.

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Middle Rio Grande Conservancy District
Education: MS, Structural Engineering, University of New Mexico, 1973

Shah, a native of Gujarat, India, is a Registered Professional Civil Engineer. Before joining the Middle Rio Grand Conservancy District in 1977, Shah gained experience in residential, commercial, and industrial design and construction. As Chief Engineer, Shah serves at the pleasure of the seven-member conservancy district board of directors, and is responsible for all facets of the conservancy district, which spans four middle Rio Grande counties. Shah is widely recognized as an expert in the technical administrative and legal aspects of irrigation, flood control, and drainage operations. He serves on the Water Providers Council of the Middle Rio Grande Water Resources Board, and is active in the Family Farm Alliance and the National Water Resources Association.

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Grogan, the biologist/planner of the Middle Rio Grande Conservancy District, is a landscape ecologist with more than 25 years of experience in land and water management. He is responsible for protection of 150 mi of the middle Rio Grande bosque, management of habitat for endangered species, co-management of Rio Grande Valley State Park, and preservation of agriculture in the middle Rio Grande valley. Sterling is a specialist in the rehabilitation of severely disturbed land. From 1974 to 1997 he managed land rehabilitation and environmental affairs for mining companies in New Mexico and Chile, and consulted on landscape ecology in the Costa Rica, Mexico, Venezuela, and the U.S. He was chair of the Albuquerque/Bernalillo County Air Quality Control Board from 1998 to 1999, and currently serves on the boards of the Cornstalk Institute and the Rio Grande Nature Center. He was a Peace Corps volunteer in Brazil and an Army interpreter in Viet Nam.

The Angostura diversion dam, operated by the Middle Rio Grande Conservancy District, is one of three major diversions of irrigation water along the middle Rio Grande valley. The dam was constructed in 1934 and rehabilitated by the Bureau of Reclamation in 1958. It has the capacity to divert 650 cfs to the Albuquerque Main Canal. It consists of a 800-ft-long concrete weir that has a structural height of 17 ft and a hydraulic height of 4.5 ft. Photo by Paul Bauer, August 2000.

Pueblo Concerns in the Rio Grande Basin

by *Herbert A. Becker*, Water Rights Consultant

Centuries before the coming of the Europeans, the pueblos lived, worked and prospered in the middle Rio Grande basin. Their ancestors used water from the Rio Grande and its tributaries for irrigation, fishing, recreation, commercial, and religious purposes as well as a source of water to meet their domestic needs. Additionally, they used resources from and occupied a much larger land area for hunting and subsistence than they presently own.

These pueblos maintained governmental relations with Spain and then Mexico during the time those countries claimed jurisdiction over the area. Today, the pueblos are federally recognized and maintain government-to-government relations with the United States and the state of New Mexico. They reside on lands that are meant to be a permanent homeland for the pueblos and their members, on which they are to live and practice their culture and maintain their traditions (Fig. 1). The pueblos possess inherent sovereignty, exercise substantial governmental duties and powers, and provide for the health and welfare of the citizens and residents of the pueblos. They also operate commercial, industrial, recreational, and other economic enterprises that provide jobs for their members and non-Indian neighbors.

Historical Action

This century has seen water replace land, as the Indian asset most craved by the state of New Mexico and her non-Indian citizens. Although the pueblos have used water from the Rio Grande since time immemorial, the state of New Mexico, her citizens, and in some cases the federal government have ignored the pueblos' prior rights to the waters of the Rio Grande.

In 1906 Congress entered into a convention with Mexico by which the United States agreed to deliver 60,000 acre-ft of potable water annually from the Rio Grande to Mexico at the Acequia Madre in Juarez, Mexico. Nothing was mentioned in the convention about the pueblos' prior rights to that water. Later, the Elephant Butte Irrigation Project was constructed on the lower section of the Rio Grande in New Mexico in conformance with an application issued by the New Mexico Territorial Engineer; that project relies on water for irrigation that is all junior in priority to the pueblos' rights. Even though the territorial engineer knew that the pueblos had a prior right to the water, the permit issued for that project did not note this when the application to divert water for irrigation purposes was granted. Dams and other diversion structures have been constructed on the main stem of the Rio Grande as well as on its tributaries upstream of the pueblos. These divert water from the river that had previously been available to meet the demands of the pueblos.

Municipalities, commercial and recreational enterprises, industrial concerns, irrigators, and governmental agencies discharge water polluted with chemicals and fertilizers upstream of the pueblos that degrade the quality of the water available to them.

Over the past 50 years, a large number of wells have been drilled in the aquifers that are connected with the Rio Grande and its tributaries, the pumping of which adversely impact the quantity of water available to the pueblos. No pueblo rights were taken into account by the entities drilling the wells or by the Office of the state Engineer in granting permits to drill these wells.

The pueblos realize that if these actions continue unabated, and steps are not taken to address the impacts that added water use will have on the scarce water resources in the middle Rio Grande basin, disaster looms ahead for all.

Actions of the Pueblos

The pueblos have taken the lead in the state to conserve water through holistic agriculture practices, to restore the bosque, and preserve and enhance water quality through the enactment of clean water standards. Isleta was the first pueblo in the United States to obtain certification as a state and have the Environmental Protection Agency (EPA) approve its clean water act standards. Later, Sandia Pueblo achieved the same status. EPA's certification of Isleta as a state for purposes of the Clean Water Act was contested in federal court by the city of Albuquerque, but the federal courts rejected the city's lawsuit and affirmed EPA's certification. Santa Ana Pueblo and Sandia Pueblo have instituted programs to restore the bosque and provide habitat for endangered species.

Several years ago, the pueblos established the Coalition of Six Middle Rio Grande Basin Pueblos. The purpose of the coalition is to permit the pueblos to join together to develop a joint strategy to protect their water resources. As noted above, the state of New Mexico, her political subdivisions, various non-Indian entities, and her non-Indian citizens have made claims to and appropriated the pueblos' water resources, and in an attempt to limit tribal water rights, have sued them in state and federal courts. Those same entities have degraded the quality of the Rio Grande through unregulated discharges and through return flows that contain large concentrations of chemicals and other pollutants. It became clear to the pueblos that none of them had the resources to check these actions and ensure that their concerns about the impacts to their water rights would be heard or addressed unless they joined together. Accordingly, the pueblos created the coalition.

The goal of the coalition is simple—to protect and preserve the pueblos' scarce water resources for use by them now and for generations yet unborn on permanent homelands where their members can practice their traditions, religion, and preserve their culture. The pueblos' water needs, existing and future, include recreation, irrigation, domestic, municipal, religious, industrial, mining, esthetics, minimum-in-stream flows, and other uses.

The coalition's goal can be achieved through cooperative efforts and agreements with their neighbors, through federal legislation, or, if need be, through litigation. It is the pueblos' desire and expectation to work amicably with the state and her citizens to arrive at an agreement that will recognize their right to water of sufficient quantity and quality to meet their present and future uses. The state should become a willing partner in this goal so that all members of the state can benefit in this effort.

This paper discusses the actions taken by the pueblos of Cochiti, Santo Domingo, San Felipe, Santa Ana, Sandia, and Isleta, located in the middle Rio Grande basin, to address their concerns over water issues in the basin. This document does not represent the position of any of the six pueblos. The views expressed here are solely my own. Herbert A. Becker.

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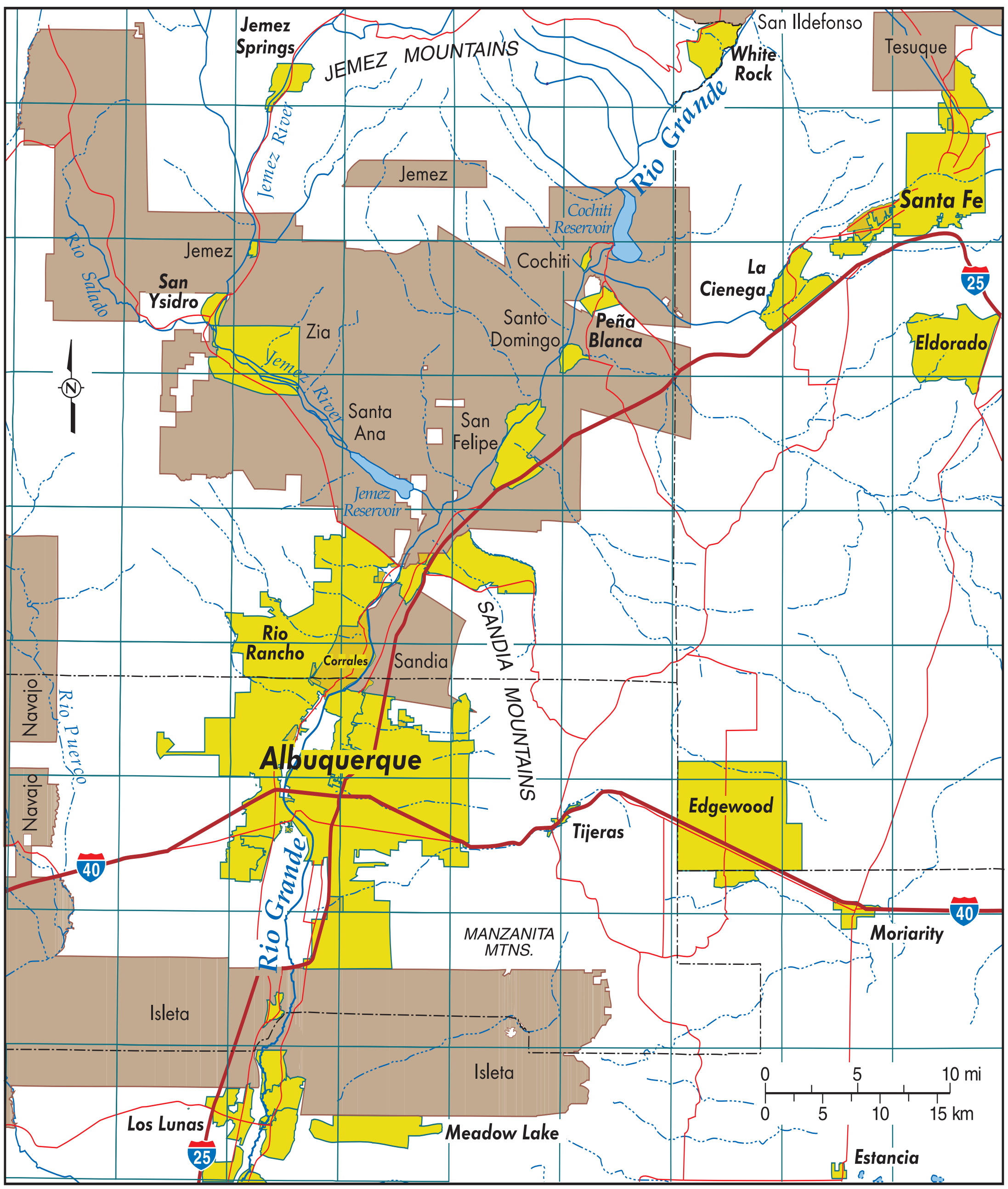

FIGURE 1—Pueblo lands in the middle Rio Grande basin.

Consequences of Endangered Species on Water Management in the Middle Rio Grande: Status, Challenges, Potential Solutions

by *Jim Wilber*, U.S. Bureau of Reclamation

Management of water resources in the middle Rio Grande in New Mexico is a complex undertaking involving considerations ranging from economic factors to hydrologic realities. Water management actions also take place within a complex framework of laws and regulations. Relatively recently, the needs of endangered species have been added to the list of considerations. Within this context, the integration of water resource management and environmental conservation has become a major focus of U.S. Bureau of Reclamation activities.

The Rio Grande silvery minnow is listed as endangered under the Endangered Species Act of 1973, as amended, and currently occurs only in the Rio Grande between Cochiti Dam and the headwaters of Elephant Butte Reservoir, a reduction of over 90% of its historic range. The silvery minnow was historically known to have occurred in the Rio Grande upstream from present-day Cochiti Reservoir, in the downstream portions of the Chama and Jemez Rivers, and throughout the middle and lower Rio Grande to the Gulf of Mexico. Recent monitoring shows that the majority of the silvery minnow are concentrated below San Acacia diversion dam, and populations in the Albuquerque and Isleta reaches are extremely reduced. In general, the native fish community of the middle Rio Grande is in decline in both abundance and diversity of species.

Potential threats to the Rio Grande silvery minnow and the associated native fish community are many. Three significant factors related to water management that affect the silvery minnow today are: (1) reductions in flow and channel dewatering, (2) habitat fragmentation and barriers to movement caused by mainstem dams, and (3) habitat loss due, in part, to channel narrowing and degradation. In light of these factors, the management of water and endangered species becomes inseparable. The challenge is how to meet multiple resource needs with a limited supply of water. The needs of water users, for example, are generally well defined and associated water management practices are already established. On the other hand, while the basic life requirements of the silvery minnow are known, an integrated water management solution to recover the species has not yet been established. Thus, in the short-term, the risk to the silvery minnow remains high, and a potential conflict between water management and endangered species is apparent.

