Chapter 4
Geology, Climate, Land, and Water Quality

Douglas G. Fox
USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado

Roy Jemison
USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Flagstaff, Arizona

Deborah Ulinski Potter
USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Albuquerque, New Mexico

H. Maurice Valett
University of New Mexico, Albuquerque, New Mexico

Ray Watts
U.S. Geological Survey, Fort Collins, Colorado

GEOLOGY

The Middle Rio Grande is part of the chain of structural basins, known as the Rio Grande depression, that extends from the San Luis Valley in Colorado to El Paso, Texas, and through which the Rio Grande flows (Chapin and Seager 1975). Bryan (1938) is credited with designating this reach as the Rio Grande "depression," because of his early research and the level of understanding he provided on the geology of the region. This area is also known as the Rio Grande "rift," a term coined by Kelly (1952), based on his belief in the possibility of significant longitudinal displacement in the "trough" or depression (Baltz 1978). The Rio Grande rift will be the term used in this discussion.

The Middle Rio Grande, as presented in this chapter, includes the area of the Rio Grande rift between Cochiti Dam, southwest of Santa Fe and Elephant Butte dam, south of Socorro, New Mexico (refer to Fig. 2 in Chapter 1). The linear distance between these locations is about 257 km. The Middle Rio Grande includes the four principle basins of Albuquerque, Socorro, La Jencia, and San Marcial (Fig. 1). The Middle Rio Grande is located in the counties of Socorro, Valencia, Bernalillo, and Sandoval, with small extensions into Torrance, Santa Fe, Cibola, Rio Arriba, and Catron counties.

The principal landforms of the Middle Rio Grande include: (1) pediments, (2) dissected slopes, (3) fault scarps, (4) terraces, (5) alluvial slopes, (6) alluvial fans and cones, (7) major stream floodplains or valley bottoms, (8) eolian blankets and dunes, and (9) volcanic fields, ridges, and cones (Kelly 1977; Fitzsimmons 1959).

CHANNEL AND BASIN DESCRIPTIONS

Lagasse (1981) described the channel of the Middle Rio Grande as a shifting sand substratum with low, poorly defined banks. The floodplain contains a mixture of cottonwood, willow, Russian olive, and saltcedar, which together form a dense growth of riparian woodland known as bosque interspersed with pasture and cultivated land. The configuration of the river may be described as one of low sinuosity with some straight reaches. Formation of sediment bars in the channel during low-flow periods and, in particular, during the recession of flood flows, together with rapid growth of vegetation, generally determine the channel configuration within the levees. The slope of the river drops about 0.95 m/km from Cochiti

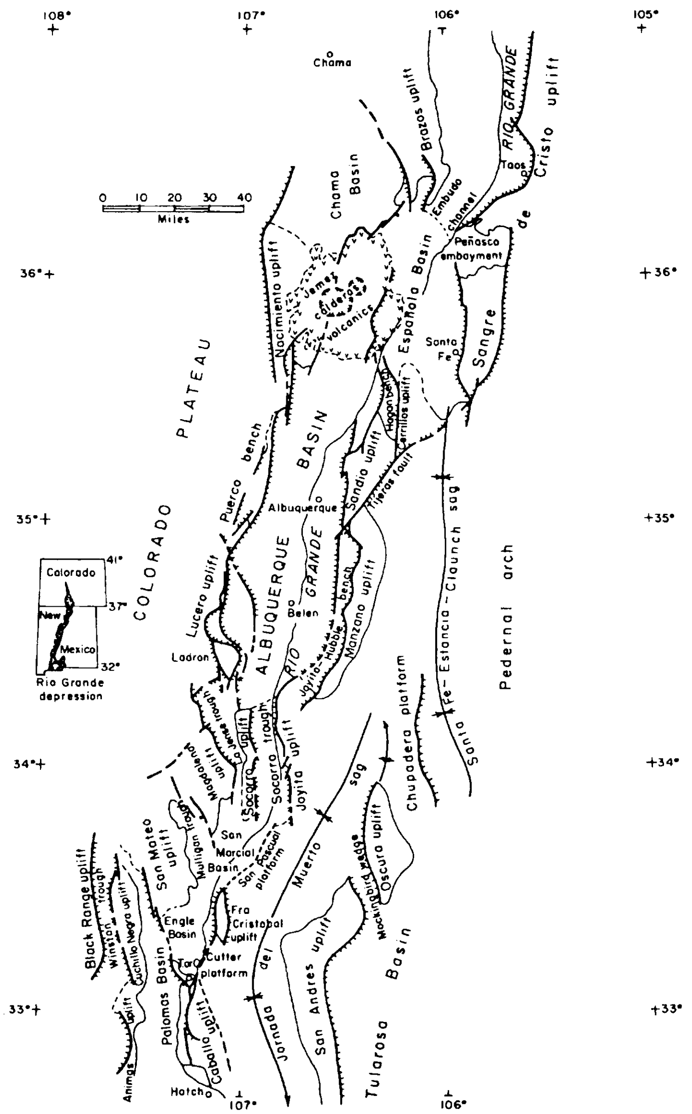

Figure 1.—Tectonic map of Rio Grande rift system (Kelly 1977).

to just below Albuquerque, and about 0.76 m/km from just below Albuquerque to the confluence of the Rio Puerco. Within the unstabilized floodway, the channel has virtually no banks, and the bed of the river is at or above the level of areas outside the levees due to sediment deposition between the levees.

The Middle Rio Grande is broken by short canyons or narrows at San Felipe, Isleta, and San Acacia, which in turn define the subvalleys or basins of Santo Domingo, Albuquerque, Belen, and Socorro. The diversion dams at Angostura, north of the Jemez River confluence and Isleta, midway between Albuquerque and Belen, act as "geologic" controls of river base level and limit upstream and downstream river response of the Rio Grande.

Albuquerque Basin

The Albuquerque Basin is the largest and most important basin in the Middle Rio Grande. The importance of this basin is that it houses the aquifer from which most of the city of Albuquerque draws water. The geology of the Albuquerque Basin has been the subject of numerous studies and publications (Thorn et al. 1993; Kelly 1977). Hawley and Haase (1992) present the status of the geology as it relates to the hydrology of this area in "Hydrogeologic Framework of the Northern Albuquerque Basin." Thorn et al. (1993) summarized much of Hawley and Haase's work in "Geohydrologic Framework and Hydrologic Conditions in the Albuquerque Basin, Central New Mexico." The discussion presented here on the Albuquerque Basin is edited from the work of Thorn et al. (1993), except where noted. Of note is the conclusion from these recent studies of groundwater: that the water supply for the City of Albuquerque and surroundings is considerably more restricted than earlier studies suggested.