Piecemeal attempts to manage endangered species rarely work. Solutions that may eventually lead to the recovery of the Rio Grande silvery minnow and reduce potential water management conflicts will likely involve a concentrated effort of all federal and non-federal entities with a stake in the Rio Grande. Improvements must be made in all the factors listed above, and more. There are not enough available resources for any one group or resource to hold the key to the recovery of the silvery minnow. A collaborative effort of all stakeholders is required.

The current limited distribution of the Rio Grande silvery minnow has forced water managers to take extreme measures to provide continuous flows in the lower reaches of the middle Rio Grande to protect the remaining populations of the species. A combination of activities including flow management, the removal of barriers to dispersal of the silvery minnow, habitat restoration, and captive rearing of fish may improve the distribution and abundance of the silvery minnow to the extent that the species will be on the road to recovery and increased flexibility in water management will be once again achieved.

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Source-to-Sea Protection for the Rio Grande: Strategic Concepts for Re-watering a Thirsty Basin

by *Steve Harris*, Rio Grande Restoration

The great challenge for water managers in the Rio Grande is to somehow balance important environmental, economic, and development goals for the basin's water and to integrate competing interests into a strategy that sustains uses of the river and its water into the foreseeable future. Today we are failing to answer this fundamental challenge, as witnessed by the fact that the ecological benefits of streamflow, in at least four segments of the river (Table 1), have been sacrificed to diversionary uses. This suggests that the river is not being considered in its proper role as a water user and provider of essential services.

The river has not yet been accorded real recognition or protection in the legal constructs governing the waters of the basin. The river has no effective seat at the table in our strategic forums. This concept paper, in suggesting a basin-wide strategy for protecting streamflows, is based on four assumptions: (1) the present state of affairs on the Rio Grande is not sustainable; (2) water uses by the river and the natural environment should be balanced with consumptive uses; (3) present consumptive uses can be balanced with environmental requirements; and (4) contrary to tradition, water is actually for cooperating over.

Rio Grande "Hydro-Reality Check"

The basic environmental condition of the Rio Grande basin has been accurately described as "a state of drought, occasionally mitigated by periods of abundance," Before the present one million acres of irrigated agriculture were developed in the basin, the river flowed with great springtime surges from the melting of mountain snow packs, receded in the hot months of summer, then often filled again during the monsoons of July through October. At approximately 20-yr intervals, the moisture from winter storms would fail to come, as it still does, quite often for periods of 2–5 yrs.

On an annual average, less than 2.5 million acre-ft were (and are) produced by the river's headwaters. Years of abundance, with up to twice this amount were (and are) balanced by years of scarcity, with as little as half the average quantity. Diversions of water for irrigation claim nearly 95% of the average annual flow of the river. Water rights claims to the waters of the Rio Grande, most of which are legally unadjudicated, exceed the actual supply. The basin's water supply picture would be even bleaker without the addition of 96,000 acre-ft of San Juan River water imported into the Rio Grande, groundwater subsidies through wastewater discharges, and the 20,000-plus annual acre-ft salvaged by the Closed Basin Project in Colorado. Today, on average, just 5% of the river's production of water survives diversion to appear as streamflow at Fort Quitman, the division point between the upper and lower Rio Grande basins.

TABLE 1—Upper Rio Grande stream segments presently subject to dewatering.

River reach	Length (mi)	Typical minimum flow (cfs)	Recurrence frequency	Season
Colorado above NM state line	~60	25	4 yrs in 10	July–Oct
San Acacia to Elephant Butte	~60	0	1 yr in 2	July–Oct
Below Caballo Reservoir	~40	0	Annual	Nov–Feb
Below Fort Quitman	~160	0	Intermittent	May–Aug

Institutional Stakeholders

It is estimated that 89% of the basin's water resources are devoted to irrigation (Ellis et al., 1993). Since about 1870 the basin's economic dependence on irrigated agriculture and the waters supplied by the river meant that security against the caprices of nature was intensely desired. In a watershed plagued with frequent shortages and wildly variable precipitation, the Federal Reclamation Service addressed the need for water storage by constructing the Rio Grande Project, including Elephant Butte (1916) and Caballo (1936) reservoirs, with 2.5 million acre-ft in storage capacity. Today, the U.S. Bureau of Reclamation plays an essential role in managing the basin's water resources, including El Vado Reservoir (1936), Heron Reservoir (1963), and the Rio Grande Project. Its sister agency, the U.S. Army Corps of Engineers, also manages two large reservoirs, whose primary purpose is flood control: Abiquiu (1963) and Cochiti (1975).

After decades of conflict, the U.S.–Mexico Treaty of 1906 and the Rio Grande Interstate Compact of 1938 apportioned water among the major irrigation sections in the states of Colorado, New Mexico, Texas, and Chihuahua. As a result, the flow of the Rio Grande in its upper basin is largely determined by water delivery requirements of the Rio Grande Compact.

Major irrigation districts further apportion water among farmers in the basin's major valleys. These quasi-governmental local districts include: Rio Grande Water Conservation District (San Luis Valley, CO), the Middle Rio Grande Conservancy District (Albuquerque, NM), Elephant Butte Irrigation District (Las Cruces, NM), and El Paso County Water Improvement District #1 (El Paso, TX).

New surface water uses continue to increase demand on the river. The burgeoning cities of Albuquerque and El Paso are busily planning projects to help them convert from groundwater mining to "renewable" surface water uses. The river, already at a competitive disadvantage, will soon shoulder the burden of new depletions for urban uses.

Why Streamflow Protection? Why Now?

Dry rivers equate to dead fish. The least hardy species that evolved in the river have disappeared, and the most hardy are considered threatened or endangered. Compliance with the Endangered Species Act will require water. Rio Grande pueblos have "prior and paramount water rights" that have never been quantified. It is but a matter of time before tribes seek to quantify their entitlements. The resolution of Pueblo Nations' water claims will require water. Even New Mexico's ability to honor its obligations under the Rio Grande Compact may be in doubt, as consumption of water increases.

The institutional arrangements that arose in response to 19th-century needs recognized only the irrigation economy as a purpose for the water supplied by the river. Today's realities include vastly larger demands for urban drinking water, new industries, and new social values, such as equity for Native American tribes and environmental quality. The sum of these demands presently subjects four critical reaches of the Rio Grande to dewatering in most years (Table 1).

Today, we are at the threshold of an important decision—will we attempt to belatedly include the river in our water supply strategies? If this region insists upon clinging to the institutional status quo, the river simply will cease to live. Only a bold, intentional change in the way we do our water business will offer hope of preserving existing uses, and balancing them with developmental aspirations and the river ecosystem. Whether we realize it or not, the decision we are making is between a living river and a dry ditch.

An honest effort to satisfy this full range of modern-day water demands will require difficult institutional adjustments and shifts in the allocation of legal rights to Rio Grande water. Securing beneficial streamflow regimes will, in large measure, depend upon some agreeable modifications in existing institutional arrangements, and small but significant accommodations by current users. Such an effort will satisfy the public interest in protecting the river-dependent natural environment from further degradation, or else we will dry up the river and flood the courtrooms.

Ironically, the basin's brightest hope is that so much of the Rio Grande's water is so inefficiently used (85% of the basin's farms use the least water-efficient methods available). If, as a basin, we could realize our water conservation potential, we could shift the savings to the environment and other new uses.

Wet Water's for Drinkin', Paper Water's for Fightin' Over

In the Western United States today, two kinds of water exist. Most citizens understand "wet water", the kind that flows downhill in response to the laws of God or nature or gravity. Wet water moves through the natural landscape in rivers and streams, and around the human landscape in ditches and pipes. Fewer understand about the second kind of water, which is paper water. Paper water, it is said, "flows uphill to money", a nifty feat whose accomplishment requires lawyers. Paper water flows through courthouses and statehouses. Unfortunately, our paper-water-rights system has over-allocated the river (assigned more rights than wet water) and given the region its knottiest problem.

Wet water, like the air around us, is an absolute requirement of life on our beautiful, blue-green planet, an entitlement that all creatures share. Paper water is too often a commodity to be captured and consumed, haphazardly, for short-term economic purposes. Our society could clearly be more deliberate in our use of water, more thoughtful of our neighbors, both natural and human.

Presently, water rights are unadjudicated in large sections of the river. In the present context of legal uncertainty, immediate progress toward legitimate river restoration goals must be made with the voluntary cooperation of a broad range of affected institutions. But time in which to make the critical adjustments to our water management institutions grows short.

In the event that we cannot place the river into the proper management context, society within the basin will likely be forced to sacrifice some or all of the environmental benefits the river has historically provided. Failure to maintain a functioning ecological base will make continued human occupation of the basin problematic. Much is at stake.

This paper suggests that a thoughtful combination of reservoir re-operations, water conservation, and water rights acquisitions, applied in the broadest interests of the users and environment, can reverse the Rio Grande's unmistakable trend toward extinction.

Streamflow Protection? How?

Maintaining Rio Grande streamflow requires maintenance of a precarious, wet-water balance. The river clings for its life to a small wet-water surplus and the obligation of several states to provide agreed-to consumptive amounts to their downstream neighbors. The wet water that accrues to the river today is entirely subject to tomorrow's consumptive uses. To achieve sustainable water for environmental needs, three conceptual criteria must be met: (1) acquisition of 8% of Rio Grande basin water resources (150,000 acre-ft) by purchase or donation; (2) obtain dedicated storage pools in major reservoirs, explicitly for environmental water; and (3) utilize the regulating capacity of reservoirs for timed releases to the greatest social and environmental benefit

It is important to note that the amount of wet water proposed for protection is small relative to the Rio Grande basin's average water production. A basin-wide water conservation target of 8% of existing uses is believed to be achievable, with sufficient incentives. To offset impacts of acquisitions on existing systems will require the most efficient possible use of water in cities and farms, and application of conserved wet water to the environmental pool.

Securing conserved water and protecting it from future depletion will require a serious public commitment to provide water explicitly for the environment. The path of least resistance in our present free market view of the resource is to secure, by purchase, lease, or other voluntary transfer, a sufficient quantity of water for the river's minimum survival needs. Whereas considerable resources may be required to fund water acquisition and capital improvements for water conservation, not all environmental water needs must be purchased. Delivery of downstream entitlements form part of the conceptualized future streamflow regime. The process will require a unified commitment by the public, decision makers, and water management officials for funding, data acquisition, and monitoring.

It will also require some storage in the basin's reservoirs and an increased understanding of delivery systems and ability to manage flows. Congressional reauthorization of some if not all facilities would be required to enable storage set-asides specifically for environmental use. Storage may, in some cases, need to be purchased. With a dedicated storage pool and improved water management operations, 210,000 acre-ft of environmental water in the upper basin is attainable (Table 2) without impacting existing users.

Finally, the river's own share of the river must be shepherded through a complex natural system and a maze of manmade diversions. An increased understanding of the river's natural system will be necessary to optimize streamflow regimes, protect existing beneficial uses, mimic the shape of the natural hydrograph, and prevent desiccation of the river. In other words, the science of the Rio Grande must continue.

A Last Word

The difficult task of balancing the Rio Grande's existing uses and development goals with the needs of a declining natural

TABLE 2—Major storage reservoirs on the Rio Grande, storage capacities, and proposed storage for environmental water.

Reservoir	Total storage (1,000 acre-ft)	Owner/Operator	Primary use	Proposed environmental storage (1,000 acre-ft)
Heron	400	USBOR	Storage/delivery of San Juan–Chama Project water	10
El Vado	180	MRGCD	Irrigation storage	None
Abiquiu	500	USCOE	Flood/sediment control and storage	50
Cochiti	5.34	USCOE	Flood/sediment control, fish and wildlife, recreation	<10 in recreation pool
Jemez Canyon	115	USCOE	Flood/sediment control	>10
Elephant Butte	2,000	USBOR	Flood/sediment control, irrigation storage	50
Caballo	330	USBOR	Irrigation storage	10
Amistad/Falcon	5,900		Flood control, irrigation storage	70
Aquifers	Unknown	Permitted water rights	Domestic/municipal supplies	80
Upper Basin	**3,530**			**210**
Lower Basin	**5,900**			**70**

environment demands that the leaders of the basin devise new strategies to sort through the conflicts among competing water uses and integrate conflicting management institutions.

Today we see urban leaders confidently planning the future conversion and ultimate consumption of tribal water, agricultural water, and the river's water. Individual water users recognize few connections to other user groups and to the river. Agriculture, already at the mercy of capricious markets, continues to build bunkers around existing water institutions, which includes their own massive diversions. Water management institutions are long on paper-water administration tools, and short on substantive knowledge about the wet-water system.

Like a fault line in an earthquake zone, great pressures are building around the Rio Grande's scarcity of water. The basin's headlong slide into the crack might be arrested gradually by application of good faith by many water users and the hard work of collaboration. The alternative, of course, is a cataclysm, the old fashioned rumble over water and a conflict with many potential losers. The living river would surely be one of the first casualties.

Perhaps we will continue to hide behind the strict constructions of our water management institutions and argue that the proposals contained here won't work—that we can't afford to devote water to rivers. We must recognize that these are rationalizations that focus on our fear of losing things that water rights holders can't bear to lose. To be sure, there are risks to water users and other decision makers in the Rio Grande basin in shouldering this task, but there are much greater risks in failing to try.

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Harris got his baptism in the Rio Grande at Boquillas, Coahuila, Mexico, in 1964: "I walked from Texas to Mexico and scarcely got my calves wet." Since 1975 he has been owner-operator of Far-Flung Adventures, a Rio Grande-based outfitting company. For the past 25 years, this has enabled him to observe the workings of the river first-hand. In 1994 he founded Rio Grande Restoration, a basin-wide streamflow protection group. With his 13 year-old daughter, Viola, he inhabits a riverside cottage in Pilar, New Mexico, from which he makes forays to forums as various as irrigation districts, legislatures, and schools, promoting awareness of the importance of the Rio Grande to people, communities and ecosystems.

"Today, the consequences of the last century of river development are coming into focus: and the picture is of a river in steep decline. It's apparent that, to change the grim prognosis for the Rio Grande, water users and managers must act purposefully, collaboratively, and soon if a living Rio Grande is to continue to serve as the life support system for our descendants."

The Value of Water in the Middle Rio Grande

by *F. Lee Brown*, Professor Emeritus of Economics, University of New Mexico

Use of the natural flow of the Rio Grande has been apportioned among the republic of Mexico and the states of Colorado, New Mexico, and Texas by international treaty and interstate compact. Under those rules, the middle Rio Grande region of New Mexico (from Otowi Bridge to Elephant Butte Dam) is entitled to consume approximately 393,000 acre-feet of water in an average water year. This natural flow has been fully appropriated since the 1950s, with regional growth accommodated since that time through the import of San Juan–Chama Project water from the Colorado River and through increased pumping of ground water.

In the last decade, however, as a result of research conducted by the New Mexico Bureau of Mines and Mineral Resources and the U.S. Geological Survey, it became apparent that the region's ground water was much more hydrogeologically limited than had previously been understood. The region has been mining ground water at an average rate of 70,000 acre-ft annually, and its total water consumption is now so great that in many years New Mexico probably would not meet its treaty and compact obligations at Elephant Butte without the return flow from ground-water pumping, a situation that is inherently non-sustainable. As a consequence, the region has been struggling to find ways to reduce its dependence on ground water and live within its limited supply of surface water.

This condition of water scarcity has given rise to markets for water rights in the middle Rio Grande, and the price of surface water rights in the region has risen steadily in recent decades, most sharply in the last few years. At this writing, the right to consume 1 acre-ft of surface water annually sells for about $4500 in the middle Rio Grande valley. Annualizing this sum at, say 6%, imputes a market value for an acre-ft of water itself of $270.

For most other commodities traded in reasonably competitive marketplaces, this type of number would be the bottom line measure for their economic value. For water in the middle Rio Grande, this figure may understate the actual opportunity cost of water use, possibly by a substantial increment. As discussed more thoroughly in a 1996 report for the city of Albuquerque titled *The Value of Water*, which I co-authored, opportunity cost is economic terminology for the opportunities foregone by using water in a particular way. As defined, it is the appropriate measure of the value of water in both private and public decision making about its use. Indeed, one of the major benefits provided by competitive markets is their ability to establish a price that reasonably measures the value of foregone opportunities. If the market price of water understates its opportunity cost—the likely historical situation in the middle Rio Grande—individuals and society collectively will tend to consume more of it than they would otherwise.

Consider the following factors, which collectively combine to create market values for water and water rights that are likely lower than their opportunity costs.

(1) Contracts or leases for water, as contrasted with water rights, tend to be tied to Bureau of Reclamation repayment costs, which reflect the capital and operation and maintenance costs of constructing and operating water storage and delivery structures but not the scarcity value of the water itself.

(2) Water rights in the main stem of the middle Rio Grande have never been adjudicated, and some informed observers believe that there may be two or three times the number of paper rights to water as there is actual wet water.

(3) Surface and ground water have been conjunctively administered in New Mexico since the 1950s, in that the state engineer requires that pumping effects on the Rio Grande be offset by the retirement of existing uses. Recent changes in his administrative rules are likely to increase the current market value of existing water rights as contrasted with past values.

(4) At the same time, moreover, ground-water pumping in the region is largely unrelated to what economists call in situ values, e.g., the prevention of subsidence, the maintenance of a drought reserve, etc. As these latter values are increasingly recognized, incorporated into water decisions, and surface water begins to be substituted for ground water, the price of surface water rights will also be bid up. (For more information on in situ values, see *Valuing Ground Water*, referenced below.)

(5) Until recently, the value of leaving surface water in the river for riparian purposes was not reflected in the marketplace for water rights because New Mexico water law has not recognized water left in-stream as beneficially used. The water needs of endangered species are now forcing change in this institutional limitation on water markets.

(6) New Mexico has enacted but not implemented a public welfare criterion in its water law that permits the state engineer to deny a water right transfer if it is deemed to be contrary to the public welfare. Some traditional water users in New Mexico, most notably Hispanic acequias, often oppose transfers of water rights as destructive of traditional culture and thereby contrary to the public welfare. To the extent that public welfare values have not previously been incorporated into market prices, those prices have understated the opportunity cost of water.

The factors above have tended to create a market price for water and water rights that is lower than the respective opportunity cost. Furthermore, there are some offsetting factors in the middle Rio Grande that tend to push the price of water and water rights artificially higher rather than lower, so that it is difficult to project what the market price of water and water rights would be if water were freely traded in a truly competitive marketplace in the middle Rio Grande. As the marketplace for water and water rights in the middle Rio Grande matures, hopefully this divergence between market prices and opportunity costs will disappear.

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Brown's professional interests are resource economics and econometrics with a specialization in water resources. In addition to his faculty positions at the University of New Mexico, he has also served as Director of the Bureau of Business and Economics Research, Director of the Natural Resources Center, Director of the Division/School of Public Administration, and Executive Director of the International Water Resources Association.

He currently serves as chair of the Middle Rio Grande Water Assembly, a volunteer non-profit organization whose mission is the development and implementation of a regional water plan for the counties of Sandoval, Bernalillo, and Valencia. This commitment reflects his view that water is key to the future of New Mexico and that the creation of institutions and policies for managing this scarce resource is one of the most important issues facing our state.

Water Planning on a Local Development Scale—The Placitas Area Microcosm

by *Robert M. Wessely*, Friends of Placitas

Placitas serves as a harbinger of water concerns that will surely surface across New Mexico. Many of the water issues that individually affect various portions of the state come together in Placitas. Placitas water planning is an opportunity, allowing us to choose to heed the scientific messages or keep our collective heads in the sand. Through a local water planning effort, Placitas is trying to make the right choice. We cannot do it alone; we need both funding and regulatory reform.

This article identifies problems and suggests paths toward solutions. Topics include Placitas land development pressure, Placitas water planning issues, how Placitas water planning fits into the state's planning picture, and actions that we urge top-level decision makers to take. While this article deals with water planning for the Placitas area, we believe the process identifies important actions needed on a statewide basis.

We suggest: (1) establishing close coordination between land-use and water-use decision making; (2) closing the regulatory loopholes that subvert resource management; (3) encouraging planning approaches and actions to focus on the long term; (4) recognizing and financing the complexity of public water-planning processes; and (5) performing the basic hydrological studies and maintain continued monitoring.

What Are Placitas' Key Development Issues?

Urban overflow—The city of Albuquerque and surrounding area is rapidly growing. Albuquerque serves as the concentration point for the state's 134,400 annual new residents—about 104,600 (78%) via immigration and 29,800 (22%) via birth. Placitas has the fortune/misfortune to lie within practical commuting distance of the urban center. And the urban center is boxed in by adjacent public and pueblo lands, limiting the quantity of private land that is available to house the growth.

A richly historic area—The numerous and historic springs in the area have given Placitas a long history of human occupation. There is archaeological evidence of settlement dating back several thousand years. There has been a Hispanic acequia community here for 200 years, characterized by extensive farming activities. Starting in the mid-1980s, the open spaces, mostly west of the village, were rapidly built out into an extensive commuter exurbia. This has exerted pressure on Placitas' rich archaeological and historically agrarian culture.

Weak water management—Recent growth has imposed a serious stress on the local water supply. Several springs have run dry. Most water is now obtained by mining ground water, either through community wells for subdivisions or through individual or shared domestic wells. Much of the development has occurred through cascading "four-lot split" subdivisions and their shared domestic wells (Section 72-12-1, NMSA 1978). Frequent and large-scale uses of these "exemptions" has enabled rapid development to evade the county and state engineer scrutiny intended by state subdivision and water legislation.

Local–state disconnects—There has been a tradition of disconnects between local government and state government in managing the impacts of growth on water. Local governments point to the Office of the State Engineer (OSE) for water policy wisdom, the OSE abdicates decisions to the local governments, and neither has been able to concentrate on the area's long term future. Similarly, the local governments depend upon New Mexico Environment Department (NMED) for inspection and enforcement of wastewater requirements, yet NMED is not sufficiently staffed to perform the function well.

What Are Placitas' Key Water Planning Issues?

Attracting public involvement—The first planning hurdle is attracting the attention of the populace. The diversity of aquifer types across the Placitas area encourages rumors, both of dearth and of plenty, which propagate without qualification. In Placitas, we now have people from relatively water-rich areas, who are accustomed to water being an automatically provided commodity. We find a general apathy toward our water future, exacerbated by the popularity of denial and fed by the multiplicity of rumors. The tendency is for the general public, as well as officialdom, to consider only the issues that directly bear on their immediate future.

Achieving constituency balance—Water planning requires balancing demand (as reflected in the needs and desires of various constituencies) against supply, in a way that will work for the long term. With New Mexico's legal structure and history of over-appropriation, the water planning balance must come from negotiation and agreement among multiple constituents. Obtaining the needed participation of the diverse constituents is tricky, and understanding what represents a reasonable and balanced compromise is even trickier.

Water sources—Water in Placitas is obtained by single or shared domestic wells, small community water systems, and springs. These withdrawals are from aquifers that recharge the Rio Grande. Some of the springs are fed through annual precipitation recharge (with water ages in months or years), whereas other springs have been measured to contain ancient water (up to 4,000 years old). Some are drought sensitive, others are not. In substantial parts of the area, the aquifers are already being mined, and water tables are dropping.

Limitations on supply—Rapid residential growth, coupled with ground-water mining, gives rise to concerns for the long-term viability of the water supply at any tolerable price. As a part of the already-stressed middle Rio Grande region and the desert Southwest, Placitas cannot expect to import water. Planning must depend upon local water, and withdrawal of local water is being authorized through land-use law, not water law, at dramatic rates.

Water-oblivious expansion—Each transfer of water rights into the area is evaluated only on its individual impact to neighbors and aquifers, with no view to the cumulative effect of multiple transfers. Furthermore, domestic wells (Section 72-12-1, NMSA 1978) are being authorized in large clusters to support large developments, each individual well being considered "de minimis." Within this environment, developers seek profits and local governments look forward to additional tax revenues.

Planning is complex—Water planning for an area such as Placitas is costly, both in effort and in dollars. We are fortunate to have an extensive hydrology study available—New Mexico Bureau of Mines and Mineral Resources (NMBMMR) Phase II study. Despite that, there exists a need for more work: quantifying water in storage, relating supply to current and future demand, and most costly, the process of obtaining proper constituency involvement to make the difficult balancing decisions.

Water rights—Another issue affecting water planning is numerous, often-competing, water rights. Placitas is bordered by tribal lands that have substantial unquantified rights to the water flowing underground from the Sandia Mountains. The village of Placitas has long-standing acequia systems with relatively senior rights. But the majority populations in the newly developed communities have junior water rights.

Balancing is not mathematical—Finally, we see before us the task of balancing the social costs against the financial costs. How do we assign values to Placitas' extensive riparian areas, agriculture and acequia traditions, and rural qualities of life versus more easily quantifiable dollar values of immigration and rising exurban property values? We need a whole community to provide the wisdom of one Solomon.

How Does Placitas Fit into Statewide Water Planning?

We are not alone—The overall context for water planning is a rapidly growing desert Southwest. New Mexico lives among thirsty and growing neighbors on all sides. State water planning faces four major hazards: drought, growth, affluent neighbors, and federal mandates.

Our state—New Mexico has established a minimally funded but urgent mandate for regions within the state to develop water plans. The plans are to address the hazards within the region. They reflect how we will manage to survive on our limited supply. These regional plans will be assembled into a statewide plan to address the same hazards on a broader scale.

Our region—The middle Rio Grande (Sandoval, Bernalillo, and Valencia Counties) is an exceptionally diverse and populous region. Like many other regions, its water resources are over-allocated (by an estimated factor of three or four). All of the water in the Rio Grande is already being used, albeit perhaps not at maximum efficiency. On average, the wet water use already exceeds the renewable supply by 70,000 acre ft/yr (Water Assembly and S.S. Papadopulos & Assoc, 2000).