The Albuquerque Basin, located in the central part of the Rio Grande rift, is the third largest basin in the rift. The basin extends about 100 miles in length from north to south and about 35 miles in width, with an area of about 7,925 km^2. The northern boundary of the Albuquerque Basin, and the Middle Rio Grande, are defined by the Nacimiento and Jemez uplifts. The Nacimiento Uplift is characterized by Precambrian plutonic and metamorphic rocks overlain by Paleozoic strata. Cenozoic volcanic rocks form the Jemez uplift (Hawley and Haase 1992). The topographically prominent eastern boundary is the eastward-tilted fault blocks of the Sandia, Manzano, and Los Pinos uplifts; the Sandia uplift is the largest and highest. These three uplifted areas are composed of Precambrian plutonic and metamorphic rocks unconformably overlain by Paleozoic limestone and sandstone (Hawley and Haase 1992). The southern boundary is defined by the Joyita and Socorro Uplifts. This area, often referred to as the "San Acacia constriction," is formed by the convergence of the eastern and western structural boundaries of the Albuquerque Basin. The Ladron and Lucero uplifts define the southwestern boundary. Precambrian granite and metamorphic rocks compose the Ladron Uplift. The westward-titled Lucero uplift is composed of Paleozoic limestone, sandstone, and shale capped by late Cenozoic basalt flows (Hawley and Haase 1992). The topographically subdued northwestern boundary is defined by the Rio Puerco Fault Zone.

The fill material in the Albuquerque Basin is mostly Cenozoic fill deposits of the Santa Fe Group. The Santa Fe Group was deposited during the middle Miocene to early Pleistocene (15 to 1 Ma). During that time the Albuquerque Basin received alluvial sediment from the adjacent highlands and fluvial sediments from Northern New Mexico and southern Colorado. The current sedimentary sequence is intertonguing basin-floor fluvial deposits and piedmont-slope alluvial deposits. Within the Albuquerque area, the source for the piedmont-slope alluvial deposits was the Sandia Mountains east of the City; they provided, for the most part, weathered granitic and limestone material to the basin. The fluvial deposits consist of a variety of material characteristic of the geology north of the Albuquerque Basin, including volcanic rock fragments from volcanic centers north and west of the Albuquerque Basin.

Hawley and Haase (1992) divided the Santa Fe Group and post-Santa Fe Group deposits into four hydrostratigraphic units and 10 lithofacies units. The hydrostratigraphic units consist of major valley and basin-fill units that are grouped on the basis of origin and age of a stratigraphic sequence of deposits. Examples include basin-floor playa, ancestral river valley, alluvial-fan piedmont, and present river valley depositional environments. Time-stratigraphic classes include units deposited during early, middle, and late stages of basin filling (lower, middle, and upper parts of the Santa Fe Group deposits, respectively). Post-Santa Fe Group valley and basin-fill deposits consist of channel and floodplain deposits beneath the modern inner valley or preserved as alluvial terraces (Hawley and Haase 1992). The 10 lithofacies represent different depositional settings, each recognizable by characteristic bedding and compositional properties having distinctive geophysical, geochemical, and hydrologic characteristics (Hawley and Haase 1992). Also dispersed throughout the Santa Fe Group are mafic volcanic flows and ash beds.

Thickness of the Santa Fe Group ranges from less than 2,400 to greater than 3,000 feet along the margins of the basin to 14,000 feet in the central part of the basin. Santa Fe Group deposition ceased about 1 million years ago when the Rio Grande and Rio Puerco started to cut their valleys (Hawley and Haase 1992). Post-Santa Fe units were deposited during a series of river incision and backfilling episodes; the latest cut and fill episode of the Rio Grande and Rio Puerco systems produced the channel and floodplain deposits of the present inner valley (Hawley and Haase 1992). For the last 10,000 to 15,000 years, the river valleys have been aggrading due to tributary input of more sediment than the regional fluvial system can remove. This young valley fill, as much as 61 m thick, functions as a shallow source of water and as a connection between the surface-water system and the underlying Santa Fe Group (Hawley and Haase 1992).

Socorro Constriction

The Socorro Basin or constriction as defined by Kelly (1952) extends about 64 km from the San Acacia channel on the north to the San Marcial basin on the south. South of the Albuquerque Basin there is, in addition to a pronounced narrowing of the Rio Grande rift, a marked change in the structural alignment of the bordering uplifts. Furthermore, volcanic rocks are prominent especially along the west side of the depression. The Socorro Channel is the main linkage of the Albuquerque Basin with the San Marcial basin through this constriction. The channel lies between the Joyita uplift on the east and the Socorro uplift on the west. The Rio Grande rift along this channel is only 8 to 16 km wide. Pre-Cambrian rocks are at the surface locally in the bordering uplifts (Kelly 1952). Work by Bruning (1973) has shown that the Socorro Basin is actually part of a structure known as the Popotosa Basin which is almost 64 km wide. Extensive late Tertiary to Quaternary erosion surfaces are developed on both sides of the Rio Grande in the area of the Socorro constriction.

The basin fill in this area is part of the Popotosa Formation, which is part of the Santa Fe Group (Chapin and Seager 1975; Baldwin 1963). Denny (1940) and Bruning (1973) provide in-depth descriptions of the Socorro Basin. In addition to fan, playa, and transitional facies (plus interbedded volcanic rocks), the Popotosa Formation contains strikingly different compositional facies. The bulk of the unit consists of reddish, well-indurated volcanic conglomerates composed mainly of clasts of basaltic andesites and ash-flow tuffs derived from the upper part of the Datil volcanic section and from the La Jara Peak Basaltic Andesite (Chapin and Seager 1975).

The Socorro area and the Las Cruces area are anomalous. They are the only areas along the Rio

Grande rift where horsts have been elevated through several thousand feet of late Cenozoic sedimentary fill near the centers of basins. The combination of thin-skinned distension, high heat flow, and other geophysical anomalies suggests the possibility of major intrusions into the rift structure (Chapin and Seager 1975).

San Marcial Basin

South of the Socorro Basin constriction the Rio Grande depression again widens into an irregular basin about 48 km long and 16 to 24 km wide. It is terminated on the south by the Pankey Channel which connects it with the Engle Basin to the southwest. The main axis of the San Marcial Basin trends essentially south-southwest and coincides with the Rio Grande. It is bounded on the east by a low edge of the Jornada del Muerto that lies to the east. This border is here termed the San Pascual Platform, and may be a sort of sub-alluvial bench surmounted by local basalt flows. The sub-alluvial bench of Santa Fe sediments probably does not connect with deep Pliocene basins in the Jornada del Muerto. The western border is more complicated and marked by the in-echelon Socorro, Magdalena, and San Mateo uplifts. The intervening troughs or down-thrown parts of the fault blocks merge with the San Marcial basin and appear to be embayments from the latter. The extensive, although much dissected, erosion surface that exists on both sides of the Rio Grande in the San Marcial Basin is largely cut upon slightly deformed Santa Fe beds (Kelly 1952).