Our watershed—Placitas is a piece of the middle Rio Grande region. Located at the base of the Sandias, Placitas is seen by hydrologists as a major ground-water tributary of the Rio Grande. Historically supplied by springs, Placitas is now mostly supplied by its ground water. As shown by the recent hydrology studies, some areas have localized ancient aquifers that will run dry. Other areas will continue to draw from the flow toward the Rio Grande. Meanwhile, we keep increasing the rate of ground-water extraction through domestic well authorizations.

Scientific basis—The geohydrology at the north end of the Sandias is complex (Connell, Geology of the Northern Sandia Mountains and Albuquerque Basin, Placitas, and Bernalillo Area, Sandovol County, New Mexico, this volume; and Johnson, Geologic Limitations on Ground-Water Availability in the Placitas Area, this volume). A $10,000 Phase I hydrological study in 1996 laid the groundwork for special subdivision regulations and a follow-up study. The $100,000 Phase II study, 1998–2000, provided necessary details on the complex hydrology and a foundation for detailed water planning.

Public involvement—In summer 1999 three community water planning workshops were conducted by Del Agua Institute under a $5,000 grant from River Network. These workshops developed a set of local values and an approach to the water planning process. As an outgrowth of the workshops, an ongoing all-volunteer core committee has been meeting monthly. To date, the committee projects and products include: draft program plan for area water planning; initial draft water plan outline; supply and demand model, based upon Phase II hydrology (Johnson, 2000) and assessor data; public outreach and education; and draft agreement with regional water planners. This effort is progressing slowly under a $1,000 grant from Sandoval County.

What Are Placitas' and the State's Future Needs?

Water information model—The primary need is a model of water availability for specific locales in the Placitas area. The model should provide information in a form that a county commissioner can easily use to understand the effects of his/her decisions on permitting development. The Placitas-area planning group is working on a preliminary version of such a model. The current model uses the hydrologic regions defined in the Phase II study (Johnson, 2000) and an estimate of water per acre in storage for each region. Then development-based subregions are defined within each hydrologic region, from an overlay of actual assessor maps. From these an approximate lifetime of water at 125, 250, 500, and 1,000 ft well depths can be calculated for the currently authorized array of lots. Finally, the model can then estimate a projected shortening of aquifer lifetime for each additional lot or building that is authorized within the subregion.

Sound scientific and public basis—The vehicle for achieving effective land-use decision making is a water plan based upon both sound science and bona fide consideration of informed public opinion. Without impartial hydrogeologic studies, land-use decisions unavoidably disregard wise water-management practices. Water supply and demand assessments are too often based upon guesses, insufficient data, and/or developer-supplied analyses. Politicians are unwilling to make the hard decisions that look innovatively toward the future because thorough public involvement and support are not there. Placitas fortunately now has the detailed NMBMMR data that allow for competent, impartial modeling analysis and provide a reasonable assurance that decisions are based on valid information. This technical credibility is enabling and encouraging public participation and collaborative decision making, which will, in turn, control our fate.

Ongoing science—Another important need is maintenance of the hydrologic database. The Phase II study monitored water levels and their changes over a 1½ year period. These data provide the scientific basis for ground-water and water development models. However, to ensure that model predictions actually reflect reality, it is important to maintain and update the current data sets with periodic measurements of the actual behavior of the aquifers under ongoing use and development.

Regulatory feform—Understanding water availability is essential but not sufficient. Placitas has been subject to substantial unmanaged growth, resulting in stress on many of the aquifers. Placitas' decision makers need to implement land-use decisions that rigorously respect the limited water resources. We need more effective regulations at both the state and county levels. An overall vision for statewide management of water resources needs to be created and implemented. Support and advice are needed from the state level for encouraging proper local regulations and for technical evaluations. Regulatory agents, both state and local, need better handles on the development process, better coordinated roles, better technical knowledge, and better controlling legislation—the loopholes to managed water deployment need to be closed.

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Wessley works to widen scientific understanding of New Mexico water issues among elected officials and the general public. Active in designing, organizing, and executing water planning activities for the middle Rio Grande region and for the Placitas area watershed. He is co-founder, chairman, and technical director of SciSo, incorporated 1971–2001. SciSo is a systems engineering management consulting compan, serving government and industry, with large-scale client projects across the United States, in Europe, and on the Pacific rim. Having coordinated diverse interest groups in developing large-scale engineering projects, his current interest is in helping New Mexico optimize its limited water resources with an eye toward future generations.

Sandoval County Subdivision Regulations—A Development Plan for the Placitas Area

by *John T. Romero*, New Mexico Office of the State Engineer

Before the 1995 amendment of the New Mexico Subdivision Act, Sandoval County had no subdivision regulations specific to the Placitas, New Mexico, area. Existing regulations required only minimal water-use and water-availability information. The disclosure statement in place in 1994 had more requirements than the subdivision regulations themselves. For example, the disclosure statement for a proposed subdivision required type and quantification of water use, delivery method, life expectancy, and water source. In the case of domestic wells the statement even required maximum and minimum depths to water, the total depth and the estimated yield of a proposed well, and a recommended pump setting. The current county subdivision regulations require essentially the same information as required by the original disclosure statement.

After the 1995 amendment of the New Mexico Subdivision Act, Sandoval County developed detailed and comprehensive land subdivision regulations that addressed water issues and concerns. The new regulations included requirements for summary review proposals and presented standards for quantification of annual water requirements, conservation requirements, non-residential demand, and community demand, as well as water availability assessments for all types of proposals. In addition to these water-related requirements, the county developed a separate set of regulations to deal with subdivision proposals in the Placitas area. These regulations are attached as Appendix A to the land subdivision regulations for Sandoval County.

A Development Plan for the Placitas Area

Appendix A to Sandoval County's land subdivision regulations is a development plan for the Placitas area. The Sandoval County Commissioners approved Appendix A on October 17, 1996, following a review by the Office of the State Engineer (OSE).

Appendix A attempts to take into account and to balance the diverse geographic area of Placitas, limitations on water supply, desires of the local inhabitants, traditional land uses, traditional cultural practices, constitutional rights of property owners, and development trends within the area. The appendix applies only to new subdivision proposals not previously reviewed and filed. The purpose of the appendix is to provide the Sandoval County Planning and Zoning Commission with sufficient information to reasonably determine the impact that a proposed subdivision will have on the terrain, water table, water availability to pre-existing water users, and drainage courses associated with ground water.

Appendix A has requirements that are generally more stringent than the Sandoval County Subdivision Regulations. For instance, a subdivider in Placitas must notify all abutting property owners and neighborhood associations before submitting a proposal to the county. In addition, the regulations require that "all new subdivisions within the Placitas area shall form a Landholders Association or Water Association which shall impose and enforce Restrictive Covenants which . . . limit the amount of water consumed per household to a range of 85 . . . to 160 gallons per day per person, plus 132 gallons per day for outdoor landscaping and require metering of all wells within the proposed subdivision." These covenants are also required to provide a penalty clause, that shall be imposed on individual households which exceed the combined indoor and outdoor domestic use.

Water Assessment Requirements for Preliminary Plat Proposals

A subdivider must prove that water exists within the boundaries of a proposed subdivision in sufficient quantities to deliver 85–160 gallon per capita per day per dwelling, plus 132 gallons per day for the irrigation of 1,600 ft^2 of landscape. This may be accomplished by drilling a well within the boundaries of the proposed subdivision, if a well does not already exist, and testing by a qualified professional to demonstrate an adequate 50-year water supply. This water supply assessment should include preliminary work such as performing demand calculations, field geologic reconnaissance, identification of known aquifers, plotting all known domestic wells, constructing a well at or above industry standards, if one does not exist, and testing the well via a step drawdown test before a constant discharge test while measuring water levels and monitoring the recovery to at least 90% of initial drawdown.

The data gained from the water supply assessment are intended to provide reliable estimates of aquifer transmissivity, storativity, specific yield, thickness, hydraulic conductivity, and an evaluation of the potential effects on nearby surface water courses. The water assessment requires review by the OSE to ensure compliance with the county's requirements for the determination of minimum lot size.

The above criteria are applied only in the Placitas area, with the purpose of managing development and lot sizes in order to control the rate of ground-water depletion and to ensure that sufficient ground water will be in storage over the next 50 years. Since not all ground water in storage in an aquifer can be withdrawn, the appendix provides a methodology to estimate the percentage of ground water in storage that can be withdrawn based on aquifer characteristics. The method is based on the following equations:

$$S = Ac \times SY \times ST \times RC$$

S = ground-water storage (acre-ft)
Ac = size of tract (acre)
SY = specific yield (unconfined aquifer) or storativity (confined aquifer)
ST = saturated thickness (ft)
RC = recovery factor, usually 0.8

$$MLS = U / (A + RE)$$

MLS = minimum lot size (acre)
U = water use per lot per 50-year period (acre-ft)
A = water availability per acre (ft) = S/Ac
RE = recharge per acre per 50 year period (ft)

These calculations will be used to determine the number of lots that can be safely sustained by each domestic well. It should be noted that the county regulation encourages multiple well connections between lots located in the Placitas area.

Requirements for Summary Review Proposals

This summary procedure applies to Type III subdivisions containing five or fewer lots any one of which is less than 3 acres in size. This is the most common type of subdivision in New Mexico.

Subdivider shall prove that water exists within the proposed subdivision boundaries sufficient in quantity to deliver 85 gallons per capita per day per dwelling, plus 132 gallons per day for outdoor irrigation of 1,600 ft^2 of landscape.

Each lot shall be equipped with a water meter in addition to all wells.

Quantity will be determined by utilizing an existing well or drilling a new well within the boundaries of the proposed subdivision and by conducting a well test for a period of 24 hrs at a rate of 0.3 gpm per dwelling proposed to be serviced by that well with water level measurements taken before the test, at 3, 6, and 24 hrs, at the end of the test, and 24 hrs after the end of the test.

A well test report will be completed by the person completing the test. (There is no requirement for a qualified professional performing the test.)

Lot size will be determined by New Mexico Environment Department (NMED) requirements for liquid waste disposal.

References

Appendix A to Sandoval County Land Subdivision Regulations, 1997.
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New Mexico Subdivision Statutes, NMSA 1978, Amended.

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A flume measures discharge from El Oso Spring near the village of Placitas. In Placitas, water rights applications require the Office of the State Engineer to determine whether springs would be affected by the new water use. Photo by Peggy S. Johnson, November 1997.

Ground-Water Administration in the Middle Rio Grande Basin, New Mexico

by *Peggy Barroll*, New Mexico Office of the State Engineer

The Office of the State Engineer (OSE) is responsible for regulating water rights in New Mexico, including ground-water rights. When evaluating applications related to ground-water withdrawal, we must consider the potential depletion of ground water (or a drop in water levels in the aquifer), the potential for the proposed ground-water pumping to diminish the flows of streams and rivers, and whether the water requested is available for use by the applicant.

When ground water is pumped from an aquifer, water levels in that aquifer decline. This decline can cause wells to produce less water and may cause some wells to dry up altogether. In some cases it is possible to mitigate these effects by drilling deeper wells, but if the productive aquifer is limited in extent, this may not be possible. Deeper water is also more expensive to lift to the surface, and may not be of suitable quality. In Albuquerque, for example, deeper wells tend to produce water with higher concentrations of arsenic. If water levels decline too much, the overlying land may subside. This has occurred already in parts of Arizona and California, causing expensive damage to buildings and infrastructure. The economy of many parts of New Mexico depends on ground water either for municipal and industrial use, as in the Albuquerque Basin, or for irrigation use, as in the Estancia and Roswell Basins. If ground water is to continue to be a reliable water source, its development must be conducted in a controlled, sustainable fashion.

Ground-water pumping can also reduce the surface-water flow in adjacent rivers, often by intercepting ground water that ordinarily would have discharged to the river as baseflow. This reduction in surface-water supply can affect downstream surface-water users and may cause serious problems on interstate streams. New Mexico is required by interstate compact to deliver prescribed amounts of river water to downstream states, and, if we fail to do so, there are serious consequences. In 1974 Texas sued New Mexico for under-delivery on the Pecos River, resulting in a lengthy and expensive lawsuit in the U.S. Supreme Court. New Mexico lost this suit and has since spent tens of millions of dollars in fines and actions to prevent further under-delivery on the Pecos River.

When evaluating a ground-water application, the OSE must estimate the potential effects of the application on water levels in the aquifer and on stream flows (in addition to other statutorily defined considerations). To do this we must develop and use predictive ground-water models, which allow us to estimate the physical effects of ground-water pumping. The OSE does not typically perform such analysis for domestic wells, for which the OSE is required to issue permits upon request.