The Rio Puerco Drainage

The Rio Puerco drainage is a major drainage that merges with the Rio Grande south of Albuquerque. The Rio Puerco Basin is more than 200 km long, encompassing approximately 19,036 km^2 straddling the boundaries among the Colorado Plateau, Southern Rocky Mountains, and Basin and Range physiographic provinces. The upper portions of the drainage basin are underlain by bedrock, whereas the middle and lower portions are underlain by thick, semi-consolidated deposits in the Albuquerque structural basin. Although most of the drainage basin is less than 2,000 m above sea level, the headwaters lie in the Nacimiento Mountains (up to 3,176 m), the Zuni Mountains (2,281 m), and Mount Taylor (3,345 m) (Popp et al. 1988). A principal erosional feature along the Rio Puerco drainage is a series of volcanic plugs that form prominent peaks above the softer Cretaceous sediments (Fitzsimmons 1959). It is assumed that the tops of the plugs represent former positions on the Rio Puerco Valley floor, and that the Mesozoic bedrock (shales and sandstones) and alluvial material through which the basalt was extruded were subsequently stripped away by the river (Slavin 1991).

The Rio Puerco is presently in a phase of incising in its northern reaches. Photographic evidence from the late 1880s indicates that the river has incised up to 15 m (50 ft) in 100 years, an extremely rapid incision rate. Paleochannels within the walls of the river's channel indicate that it has undergone many cycles of cutting and filling. It is possible that the incision of the Mesozoic shales and alluvial material surrounding the Puerco necks was similarly rapid, and that an extraordinarily fast base-level change is recorded in the surfaces of the Rio Puerco valley. It is conceivable that 400 m or more (>1,312 ft.) of bedrock and alluvial material were removed over a very short span of time (e.g., tens of thousands to only thousands of years, based on the above incision rate for the alluvial material eroded over the past 100 years). Even if the erosion of 400 to 500 m (1,312–1,640 ft.) of material has occurred over as much as the last 2.2 million years, these postulated incision rates may force a reconsideration of previously held notions that geologic processes occur slowly over long periods of time (Slavin 1991).

The general features of the landscape as we see them today began to appear in the Cretaceous as a consequence of incipient Laramide deformation. The first deformation may have been by warping, but faulting soon followed. Mountainous areas formed to the north and the Rio Grande depression began to appear on the east in the middle Tertiary. Erosion of the highlands caused filling of the basins and, as the mountains were worn down, erosion surfaces developed arroyos and edges of older and younger beds were beveled. Subsequent uplift has caused streams to cut into these surfaces and to initiate at lower levels new erosional surfaces that have not yet had sufficient time to become large regional features. Faulting and accompanying volcanic eruptions have occurred throughout the Tertiary and Quaternary. Lavas intercalated between basin-filling sediments and faulted lavas, and basin sediments attest to continued and contemporaneous faulting, sedimentation, and volcanic activity (Fitzsimmons 1959).

The major landscape features of the Rio Puerco are sloping valley margins commonly cut into bedrock or in semi-consolidated basin fill. The valley floor is underlain by thick alluvial deposits and the incised axial stream channel. The Rio Puerco and its major tributaries have developed distinct geomorphic features within confined arroyo walls that range from 8 to 13 m high and 145 to 245 m wide (Popp et al. 1988). Love et al. (1983) and Shepherd (1976) described the inner channel as a complex of meanders, straight reaches, and slightly arcuate reaches. The inner channel and floodplain include sandbars and ripple marked surfaces along the floor, slightly finer-grained sandbars along the margins of the inner channel natural levees along the outer margins, and coppice dunes.

The Rio Puerco is an ephemeral stream for most of its length and flows only in direct response to rain or snowmelt. This stream is infamous for large discharges and high sediment loads. It has been estimated that the Rio Puerco contributes more than 50 percent of the sediment load to the Rio Grande in central New Mexico while carrying less than 16 percent of the water (Waite et al. 1972; Popp and Laquer 1980). The Rio Puerco is also highly mobile. Studies of the lower channel (Young 1982) determined that more than 90 percent of the lower channel has shifted laterally since 1954. In this same time, the channel changed from being relatively wide with low banks and unvegetated in the 1930s to relatively narrow with high banks in the 1980s.

The lower Rio Puerco is a losing stream, that is, it loses water to its bed. A flow of as much as 0.14 m^3/s at the stream gauge along Highway NM–6, west of Los Lunas, is lost to seepage and evaporation before it reaches the stream gauge at Bernardo (Heath 1983). In this reach west of Belen, the permanent water table is 10–13 m below the base of the modern channel, but there are seasonally fluctuating perched water tables on clay layers within the alluvium above the permanent water table. These perched water lenses tend to be recharged from the Rio Puerco when it is flowing on loose sand and can be depleted by seepage to lower levels and by transpiration by tamarisks and willows.

The channel shape of the lower Rio Puerco reflects repeated attempts at adjustment to extremely variable flows and an extremely high sediment load. Flows much larger than bankfull tend to scour the base of the channel and the floodplain locally. Smaller flows tend to build sand bars attached to both sides of the channel and to aggrade the floor of the channel. The dynamics of the Rio Puerco arroyo system will be discussed in greater detail below.

HUMAN ACTIVITIES, GEOLOGY, AND THE RIO GRANDE

Over 10,000 years of human occupation is preserved in the Rio Grande rift. This occupation was and continues to be intimately related to the geological processes. The rifting that created the Rio Grande trough concentrated the runoff and created a drainage corridor and a perennial water source (Ware 1984).

The rift almost certainly influenced the seasonal movements of early hunters and gatherers in northern New Mexico. The region's first PaleoIndian inhabitants were undoubtedly drawn to the water source, as were the herds of Pleistocene animals they hunted. As water became increasingly scarce during the millennia-long droughts that followed the close of the Pleistocene, the river exerted an important influence on settlement patterns and seasonal population movements.

The rift concentrated important resources other than water. Volcanism associated with rifting produced obsidian for stone tools, altered land forms, and created elevations, ecological diversity, and a greater variety of wild plant and animal resources. The floodplain of the Rio Grande eventually attracted farming settlements. When large areas of the Colorado Plateau were abandoned by prehistoric farmers during the first centuries of the present millennium, many of those who were displaced migrated to the rich bottomlands of the Rio Grande and its tributaries, where there was perennial stream flow and longer growing seasons (Ware 1984).

The Effect of Dam Construction on the Middle Rio Grande

Dams were constructed across the Rio Grande at Elephant Butte, Cochiti, Angostura, and Isleta to control river flow for irrigation, flood control, and sediment detention. Studies near Elephant Butte and Cochiti dams have shown that these dams have had significant effects on the Rio Grande channel above and below the locations of the dams.

Elephant Butte Dam

Elephant Butte Dam, completed in 1916, was built to provide continuous and regulated river flow to the agricultural districts downriver from the dam.

The response of the Rio Grande channel, below the dam, was monitored from 1917 to 1932. After the closure of the dam there were two primary sources of sediment for flows through the Rio Grande below the dam: riverbed scour by the clear water released from the reservoir, and tributary inflow. The material derived from the steep-sloped, ephemeral tributary channels (arroyos) ranged from sand and gravel to boulder size, and was deposited in a fan or delta at the tributary outlet, where it was available for transport by main channel flows. Scour of the river channel itself by clear water released from storage was considered to be the principal sediment source, particularly in the sand size range. It was expected that this would remain the primary source of sands so long as the readjustment of the river channel to the changed conditions of clear regulated flows continued (Lagasse 1981).

Where an arroyo or tributary deposited directly into the main channel in a valley section below Elephant Butte Dam, the coarser material, which was beyond the competence of regulated main channel flows, forced the Rio Grande channel away from the tributary outlet through erosion of the opposite bank. Where the tributary channel entered the Rio Grande in a canyon section, the deposits of heavier debris created obstructions in the river channel, causing backwater above and rapids over the tributary delta. Regulated high flows were not of sufficient magnitude or duration to transport this coarser material downstream. Thus, arroyo and tributary deposits created base-level controls along the mainstream and strongly influenced the processes of degradation and aggradation (Lagasse 1981).

An analysis of the effects of clear-water scour along the Rio Grande below Elephant Butte Dam using successive cross sections indicated that there was a lowering of the river channel near the dam of approximately 0.6 m during the first 15 years of reservoir operation (Lagasse 1981).

The Rio Grande above Elephant Butte Reservoir is aggrading. The cause of this is, in part, the raising of effective local base level by delta building in the lake. This is not the only cause of aggradation, however, and probably not the most important. Arroyo cutting, contributing great qualities of sediment from tributary streams, may be the most significant process of all. Other causes are: windblown silt, increased loss of water because of domestic and irrigation usage, and prevention of flooding by artificial levee building, thus preventing a natural discharge of debris flow over the floodplain and consequently confining all aggradation to the channel. Measurements collected from 1936 to 1941, along the course of the Rio Grande from Cochiti Dam to the head of Elephant Butte Reservoir, indicated that the average annual increment of sediment added to the channel was about 15 cubic hectometers (Happ 1948). About half of that settled in the 23 km stretch immediately above the head of the lake (Fitzsimmons 1955). This will be discussed further in the section on arroyo dynamics.

Cochiti Dam

Cochiti Dam was built in November 1973. Cochiti Dam permits control of the main stem of the Rio Grande above the Middle Valley. This dam was originally intended for flood control and sediment control only. Multipurpose development objectives included arresting damaging flood flows, retaining sediment, and inducing degradation. Concern for recreation led to a modification of the authorization, and a permanent pool has been formed.

The floodway between Cochiti and Bernardo is generally confined by levees and averages 458 m wide through intensively developed rural and urban areas. The Bureau of Reclamation and the Corps of Engineers installed jetties in this reach, varying the density and widths as guided by hydraulic model studies. Design channel widths decrease in a downstream direction from 274 m in the Cochiti reach to 168 m at Bernardo. Operated in conjunction with upstream reservoirs, this channel work was intended to reverse the trend of aggradation and to allow the channel to degrade back to essentially a 1936 condition.

Before construction of Cochiti Dam and upstream tributary dams, the floodway of the Rio Grande was aggrading at rates as high as 0.6 m every 50 years near Albuquerque and as much as 5 m in 50 years near San Marcial. The ultimate result of aggradation is an increase in the height of the river bed or floodway above the adjacent flood plain. By 1960, the river channel near Albuquerque was 1.8 to 2.4 m above the elevation of lands outside the levees. Woodson and Martin (1963) provide an excellent summary of the effects of the Rio Grande Comprehensive Plan on the river regime throughout the middle valley of the Rio Grande. As of 1963 it was apparent that the "Rio Grande within the Middle Valley is still an aggrading stream, and construction of the floodway has not halted aggradation. Aggradation has occurred in amounts varying from practically zero in the Cochiti Division at the upstream end of the valley to a maximum of about 0.01 m per year in the Albuquerque Division" (Woodson and Martin 1963: 359).

Lagasse (1981) reported on a qualitative analysis of the effects of the construction of the Cochiti Dam on the Rio Grande. In the Cochiti to Isleta reach, sediment inflow from arroyos and tributaries has dominated the response of the main-stem Rio Grande to altered conditions of flow and sediment transport following closure of Cochiti Dam. Regulated flows of the post-dam period generally are not capable of transporting the coarser sediment load and volume of material carried to the main stem by arroyos and tributaries. Between Cochiti and the Jemez River, deltaic deposits at the confluence of tributaries and arroyos are sufficiently stable to influence planform, to create reaches of base-level control, and to influence the processes of aggradation, degradation, and armoring on the Rio Grande.

The reach immediately below the dam from Cochiti to Galisteo Creek had essentially completed adjustment to the closure of Cochiti Dam by 1975. Degradation and armoring progressed downstream through the San Felipe reach, and by summer 1979 the upper portion of the study reach had attained a level of stability yet to be achieved in the study area below the Jemez River. The Cochiti to Isleta reach of the Rio Grande will continue to respond to the closure of Cochiti Dam. Even the upstream reach that has adjusted to the altered conditions of flow and sediment transport will experience sequences of aggradation and degradation as sediments move through the system.

Recent evidence indicates that arroyos and tributaries below the Jemez River will play an increasingly important role in main-stem processes as degradation and armoring progress downstream. Response in the lower portion of the study reach will eventually parallel that above the Jemez River. However, the level of stability between the Jemez River and Isleta may never reach that of the Cochiti to Angostura reach, primarily because tributaries and arroyos with a drainage area necessary to influence main-stem processes are less common below Angostura.