The Placitas area straddles two very different hydrologic regimes. The village of Placitas is up out of the valley, and wells in the area obtain ground water mostly from fractures and porous zones in hard rock (Johnson, Geologic Limitations on Ground-Water Availability in the Placitas Area, Sandoval County, New Mexico, this volume). The area is very complex, and productive aquifer zones are limited. Water rights applications in this area have typically been evaluated using models designed to represent this complex region, which provide estimates of how much drawdown a proposed well would cause and by how much the flows of Placitas Springs would be reduced. These models are designed based upon the hydrogeologic data collected by agencies such as the U.S. Geological Survey, New Mexico Bureau of Mines and Mineral Resources, and other investigators.

West of Placitas we enter the Albuquerque Basin where wells obtain water from the spaces between grains of sand, gravel, and silt of an alluvial aquifer. This aquifer is hydrologically connected to the Rio Grande, and ground-water pumping from the aquifer can diminish the flows of the Rio Grande. Hydrologic effects associated with this aquifer can be calculated using a numerical model originally developed by the U.S. Geological Survey and modified for OSE use. This model includes vast amounts of hydrologic and geologic data, which have allowed us to use the model to reproduce the past behavior of the aquifer with some accuracy, thus giving us confidence that future predictions using the model will be fairly realistic.

The Middle Rio Grande Guidelines for Review of Water Right Applications (Year 2000) describe how this model is to be applied by the OSE. These guidelines also define Critical Management Areas (Fig. 1), areas of extensive ground-water development where observed and/or predicted drawdown rates are very high (greater than 2.5 ft/yr) and where the OSE has determined that ground-water withdrawal rates should not be allowed to increase.

In addition, serious consideration has been given to the problematic effects of ground-water pumping upon the Rio Grande. The Rio Grande is the subject of a compact with Texas just as the Pecos River is. To ensure compact compliance, it is crucial that all new pumping effects on the flows of the Rio Grande be offset by the retirement of valid water rights and uses. For many years the OSE has required that estimated impacts to the Rio Grande be offset at the time the effect is calculated to reach the river. But because there is a time lag between initiation of ground-water pumping and its effect on the river, many ground-water users have not yet acquired all the rights that they will eventually need to retire. Large ground-water applications are currently pending with the OSE and more continue to be filed. Concerns have been raised as to whether there will be sufficient water rights available to offset the effects of presently permitted ground-water users. Offset of future ground-water permits is an even greater concern.

To address this issue, the OSE's Middle Rio Grande Guidelines require new ground-water permittees to obtain, before pumping, the water rights they will eventually need to offset the effects of that pumping. Since the total effects of that pumping will not actually reach the Rio Grande immediately, the permittee may lease back the use of the offset water to its original use until needed to offset the stream effects calculated by the model. This requirement to obtain water rights up front is deemed necessary to prevent the Albuquerque Basin from becoming overdrawn at the water bank. This requirement is prudent when one considers that the price of water rights within the basin is only likely to increase, and there may be additional allocation of water to pueblos and to meet endangered species requirements, which will further limit the availability of water rights for offset.

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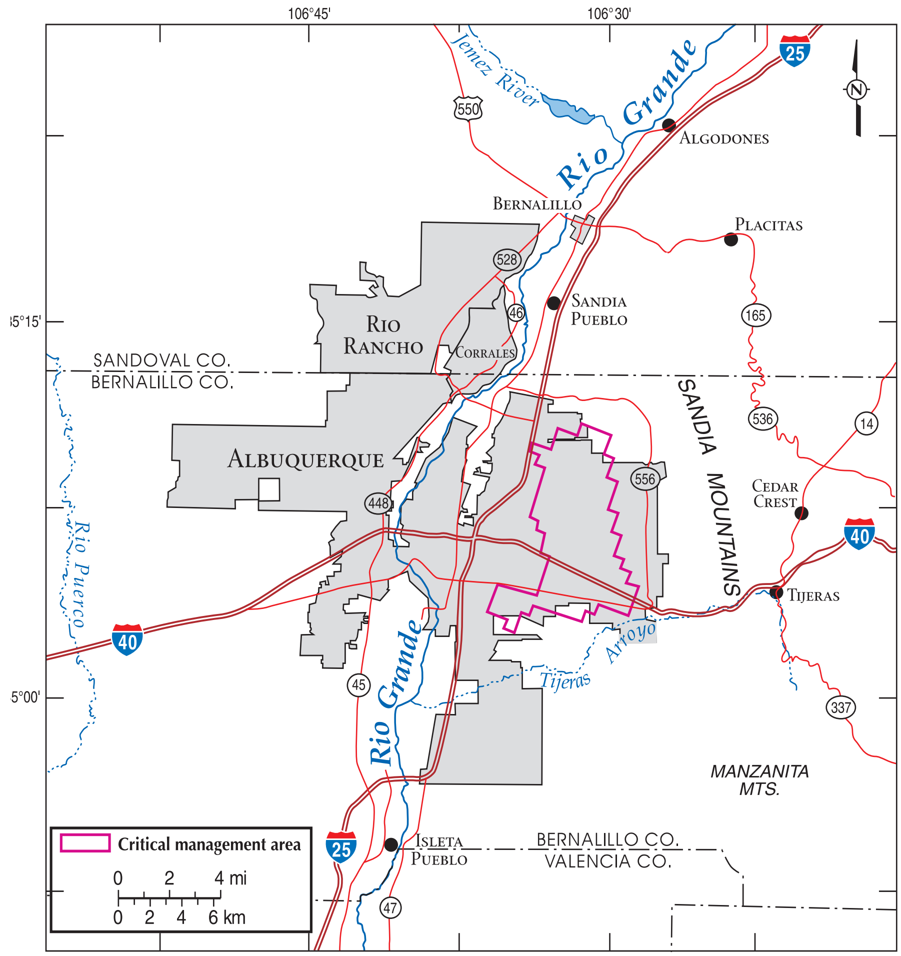

FIGURE 1—Location of the middle Rio Grande basin critical management area (CMA).

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After finishing her PhD, Barroll worked briefly for D. B. Stephens & Associates, modeling contaminant transport. For the last 9 years, she has worked at the Hydrology Bureau of the Office of the State Engineer, doing ground-water modeling and evaluating the hydrologic effects of water rights applications. Much of her work involves simulating the interaction between ground-water and surface-water systems. She has worked extensively in the Carlsbad area of the Pecos River basin, and more recently has been working on the lower Rio Grande and middle Rio Grande areas. She is collaborating with Doug McAda on a new ground-water model of the middle Rio Grande, which will incorporate the new hydrogeologic data collected over the last several years. Her lower Rio Grande work is related to ongoing and potential litigation related to the lower Rio Grande adjudication and disputes with Texas over the flows of the Rio Grande. She lives in Santa Fe with her husband, Hans Hartse, and their two children, Sara and Jeremy.

Geology of the Northern Sandia Mountains and Albuquerque Basin, Placitas, and Bernalillo area, Sandoval County, New Mexico

by *Sean D. Connell*, New Mexico Bureau of Mines and Mineral Resources

The northern flank of the Sandia Mountains contains a diverse array of rocks and geological structures that form the outstanding landscape of the Bernalillo–Placitas area. The Bernalillo–Placitas area was formed as sediments were preserved during successive geologic cycles of deposition, partial erosion, folding, and faulting. The distribution and character of the rocks and crosscutting geological structures strongly influence the availability and flow of ground water in the subsurface. Geologic structures such as faults often form obstacles to ground-water flow and generally serve as boundaries for ground-water aquifers. In particular, faults can juxtapose aquifers with different yields and can control the locations of springs and ground-water recharge areas.

Due to rapid residential development in southeast Sandoval County and resulting concerns regarding the long-term availability of potable ground water, the New Mexico Bureau of Mines and Mineral Resources and the University of New Mexico have been investigating the geology and ground-water resources of the Placitas area. These studies resulted in the completion of detailed geologic maps depicting the locations of major faults and geologic units (Connell et al., 1995; Connell, 1998; Johnson, 2000). A simplified geologic map (Fig. 1) illustrates the surface distribution of faults, folds, and geologic units (see inside back cover), which are grouped in order to illustrate the general geologic framework of the area. Geologic units are projected below the ground surface on geologic cross sections to determine the depth of buried formations and the influence of faults and folds (Fig. 2). Geologic cross sections can then be used to predict where and at what depth a particular well should be drilled in order to intersect a particular formation.

The Bernalillo–Placitas area lies at a geologically complex transition between the Albuquerque Basin and Sandia Mountains uplift. The Placitas area, on the north flank of the Sandia Mountains, is underlain by north-sloping rock layers that are broken and deformed by numerous faults. On a traverse from Tunnel Spring north to Las Huertas Creek (Fig. 1), one can walk through the rock section and examine rocks that represent the major hydrogeologic units of the Placitas area (Figs. 2, inside back cover). The Rincon-Placitas-San Francisco faults delineate the geological (structural) boundary between the Sandia Mountains and upland areas of the East Mountains, where the oldest rocks in the region are exposed. These rocks consist mainly of granites that form much of the Sandia Mountains (Fig. 1). Water typically flows through these rocks along rare open fractures and near faults. These old crystalline rocks are overlain by younger sedimentary rocks of the Pennsylvanian and Permian Periods, which contain limestone, mudstone, evaporites, and some conglomerate and sandstone. The oldest of these rocks form the banded crest of the Sandia Mountains. Water flowing through fractures in the limestone typically contains calcium carbonate resulting in increased hardness of the water. With time, these fractures develop into larger channels potentially capable of transmitting large quantities of water. Water wells drilled into these fractured and faulted zones commonly have high yields; elsewhere, wells drilled into non-fractured rock typically yield little water or are dry. Rocks of the Mesozoic Era (Age of Dinosaurs; Fig. 2) are exposed east and southeast of the Ranchos, Lomos, and Escala faults. These rocks represent deposition during the Triassic, Jurassic, and Cretaceous Periods and contain fine-grained sediments that only locally contain significant sources of ground water, generally near north-trending fault zones (Johnson, 2000). The youngest of the Mesozoic sedimentary rocks contain mudstone and sandstone of the Cretaceous Period, which typically are the poorest aquifer units of the area. Sandstone interbeds can locally be exploited for ground water, but commonly yield poor-quality water.

Deposits of the Santa Fe Group of the Cenozoic Era (Age of Mammals) comprise the regional aquifer of the Albuquerque Basin. The thickest and most productive layers in the Santa Fe Group lie west of the Ranchos, Lomos, and Escala faults, which form the eastern boundary of the middle Rio Grande ground-water basin. Alluvial deposits of the Santa Fe Group are present east of these faults, but are typically thin, moderately cemented, and are poorer aquifer units in comparison to alluvial deposits west of the faults. The communities of Rio Rancho, Albuquerque, Bernalillo, and the pueblos of Sandia, San Felipe, and Santa Ana obtain their water from Santa Fe Group alluvial sediments. The Santa Fe Group is thousands of feet thick and was laid down by streams originating in the Sierra Nacimiento and Jemez Mountains, the ancestral Rio Grande, and from smaller streams draining the Sandia Mountains watershed. Deposits of the ancestral Rio Grande, which flowed 2–4 mi east of the present valley, in the Bernalillo–Placitas area, form a relatively narrow belt of sediments that form the most productive aquifer beneath the city of Albuquerque (Connell et al., 1999). These ancient river deposits interfinger with sand and gravel deposits derived from the Sandia Mountains, which generally contain potable water but do not transmit water as effectively as the clean sand and gravel deposited by the ancient Rio Grande.

The youngest deposits record episodic erosion, deposition, and recycling of sediments as the ancestral Rio Grande began to cut the modern river valley approximately 1.2–0.7 million years ago, in response to climatic changes in northern New Mexico and Colorado during glacial episodes. This ice-aged entrenchment lowered the water table in the Santa Fe Group and partially drained the uppermost part of the Santa Fe Group alluvial aquifer.

Detailed geologic mapping of the region, studies of exposed rocks, and examination of well borings has greatly improved the level of understanding of the architecture of the Albuquerque Basin and its ground-water resources. Ongoing studies of the Santa Fe Group basin fill will eventually result in a better understanding of the entire basin and its ground-water resources.