The response at the Jemez River confluence supports the conclusion that the base level of the main stem is extremely sensitive not only to coarse material carried in from steeper arroyos, but also to a large volume of finer material contributed by a major tributary. As a result, a decision to establish a permanent pool at an existing dam on a major tributary or to construct sediment-detention dams on smaller arroyos must be supported by a detailed analysis of potential response of the main-stem Rio Grande.

During the extended low-flow period following closure of Cochiti Dam, the well-developed gravel armor above Angostura and stabilization of point bars and closure of chute channels by vegetation "locked" the Rio Grande into the low-flow channel pattern. Flows in excess of 170 m^3/s were required to initiate a transition to a high-flow channel pattern. To prevent the development of a channel pattern "locked in" to low-flow conditions and recurrence of problems associated with the April-July 1979 sustained high flows, releases from Cochiti Dam of about 170 m^3/s should be scheduled annually.

Processes set in motion by the closure of Cochiti Dam will eventually limit the effectiveness of the existing jetty fields. In the post-dam period less frequent inundation of floodplain areas, a reduction in sediment supply from major source areas such as the Jemez River, and degradation and armoring in the upstream channel all dictate against the installation of new jetty fields for channel stabilization. As the Kellner jetties become a less effective device for channel stabilization in the post-dam period, protection of the banks by vegetation will become increasingly important. Control of the beaver community along the banklines may be required, and traditional flood-fighting techniques that involve cutting of trees along the bankline should be reconsidered.

The problem of predicting river response below a dam and the extent to which development of an armor layer will limit degradation is extremely complex. While it is recognized that bank erosion, discharge variability, meandering, and sediment inflow from tributaries affect channel response below dams, analytical techniques currently available in the literature do not address response in the complex environment implied by these variables. Physical process computer modeling offers the most promising approach to solving this complex problem.

GEOLOGY AND ENVIRONMENTAL CONCERNS

The Middle Rio Grande along with the whole of New Mexico faces a special set of environmental problems associated with rich mineral resources, a dry climate, and vast areas of low population. Complex interactions between geology and environmental concerns involve geologic processes that have adverse effects on human activities and our use of mineral, land, and water resources. Geologic processes include moderate-intensity earthquakes, surface subsidence due to rock solution, stream floods, debris flows, and landslides. Geologically related human impacts on the environment include surface and subsurface extraction of economic mineral deposits (primarily energy minerals), groundwater development, construction of dams and power plants, disposal of hazardous wastes, and establishment of large-area reserves for military operations and scientific research (Hawley and Love 1981).

Geologists have a major role in helping to solve environmental problems resulting from effects of geomorphic processes and the development of mineral, water, and land resources. Inventories must be made of these processes and resources in order to put complex process-resource-human interactions in proper space and time perspective. Guidelines can then be formulated for mitigation or prevention of geology-related problems. For example, mined lands need to be reclaimed, cities need to be planned, and sites need to be selected for hazardous waste disposal (Hawley and Love 1981).

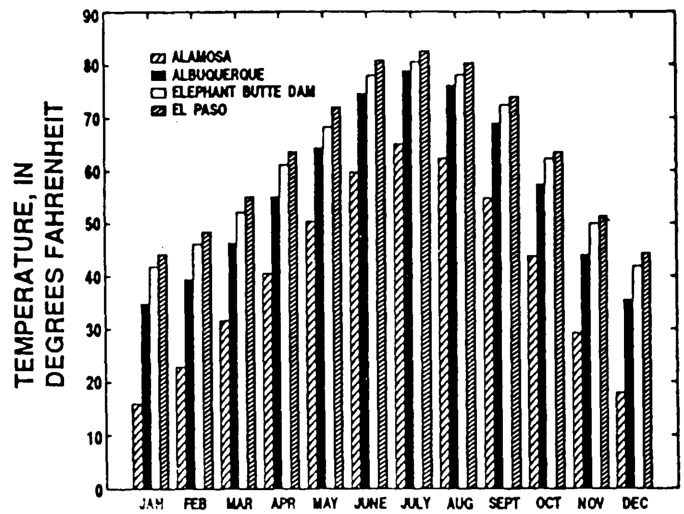

Figure 2a.—Mean monthly temperature for selected sites, 1951-1980 (from Ellis et al. 1993; permission to reprint granted by American Water Resources Association).

CLIMATE

Dorroh (1946) presents data for average annual and seasonal precipitation in New Mexico. His results illustrate that two factors, topography and general atmospheric circulation patterns, exert the major influences on climate of middle Rio Grande region. Thornthwaite et al. (1942) identified five principal source regions of air contributing to the Southwest climate: (1) Cold Dry Continental; (2) Cool, Moist North Pacific; (3) Hot Dry Continental; (4) Warm, Moist Gulf; and (5) Warm, Moist South Pacific. Bryson & Hare (1974) provide monthly mean streamlines of circulation for all of North America. Their January map is illustrative of a rather complex circulation pattern that is the norm in the Rio Grande. Because of this complex circulation, the climate is prone to exhibit swings of substantial variation from mean conditions. These variations are a prominent feature of the climate in the region.

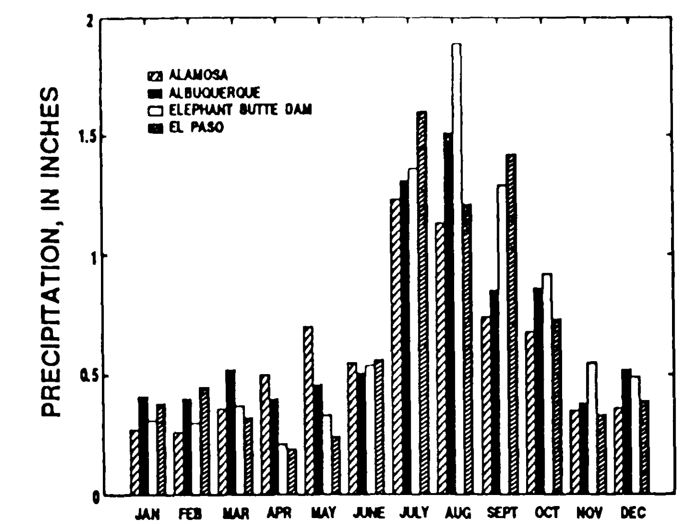

Figure 2b.—Mean monthly precipitation for selected sites, 1951-1980 (from Ellis et al. 1993; permission to reprint granted by American Water Resources Association).

A modern map of annual precipitation for the Middle Rio Grande was published by Ellis et. al in 1993. They make the point that precipitation varies from a high of greater than 50 inches annually in the headwaters in Colorado to less than 6 inches near Albuquerque. A similarly wide variation in temperature is exhibited from the northern headwaters region where mean January temperatures are below 25°F to mean July temperatures above 75°F in central New Mexico. Figure 2 illustrates the annual mean monthly temperature and precipitation for the headwaters (Alamosa), north central (Albuquerque), south central (Elephant Butte Dam), and southern (El Paso) region of the Middle Rio Grande. A map presented by Ellis et al. also illustrates that mean annual evapotranspiration as high as 80 inches occurs near Elephant Butte; that value falls to 75 inches at El Paso, 60 inches at Albuquerque, and 50 inches at Alamosa.

Of perhaps greater interest is the variation of wet and dry years (Diaz 1991; Diaz et al. 1985). In areas such as the middle Rio Grande, dry years and their persistence are particularly important. The relationship between these manifestations of climate and other natural and human disturbances may be among the most significant factors influencing ecological systems in New Mexico (Betancourt et al. 1993).

Of particular interest is the effect of global climate on the Rio Puerco basin as represented by the El Niño-Southern Oscillation (ENSO) meteorological disturbance. Investigators have identified relationships between ENSO events and southwestern United States climate (Ropelowski and Halpert 1986, 1987; Andrade and Sellers 1988; Kiladis and Diaz 1989; Molles and Dahm 1990; Betancourt et al. 1993). D'Arrigo and Jacoby (1991) developed a thousand-year record of winter precipitation for northwestern New Mexico based on dendrochronology and correlated it with ENSO. Dahm and Moore (1994) recently demonstrated a statistically significant correlation between observed precipitation at Socorro, New Mexico, and ENSO events of both polarities. The correlation is strongest in October, significant from November through May, but not significant during the summer (convection) season. Correlation of ENSO or other large-scale climate indicators with regional meteorological conditions is important for model development because weather records are sparse and represent conditions at only a single point, while weather has significant spatial variation. Large-scale indicators are expected to correlate more closely with whole-basin conditions. Furthermore, since ENSO events are predictable phenomena of the global climate (Latif et al. 1994), it is possible that regional effects of global change may be somewhat more predictable when correlated with ENSO events.

A sustained La Niña condition in 1917 may have been a contributor to the high sedimentation rates observed in the Elephant Butte Reservoir during its first decade. A single dry year, however, seems unlikely to degrade vegetation condition to such a degree that a decade or more of enhanced sedimentation would ensue. Thus, multi-annual variations may be a better indicator of vegetation stress and erosion risk factor. The 3-year period that ended in 1919 was one of potential stress on the region (Watts et al. 1994).

ENSO is, however, only one of many signals that determine regional weather; it is certain that uncorrelated weather patterns and events are superimposed on ENSO signals. It is particularly interesting that a dramatic shift from sustained drought to unusually wet climatic conditions occurred between 1895–1904 (strong drought) and 1905–1928 (wet). This was evident in a thousand-year reconstruction of the northern New Mexico paleoclimate (D'Arrigo and Jacoby 1991).

In recent work with the NCAR regional climate model, RegCM, Mearns et al. (1994) have compared simulated current U.S. climate with a simulated double CO_2 climate. For the Southwest, their results show a significant increase in diurnal temperature range, a decrease in cloud cover, and a significant decrease in precipitation frequency for summer conditions. A more uncertain increase in summer precipitation intensity is also suggested. Although these results are too preliminary to draw any conclusions from, they suggest that it is possible for the middle Rio Grande to experience an increase in temperature, a decrease in cloudiness, a reduction in precipitation events, and possibly an increase in storm intensity.

Weather and climate questions can be studied with a "nested" hierarchy of increasingly finer-resolution climate models. The objective of such a model linkage would be to provide a realistic simulation of the spatial and temporal distributions of the middle Rio Grande's climate, in particular of the climate's features that influence sediment production and transport. It is likely that high intensity rainfall events are the most significant climatic feature for land management concerns. Preliminary inspection of the weather records suggest that such precipitation events are infrequent. Hourly (and daily) time series of precipitation can be used to develop a history of significant events. Each of these significant events can be developed as an historical case study. The synoptic patterns in which these events are embedded can be developed from archived analyses (the initial condition field for routinely performed numerical weather predictions). Analysis fields consisting of temperature, pressure, and humidity distributions over a 0.5-degree latitude and longitude grid (approximately 50 km) can be obtained.

These analysis fields can be used to initiate "nested" runs of the RAMS model (Tremback et al. 1986) and/or of the RegCM model (Dickenson et al. 1989; Giorgi et al. 1994; Mearns et al. 1994) at a grid resolution on the order of 10–50 km. Precipitation predicted by these models can be used to drive other components in a simulation of the land response to this significant event. Even finer-scale spatial resolution in predicted precipitation and temperature fields can be obtained from the higher resolution climate modeling efforts currently underway at Utah State University in collaboration with the USDA-FS Intermountain Research Station (Bowles et al. 1994; Bingham et al. 1995; Luce et al. 1995).

Mesoscale and local-scale (if necessary) models can be "driven" by the larger-scale synoptic analysis (e.g., the larger scale represents both initial and boundary conditions for the higher resolution models), to simulate the most significant precipitation events. Assuming the number of these events is small, it will be possible to "drape" a finely resolved precipitation distribution (order 1 km or less) over the Rio Puerco watershed. The significant events will be simulated from within a time series that simulates the long term climate. The ENSO phenomena would be incorporated in the global scale initialization analyses, thus carrying the global signal to precipitation on the Rio Puerco.

WATER QUALITY

Background

The Middle Rio Grande Basin includes 257 km along the main stem of the Rio Grande between Elephant Butte Reservoir and Cochiti Dam. Tributaries in the Middle Rio Grande Basin are the Jemez River, Rio Salado, and Rio Puerco. Other streams include Abo Arroyo in the Manzano Mountains, Tijeras Creek, Las Huertas Creek, Galisteo Creek, and the Santa Fe River below Cochiti Dam. Secondary tributaries include the Rio San Jose, Bluewater Creek, Rio Paguate, Rio Guadalupe, Vallecito Creek, Rio Moquino, and Seboyeta Creek. Designated uses and corresponding water quality are classified in the state standards and vary from that suitable for a high quality coldwater fishery (e.g., the Jemez River above State Highway 4 near Jemez Springs, and the Guadalupe River and its tributaries) and domestic water supply, to limited warmwater fishery in the main stem above Elephant Butte Reservoir (NMWQCC 1991).