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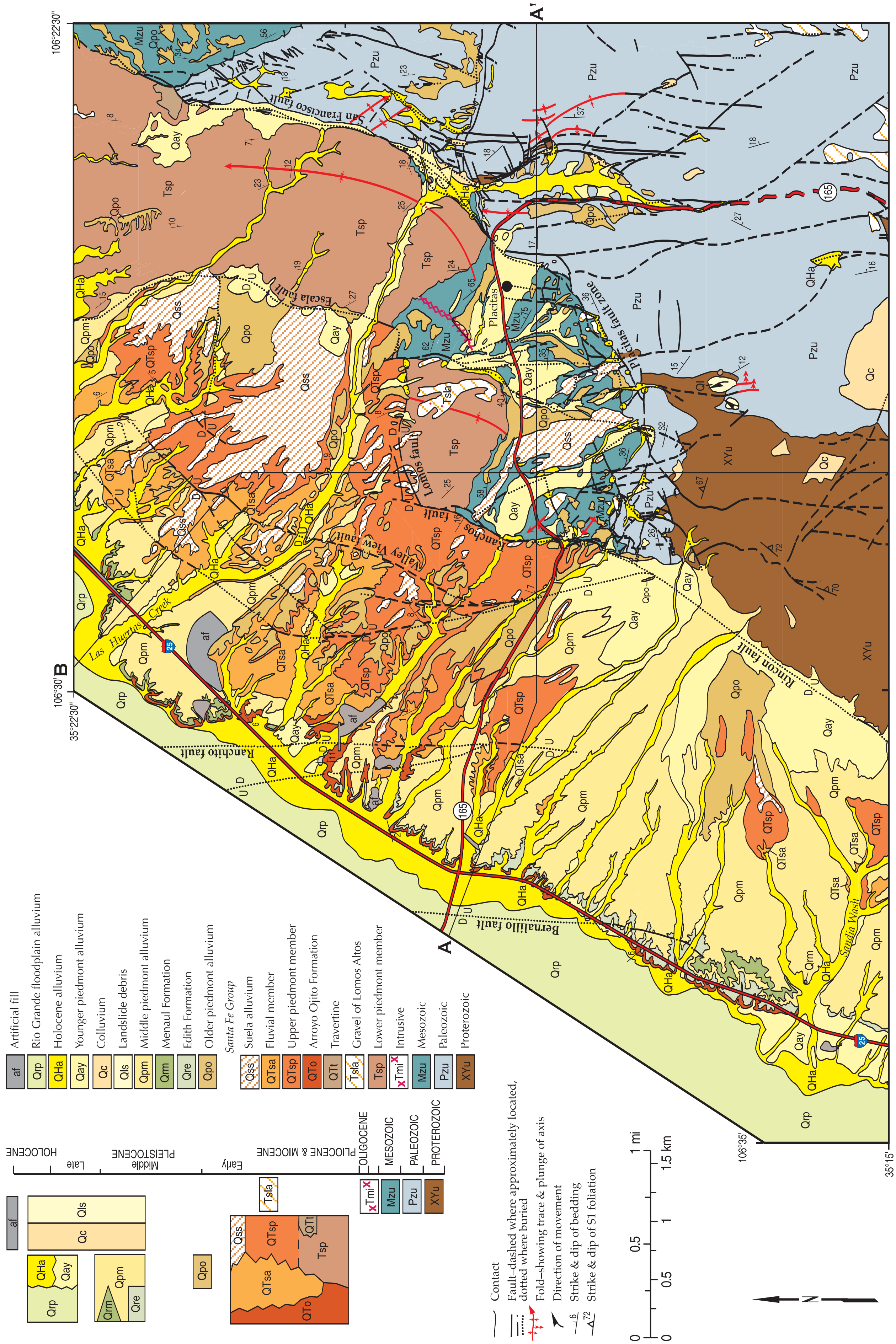

FIGURE 1—Simplified geologic map of the Bernalillo and Placitas 7.5-min quadrangles (modified from Connell et al., 1995; Connell, 1998).

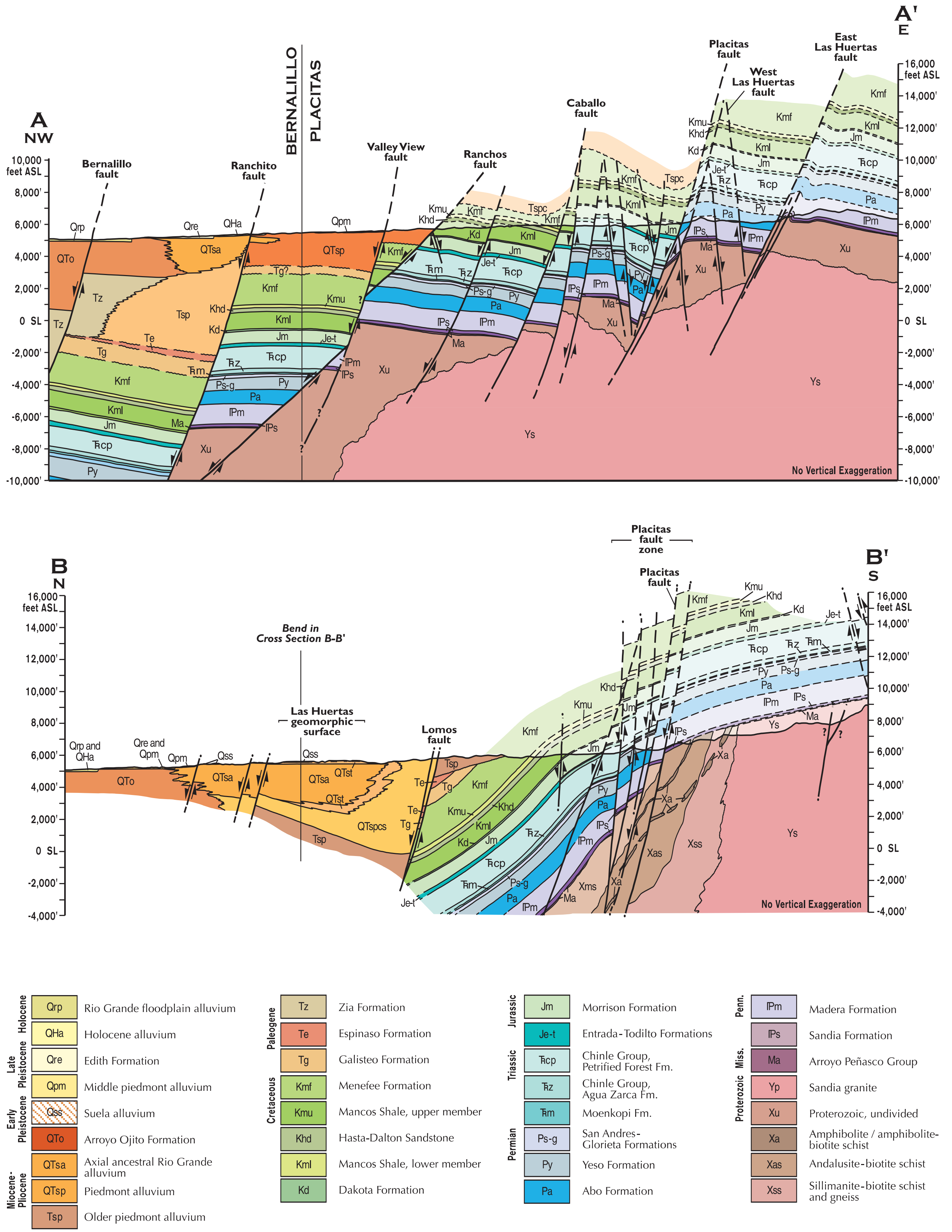

FIGURE 2—Simplified geologic xross sections of the Placitas area (modified from Connell et al., 1995, Connell, 1998).

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Before joining the NMBMMR, Connell worked for a consulting engineering geology firm in southern California, where he was involved in the evaluation and development of property for residential, commercial, and light-industrial tract development, including investigations of active faults. Connell was also involved in contract work involving soil-stratigraphic and geomorphic studies of Quaternary active faults and reconnaissance geologic and geomorphic mapping for archaeological studies in southern California.

Since joining the NMBMMR in 1996, Connell has contributed to 11 geologic quadrangle maps, encompassing an area of about 1,100 km^2. He has also been studying the stratigraphy of the alluvial aquifers of the Santa Fe Group, and has been an active participant in an ongoing program to analyze the geology at nested piezometers in the Albuquerque Basin. Connell is currently involved in regional geologic map compilations, and stratigraphic and environmental geological studies in the Albuquerque Basin, including compilations of geologic maps of the Isleta Reservation, and the Albuquerque-Rio Rancho metropolitan area.

Geologic Limitations on Ground-Water Availability in the Placitas Area, Sandoval County, New Mexico

by *Peggy S. Johnson*, New Mexico Bureau of Mines and Mineral Resources

The Placitas area, situated in the picturesque northern Sandia foothills, has been intensively developed during the past three decades. The region has evolved from a sparsely populated, rural agricultural area, to a mixed suburban environment. Population growth of 85% during the 1970s and from 20% to 30% during the 1980s and early 1990s (Middle Rio Grande Council of Governments, 1992) has relied entirely on development of ground water for a domestic water supply (Fig. 1). Increased ground-water withdrawals combined with a 2-year drought in 1995 and 1996 resulted in numerous dry wells and raised awareness of the potential for over-development of the area's limited ground-water resources. A thorough understanding of the hydrogeology of the Placitas area is essential to achieving sustainable ground-water development. Before detailed geologic mapping of the area in 1995 (Connell et al., 1995) and a comprehensive hydrologic study in 1997–1999 (Johnson, 2000), this understanding was hampered by a general absence of detailed hydrologic and geologic data and by the area's complex geology.

The Placitas area is geologically complex because it straddles the geologic boundary between the Sandia Mountains and the Albuquerque Basin of the Rio Grande rift. Major rift-margin faults, including the San Francisco-Placitas fault zone and numerous smaller faults, cut through much older (360–66 million years old) Paleozoic and Mesozoic sedimentary rocks, rotating them downward (to the north) below younger (23.7 million–700,000 years old) Santa Fe Group basin fill (Fig. 2). These faults behave both as barriers to and conduits for ground-water movement. Older layered rocks have been deformed by some faults into a nearly vertical orientation. In some cases, vertical, low-permeability rock layers such as fine-grained shales and mudstones form stratigraphic barriers that also compartmentalize ground water into small isolated aquifers.

This geologic setting of layered rocks with dramatically different aquifer properties, broken and deformed by faulting, is what makes identification of Placitas' aquifers such a challenge to scientists, well-drillers, developers, and home buyers. These characteristics are not unique to Placitas; they are quite common in other mountainous, developing areas of New Mexico such as the East Mountains and southeast Santa Fe County. By studying surface and subsurface geology, well hydrographs (measurements of ground-water levels over time), and chemical tracers in ground and surface water, hydrologists have identified an assortment of confined (under pressure) and unconfined (open to the atmosphere) aquifers near Placitas. These aquifers possess a wide range of water quality, productivity, ground-water age, and varying degrees of hydraulic connection and recharge (water replenishing an aquifer).

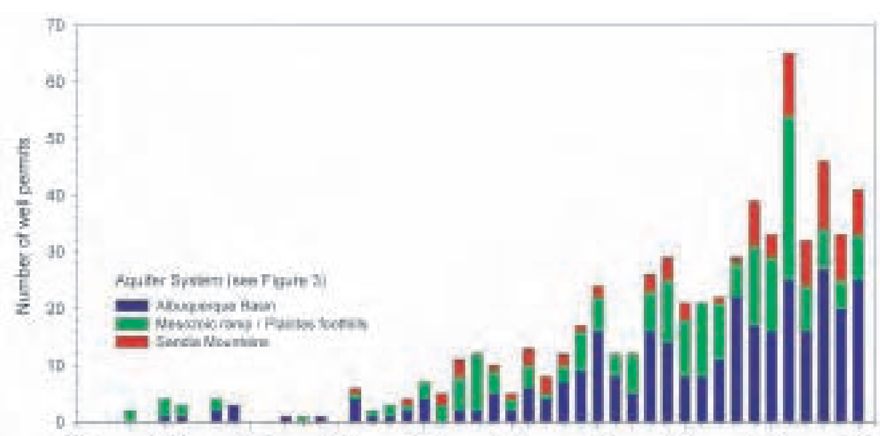

FIGURE 1—Number of wells drilled in the Placitas area, 1958–2000, from records of the New Mexico Office of the State Engineer.

Placitas' Aquifers

The Placitas area contains three distinct aquifer systems: the Sandia Mountains, the Placitas foothills (known as the Mesozoic ramp), and the Albuquerque Basin (Fig. 3). In general, large supplies of ground water are not available in the mountain system or in the Mesozoic ramp. Only aquifers in the Santa Fe Group deposits that fill the Albuquerque Basin are capable of supporting large-scale ground-water withdrawals.

The most important aquifer in the mountain system is contained in the Madera Limestone, the layered rock that caps the Sandia Mountains. This limestone aquifer stores and transmits water through fractures in the rock as well as small pores, and thus is called a dual-porosity aquifer (Johnson, 1999). Because the flow of ground water is concentrated along discrete fractures or cracks in the rock, its availability is highly variable, and dry holes are relatively common. On a regional scale, the Madera Limestone possesses very high transmissivity (it transmits large volumes of water) but relatively low storage. These are properties that allow the Madera Limestone to efficiently transmit fresh ground water from the Sandia Mountains down towards the basin, but which also limit the amount of water stored in the aquifer.

Exposures of Madera Limestone in the Sandia Mountains form major ground-water recharge areas that are fed by snowmelt, winter-spring precipitation, and surface water from Las Huertas Creek and other drainages. This recharge water flows through the limestone along fracture systems in the subsurface until it is intercepted by a low-permeability barrier such as the Placitas fault zone or a fine-grained rock, where it either discharges as spring flow, or continues on through a few permeable windows in the rock. Tunnel Springs, the Placitas Springs, and Old San Francisco Springs are examples of springs that discharge from the Madera Limestone along a fault barrier. This recharge water also possesses unique water chemistry characterized by dissolved calcium and bicarbonate, low concentrations of total dissolved minerals, a temperature less than 61° F (or 16° C, the area's mean annual temperature), a high dissolved oxygen content, and no significant trace elements. By mapping these chemical characteristics we have identified pathways for ground-water movement and aquifers that are connected to or isolated from sources of recharge.