The state authority for water quality is the New Mexico Water Quality Control Commission. The Pueblo of Isleta was the first tribe to adopt water quality standards in New Mexico (in December 1992) to protect pueblo lands from off-reservation pollution. Standards were subsequently adopted by the Pueblo of Sandia, San Juan Pueblo, and the Jicarilla Apache Nation outside of the Middle Rio Grande Basin. Northern Pueblos that have published a notice of intent to adopt water quality standards include Nambe, Picuris, Pojoaque, Santa Clara, and Tesuque (Blane Sanchez, water resources specialist for Isleta Pueblo, personal communication). The State is primarily concerned about the level of pollution from nonpoint sources (NMWQCC 1992), but Isleta Pueblo is concerned about point source discharges from the City of Albuquerque (Blane Sanchez, personal communication).

Two recent reviews discuss water quality in the Rio Grande Valley, but not throughout the entire Middle Rio Grande Basin (Ellis et al. 1993; Crawford et al. 1993). Water quality throughout the state is reported to Congress every two years in the 305(b) report of the New Mexico Water Quality Control Commission (NMWQCC 1992).

There are four U.S. Geological Survey monitoring stations along the main stem of the Rio Grande between Cochiti Lake and Elephant Butte Reservoir (at San Felipe, Isleta, San Acacia, and San Marcial). Land uses upstream of these sites include various communities, ski areas, summer homes, silviculture, grazing, molybdenum mining, and irrigated agriculture. Water quality from Isleta upstream to Cochiti Reservoir is affected by the City of Albuquerque and other urban areas, wastewater discharges, runoff from dairies, and grazing. The lower portion of the Middle Rio Grande Basin is affected by irrigation return flows, uranium mining in the Rio San Jose watershed, and sediment contributions from three intermittent streams (the Rio Puerco, the Rio San Jose, and the Rio Salado) channeled over unconsolidated sediments. Trends for the following parameters are reported: conductivity, bacteria, alkalinity, sulfate, dissolved solids, dissolved nitrite plus nitrite, and suspended sediment concentrations. For example, suspended sediment concentrations at the mouth of the Rio Puerco are as high as 200,000 mg/L (USGS 1992), with a mean annual suspended sediment load of 2,580,000 tons per year (Ellis et al. 1993; USDI 1994). Others, however, note that sediment concentrations in the Rio Puerco reach 680,000 mg/L during major storm events (USDI 1994).

In addition to the fixed monitoring sites listed above, the USGS is conducting a study of the Rio Grande Valley in the United States as part of the

National Water Quality Assessment Program (NAWQA). Nine sites, including three on the main stem plus floodway and conveyance channel sites, are located on the Rio Grande from just below Cochiti Dam to San Marcial. Additional tributary stations include the Rio Puerco near Bernardo and the Jemez River below Jemez Canyon Dam (Ellis et al. 1993). The state Environment Department (NMED) has sampled tributaries in the Middle Rio Grande Basin as well as the main stem during intensive surveys, e.g., sampling a suite of stations for water chemistry, flow, and biological data at various times throughout a week-long survey. These data are available through the EPA STORET system, are published by survey, and catalogued through the NM State Library (Pierce 1989; Potter 1987a, b; Potter 1986; Potter and Tague 1986; Potter 1985a, b; Potter 1984a-c; Jacobi and Smolka 1984). Reservoir water quality is also monitored by NMED, and data are available for Cochiti and Elephant Butte lakes, as well as upstream reservoirs.

Surface Flows

Surface flows for the main stem are highly modified for flood control, sediment control, irrigation, hydroelectric power, recreation, and reservoir storage for water supply. Reservoirs affecting the Middle Rio Grande Basin hydrology include Heron, El Vado, Abiquiu, Cochiti, Jemez Canyon, Galisteo, and Elephant Butte. These modifications have resulted in intermittent or ephemeral flows in areas that were probably historically perennial flows (Crawford et al. 1993). Recent efforts to mimic natural hydrographs in the main stem include flooding of the bosque habitat. There is also interest in reestablishing the natural surface-water/groundwater exchange (Crawford et al. 1993). Long-term flow data are available for the main stem at Otowi bridge above Cochiti Lake. Flow in the Rio Puerco is not controlled for flooding or water supply and contributes 4 percent of the annual water yield for the Rio Grande at San Marcial (Crawford et al. 1993).

Contaminants

Nutrient enrichment

A number of nutrient loading studies have been conducted in the Middle Rio Grande Basin. A nutrient transport simulation model was developed to define rate constants and transport mechanisms (Wilson and Babcock 1979; Wilson, Tague, Snavely, and Babcock 1984). The state sampled the Rio Grande conveyance channel and Socorro Main Canal to evaluate the effects of irrigation return flow on Rio Grande water quality, and it concluded that irrigated agriculture did not noticeably contribute to the nitrogen and phosphorus loading of the river. Similarly, a New Mexico State University study indicated that less than 20 percent of the nutrients contained in irrigation waters were discharged to the central drain (Wierenega, Duff, Senn, and Gelhar 1981; NMEID 1982).

A study by Tague and Drypolcher (1979) indicated that the annual mass loading rates of both N and P from stormwater was low compared to the loading rate from the Albuquerque wastewater treatment plant, although a single event generated a temporarily high load. In another study, significant correlations and regressions between urban runoff volume and stormwater quality were calculated using data for the Alameda floodway (Diniz 1984).

More recently, high concentrations of un-ionized ammonia, which is toxic to some fish and invertebrate species, have been attributed to water use impairment in the main stem of the Rio Grande from Isleta Diversion Dam to the Jemez River (NMWQCC 1992).

Trace metals

Trace metals occur at detectable levels at various sites throughout the Basin due to a combination of natural and anthropogenic sources. For example, natural arsenic sources (geothermal springs) from the watershed of the Jemez River result in high concentrations of arsenic. Outcrops of organic-rich rocks such as humates and dark shales are a natural source of trace metals in the Rio Puerco Basin (USDI 1994). Popp et al. (1980) collected samples for trace-metal and pesticide analysis at six river sites from Bernalillo to Elephant Butte Reservoir. Water-use impairment in the Middle Rio Grande Basin is attributed to trace metals in the main stem of the Rio Grande from San Marcial to the Rio Puerco, Rio Puerco to Isleta Diversion Dam, from Isleta Diversion Dam to the Jemez River, and from Jemez River to Cochiti Dam (NMWQCC 1992).

Isleta Pueblo will be initiating a joint water quality monitoring program in accordance with an April 1994 settlement agreement regarding the City of Albuquerque's National Pollutant Discharge Elimination System (NPDES) permit for discharge of municipal waste. Concentrations of four metals—aluminum, arsenic, cyanide and silver—will be monitored from San Felipe to Los Lunas (Blane Sanchez, personal communication).