The Mesozoic ramp is a region of older (240–60 million year old) sedimentary rock, situated in the Placitas foothills, that is broken and deformed by many faults. Ground water here is limited to isolated sandstone aquifers and rocks that are highly fractured. Rotation of layered rock by up to 65° has created a network of subvertical strip aquifers,

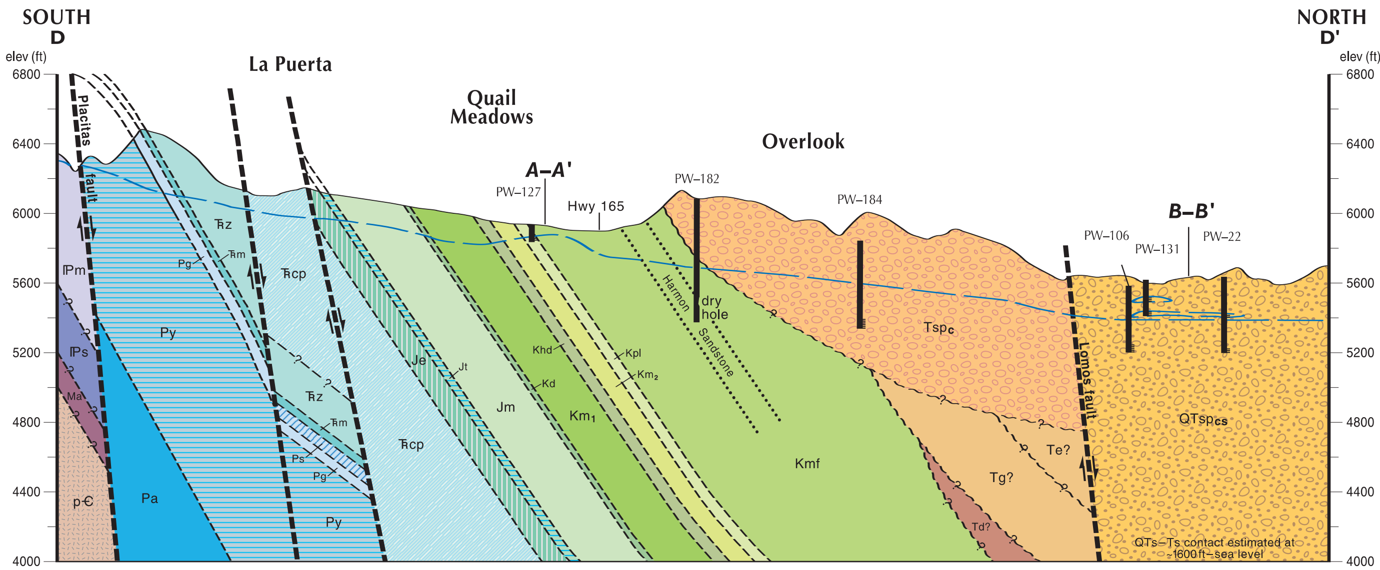

FIGURE 2—Geologic cross section through the La Puerta, Quail Meadows, and Overlook communities of Placitas showing subvertical strip aquifers layered between aquitards.

many of which are isolated by aquitards (geologic units incapable of transmitting significant quantities of water) of mudstone, shale, and siltstone, and by north-south faults (Fig. 2). Many of the aquifers produce ground water with elevated temperatures up to 77° F (25° C), low dissolved oxygen, and elevated concentrations of dissolved minerals (sodium, sulfate, iron, copper, manganese, zinc, and arsenic), all characteristics of very old water. Dating Placitas' ground water using carbon-14, a radioactive isotope of carbon, indicates a wide range of ages within this relatively small area, from recent to over 35,000 years (Fig. 3). This chemistry indicates that ground water in many of these isolated aquifers is disconnected from active recharge and has been sequestered for thousands to tens of thousands of years (Johnson et al., in press).

Ground-Water Mining

The age of ground water has important implications for water resource management and development. The ground-water ages shown in Figure 3 represent the average time elapsed since the water entered the aquifer. These ages indicate that much of the ground water stored in Placitas' aquifers is not actively recharged, and hence is susceptible to overdraft (withdrawal of ground water at excessive rates resulting in overdevelopment and other undesirable effects). Depleting ground water that is not actively recharged typically results in a progressive decrease in the amount of water stored in the aquifer, and when accompanied by a progressive decline in water levels constitutes ground-water mining. Whereas this practice may be necessary in certain circumstances, it is certainly not sustainable and can lead to other harmful consequences such as reduced flows to streams and springs, drying of wetlands, and land subsidence. On the other hand, ground waters that are actively recharged are part of the modern hydrologic cycle and are constantly being renewed. Exploitation of these sources is potentially sustainable.

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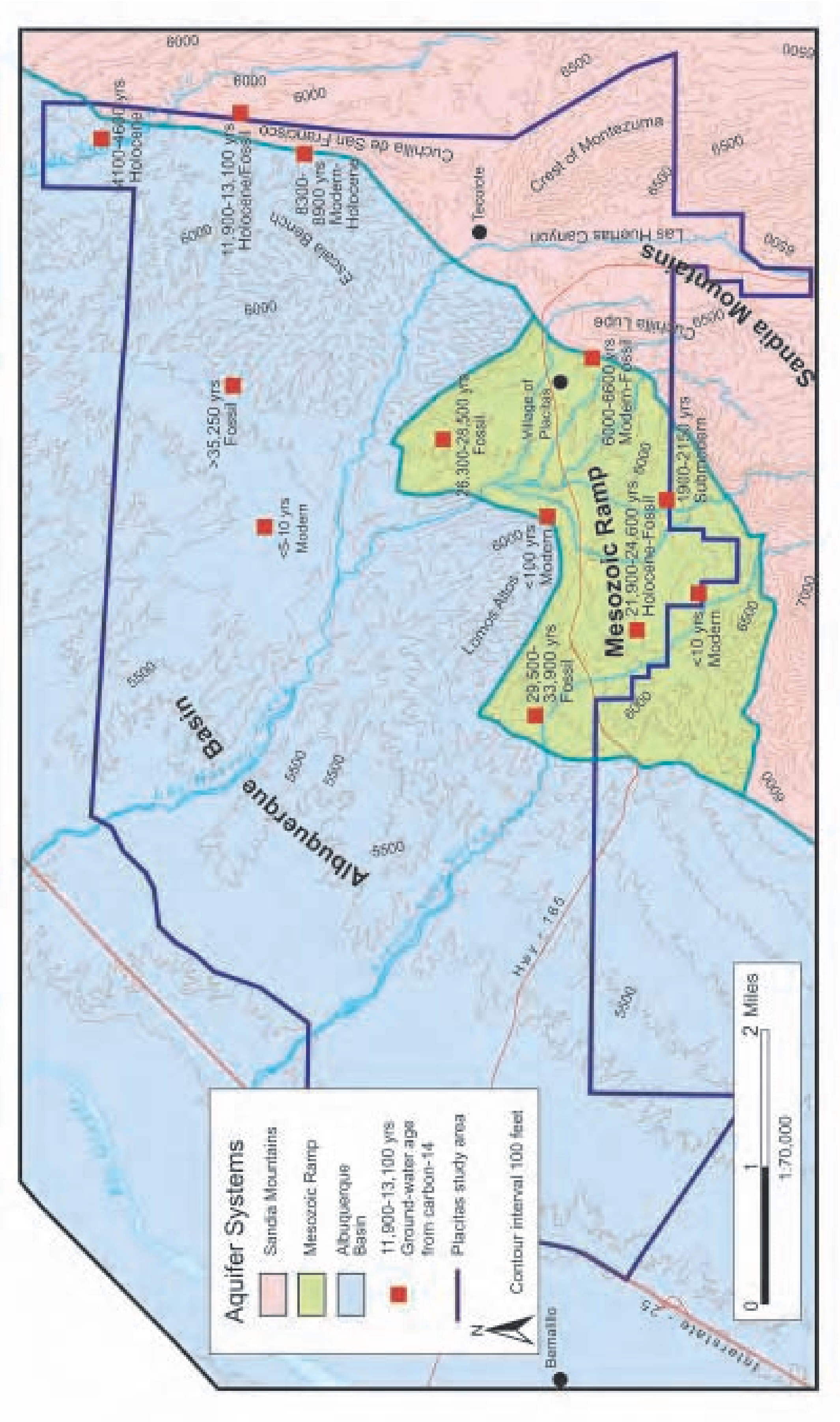

FIGURE 3—Ground-water ages in aquifers near Placitas, New Mexico.

Day Three

The Challenge of Sustainable Ground-Water Development

by *Peggy S. Johnson*, New Mexico Bureau of Mines and Mineral Resources

Ground water is one of New Mexico's most important geological resources. Withdrawals of ground water supply 90% of the state's drinking water. Ground water constitutes the state's principal store of fresh water and most of our future potential water supply. Most rural communities such as Placitas rely totally on ground water for their current and future domestic supply (Johnson, Geologic Limitations on Ground-Water Availability in the Placitas Area, this volume). Ground water is also linked to flow in rivers, streams, and springs and supports our limited but treasured riparian areas. Ground water is not a nonrenewable resource like a mineral deposit or a petroleum reserve, but neither is it completely renewable within a short time frame. Ground-water resources may appear ample, but availability actually varies widely, and only a portion of the ground water stored in the subsurface can be withdrawn economically without adverse consequences. In the past decade attention has been placed on how to manage New Mexico's ground water (and surface water) in a sustainable manner—that is, in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences (Alley et al., 1999). In this paper we examine the concept of sustainable development of ground-water resources, but first we must understand the aquifer.

Understanding the Aquifer

Aquifers are dynamic—Under natural conditions, aquifers are in a state known as dynamic equilibrium—that is, recharge or replenishment of the aquifer approximately equals discharge. Ground water moves along flow paths from areas of recharge, such as mountains, rivers, or arroyos, to areas of discharge, like springs, wetlands, and streams. Water withdrawn for human activities affects the amount and rate of movement of water entering, leaving, and stored in the system. Pumping from a well diverts ground water that was moving slowly to its natural, possibly distant, area of discharge. Whereas the source of water pumped from wells is primarily aquifer storage, eventually that diversion means a decrease in discharge to streams, springs and wetlands, and less water available to plants.

Recharge from precipitation continually replenishes ground water, but typically at much smaller rates than rates of pumping. In New Mexico the amount of recharge from precipitation is both small and relatively fixed, with estimates ranging from 0.03% to 20% of mean annual precipitation (Stephens et al., 1996). Water levels in undeveloped aquifers fluctuate seasonally and from year to year in response to natural changes in recharge (precipitation) and discharge. A seasonal rise and fall in water levels indicates that the aquifer is well connected to a seasonal source of recharge, such as snowmelt, presipitation, irrigation, or ephemeral streamflow. Significant recharge is extremely localized along streams, arroyos, mountain fronts, and faults. By mapping natural ground-water fluctuations, hydrologists can determine which aquifers, or portions of aquifers, are actively replenished. High ground-water use in areas of little recharge eventually causes widespread declines in ground-water levels and a significant decrease in storage in the ground-water reservoir.

Aquifers are complex—Aquifers are not simple,rather they are complex, three-dimensional flow systems, with subsystems at local, subregional, and regional scales (Fig. 1). The rate of movement of ground water through an aquifer ranges from 1 ft per day or greater to as little as 1 ft per year or even 1 ft per decade. Aquifer systems are made up of complicated arrangements of high and low conductivity aquifer units operating on scales of tens of feet to hundreds of miles within time frames of days to hundreds, thousands, or tens of thousands of years. Development of regional aquifers may take place over a number of years and the effects of ground-water pumping tend to manifest slowly over time. The full effects of ground-water development may not become obvious until undesirable effects are evident. It's no wonder that sustainable development of ground-water resources is a challenging and somewhat unpredictable process.

Ground-Water Mining in New Mexico

In some areas of New Mexico, decades of ground-water pumping have resulted in prolonged and progressive depletions of ground-water storage and declining water tables indicative of ground-water mining. For example, water level declines of up to 140 ft occurred in northeast Albuquerque between 1960 and 1992, a condition that will ultimately reduce flow in the Rio Grande raise grave concerns about drinking water supplies, riparian bosque, critical habitat, and land subsidence. Other mined ground-water basins include the Mimbres and Estancia Basins, portions of the Española Basin, and the Ogallala aquifer in eastern New Mexico. Ground-water development in the area surrounding Placitas, New Mexico has occurred at an exponential rate over the last 30 years (Fig. 2), resulting in water level declines of up to 120 ft in the area of Quail Meadows (Fig. 3). These declines in water levels, and associated reductions in storage, are large compared to natural fluctuations in water levels. Widespread pumping that results in regional water level declines can also result in other undesirable effects such as large decreases in

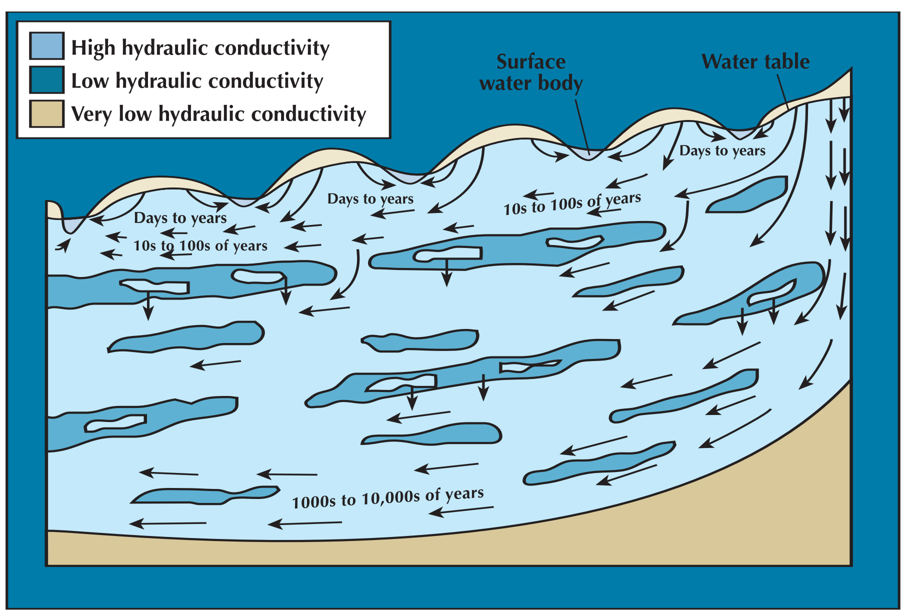

FIGURE 1— A regional ground-water flow system is made up of subsystems at different scales in a complex hydrogeologic framework (after Alley et al., 1999).

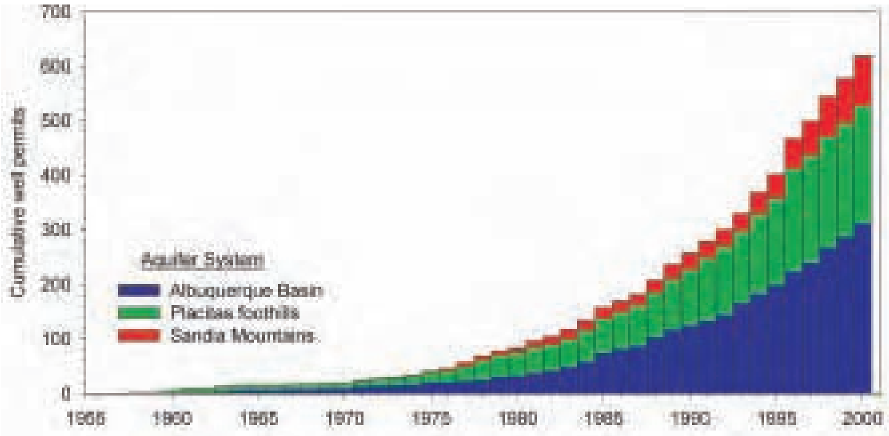

FIGURE 2—Exponential growth in number of wells drilled in the Placitas area, 1958–2000, from New Mexico Office of the State Engineer records.

aquifer storage, particularly in unconfined aquifers, shallow wells that go dry when the water level drops below the screened or open intervals of wells, increased costs of pumping or drilling of additional wells, less water flowing to rivers, streams, springs, and wetlands, less water available for vegetation as the water table declines, and increased risk of a pumping well intercepting contaminated or poor-quality ground water.

Ground-Water Sustainability and Public Policy

Implicit in the concept of ground-water sustainability is a definition of unacceptable consequences, which can be subjective and open to public debate. The various effects listed above illustrate the potential societal costs of ground-water mining and, by a public standard, may be defined as unacceptable. The tradeoffs between ground-water pumping and environmental impacts must be evaluated on a public stage with input from scientists, engineers, citizens, and policy makers. Scientists and engineers must provide the necessary, high-quality hydrogeologic data (Table 1) and sound evaluations of aquifers and ground-water systems. Each ground-water system and development scenario is unique and requires a site-specific analysis in the context of local water, cultural, economic, and legal issues. Citizens, through public dialogue, must make known their vision of the community's future and provide direction as to what constitutes unacceptable consequences. Policy makers play a crucial role and must contribute on multiple fronts:

(1) Commit to fund necessary data collection and objective scientific evaluation
(2) Solicit public participation regarding water use and environmental priorities
(3) Incorporate scientific findings and public opinion into a water management strategy that honors both
(4) Continue to monitor the aquifers and extend the hydrologic database through time
(5) If necessary, revise the plan to achieve sustainable development and minimize or eliminate unacceptable consequences.

The key challenge is to present clear and accurate hydrologic data and frame hydrologic implications of ground-water development and management strategies so they can be properly evaluated. Scientists are continually challenged to refine their analyses and address new problems and issues when they arise, using improved and innovative techniques. Citizens are challenged to self-educate and participate in public forums on water issues. Decision makers are challenged to evaluate alternative management strategies and implement those that honor both sound scientific data and public welfare (as defined by local residents, not outside interests). These are daunting challenges for everyone—challenges that are far easier to ignore than address. However, the path and process are well defined. The first step is a realization that if we choose a path of ignorance, future generations will suffer the unacceptable consequences.

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TABLE 1—Types of hydrogeologic data required for analysis of ground-water systems (modified from Alley et al., 1999).

Physical Framework

Topographic maps showing the stream drainage network, surface-water bodies, landforms, and locations of structures and activities related to water
Geologic maps of surficial deposits, bedrock, and geologic structures (faults and folds)
Hydrogeologic maps showing extent and boundaries of aquifers and confining units
Saturated-thickness maps of unconfined (water table) and confined aquifers
Maps showing average hydraulic conductivity, transmissivity, and variations in storage coefficients for aquifers and confining units
Estimates of ground-water age at selected locations in aquifers

Hydrologic Budgets and Withdrawals

Precipitation and evaporation data
Streamflow data, including measurements of gains and losses of streamflow
Maps of the stream drainage network showing extent of normally perennial flow, normally dry channels, and normally seasonal flow
Estimates of total ground-water discharge to streams
Measurements of spring discharge
Measurements of surface-water diversions and return flows
Quantities and locations of interbasin diversions
History and spatial distribution of pumping rates in aquifers
Amount of ground water diverted for each use and the quantity and distribution of return flows
Well hydrographs and historical water-level maps for aquifers
Location of recharge areas and estimates of recharge

Chemical Framework

Geochemical characteristics of the aquifer materials, and naturally occurring ground water
Distribution of water quality
Temporal changes in water quality, particularly for contaminated or potentially vulnerable unconfined aquifers
Sources and types of potential contaminants
Chemical characteristics of artificially introduced waters or waste liquids
Maps of land cover and land use
Streamflow quality, particularly during periods of low flow

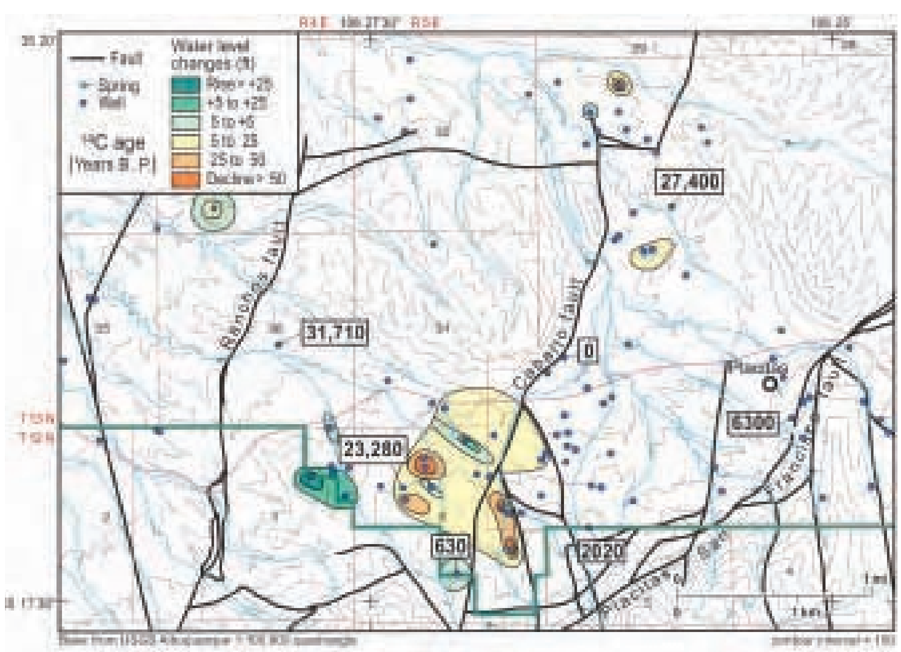
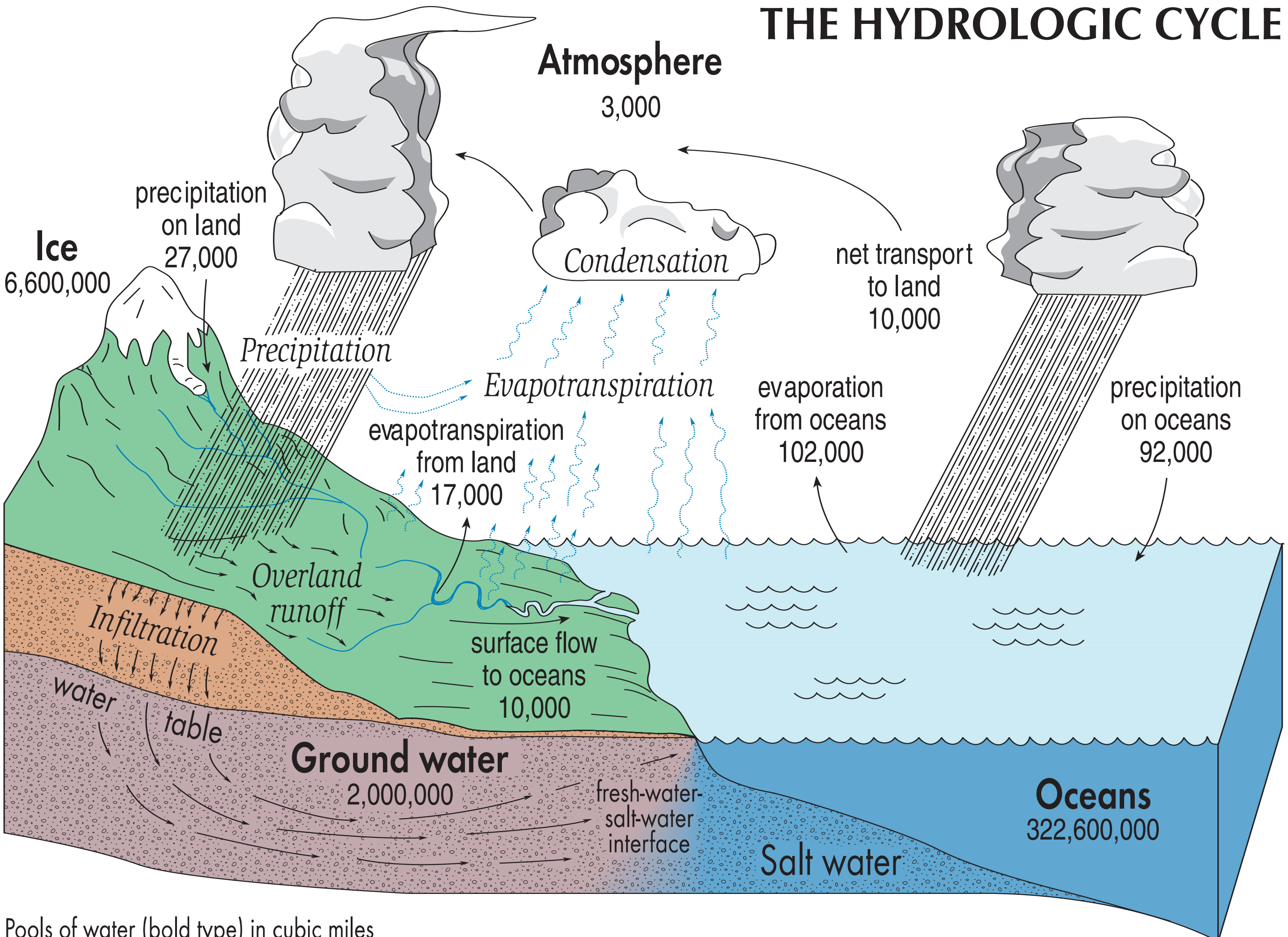


FIGURE 3—Long-term water level changes in the Placitas area.

Day Three

THE HYDROLOGIC CYCLE



Pools of water (bold type) in cubic miles
Fluxes between pools in cubic miles per year