Several studies have been directed at the bioaccumulation of metals. Mercury, arsenic, and zinc concentrations are higher in fish tissue collected at Middle Rio Grande sites than other sites (Ellis et al. 1993). As a result of statewide sampling for mercury contamination in fish tissue, the state has issued fish consumption guidelines (NMWQCC 1992).

Radionuclides

Uranium-rich rock of the Rio Puerco Basin is a source of radionuclides. The Rio Puerco has elevated levels of uranium, gross alpha, and gross beta, and high concentrations of cesium 137 and lead 210 in Paguate Reservoir on the Paguate Creek tributary of the Rio Puerco (Ellis et al. 1993). Uranium mining and milling activities near Grants, New Mexico, have accelerated the downstream transport of radionuclides and metals. Eroding tailings piles may continue to result in water pollution.

Biocides

Biocide contamination occurs from agriculture, as well as from the cumulative impact of residential and commercial landscaping activities. Potter (1987b) sampled pesticide and herbicide concentrations at three Rio Grande main-stem sites in Socorro County. In general, concentrations were below detection limits. Although chlordane and 2,4-D were detected at the San Antonio station, only the former exceeded the recommended chronic criterion for aquatic life and limits for fish consumption.

Other pesticides found at detectable concentrations in the Rio Grande main stem include diazinon. Also, p-p' DDE was detected in the Middle Rio Grande by the U.S. Fish and Wildlife Service (Ellis et al. 1993). Water-use impairment in the Rio Grande is attributed to pesticides in the main stem from Isleta Diversion Dam to Jemez River and from San Marcial to the Rio Puerco (NMWQCC 1992).

Volatile organic compounds

VOC detectable in the Middle Rio Grande at Isleta include trichlorofluoromethane, chlorpyrifos, and trichlorofluoromethane (Ellis et al. 1993). Organic compounds are not considered to impose a major impact on New Mexico streams (NMWQCC 1992).

Other causes of water use impairment

Other causes of water-use impairment in portions of the Middle Rio Grande Basin include chlorine, pathogens, siltation, reduced riparian vegetation, and streambank destabilization. Sources that contribute to water quality degradation resulting in use-impairment are as follows: agriculture, municipal point sources, urban runoff, storm sewers, spills, hydromodification, and "others" (NMWQCC 1992). The primary in-basin concerns related to water quality are non-point sources of pollution, water quantity and timing, and ecosystem integrity.

Water Quantity and Timing

Stream flow rate is affected by reservoir releases, irrigation withdrawals, irrigation return flows, and precipitation variability. Changes in precipitation can have a disproportionate (e.g., nonlinear) change on streamflow. For example, under global warming scenarios, a 2° C temperature increase is predicted to result in a 10 percent decline in precipitation, but a 75.7 percent decline in annual stream discharge is predicted within the Rio Grande Basin (Revelle and Waggoner 1989). This is the largest predicted percent change per basin in the United States.

In 1990, total water withdrawal (groundwater and surface water) from the Rio Grande Basin in New Mexico was $2,258 \times 10^6$ m^3 (1,830,628 acre feet), significantly exceeding a sustainable rate (Schmandt 1993). Average annual outflow of the Rio Grande from Colorado to New Mexico is 370×10^6 m^3 (300,000 acre-feet) (Schmandt 1993). Significant changes in water supply in the main stem ultimately affect the distribution of water as defined by existing treaties and compacts. The International Boundary and Water Commission has already exercised its authority to protect water quality (e.g., salinity of the Colorado River) delivered to Mexico, and similar requirements could be imposed for the Rio Grande in the future (DuMars 1993). Both streamflow and reservoir storage are affected by terms of the interstate Rio Grande Compact and treaty with Mexico, while the Reclamation Act of 1902 addresses irrigation uses. Such legal implications of changes in water supply extend to various state and federal regulations of water quality and appropriation. For example, "conjunctive management" of surface and groundwater requires that to obtain rights to drill a well in an underground aquifer that recharges a surface stream, an equivalent surface water right must be purchased and retired (Gosz 1992).

The hydrologic effects of floods and droughts in semiarid regions is quite different from mesic regions. In the Rio Salado, for example, loss of streamflow in the summer occurs after wet winter/springs, while summers with high flooding occur after dry winter/springs. Hypothetical reasons for this observation include: less vegetation biomass is available after a dry winter/spring to slow overland flow so runoff therefore increases; wet winter/springs result in reduced hydrophobic tendency of the soils and increased infiltration; and due to the effect of soil temperatures, more intense summer storms may occur after a dry winter/spring and produce high runoff (Molles et al. 1992).

Anthropogenic Effects on Water Quality

Anthropogenic effects on water quality in the Middle Rio Grande Basin are the result of activities associated with irrigation, urbanization, mining, grazing, timber harvest, construction, and recreation (Crawford et al. 1993; NMWQCC 1991, 1992; Ellis et al. 1993; USGS 1992). Additional activities upstream from Cochiti Dam to the San Luis Valley in Colorado also contribute to the cumulative effect on water quality.

Irrigation return flows and runoff affect both water quantity and quality. Irrigated agriculture is the principal water use and a main economic activity in the Basin. Water withdrawals from irrigated agriculture are declining, e.g., from $1,536 \times 10^6$ m^3 to $1,227 \times 10^6$ m^3 (1,244,900 to 995,000 surface water acre-feet) in the New Mexico portion of the Rio Grande Basin (Schmandt 1993). DuMars distinguishes between "commercial agriculture" and "culturally significant marginal agriculture" of rural communities and Indian Pueblos (DuMars 1993).

Urbanization has resulted in commercial and industrial activities that have the potential to affect water quality. It has also resulted in increased levels of treated sewage discharged to streams. Perhaps most importantly, it has increased the demand for water supply, although municipal use relies on groundwater. Urban population growth is predicted to continue in the next century, e.g., when the effects of accelerated climate change may be evident. In contrast, rural populations have remained rather constant in the Basin (Schmandt 1993).

The rate of depletion of Albuquerque's water supply is currently a great concern. The aquifer on which the City of Albuquerque depends for water supply is less extensive and thinner than was previously estimated, and it has dropped 40 feet from 1989 to 1992 in the eastern, northwestern and south-central areas (Thorn et al. 1993). Over 1.5×10^{11} l (40 billion gallons) of water a year are withdrawn from the aquifer, at a rate exceeding that of recharge (City of Albuquerque 1994). Consumption rate is 947 l (250 gallons) per person per day, and residential use is 71 percent of total. The remainder is consumed by commercial use (17 percent), institutional use (9 percent), and industrial use (3 percent) (City of Albuquerque 1994). Mayor Martin Chavez states that reducing water use is "the most important issue facing the City of Albuquerque, bar none." Groundwater quality is also lower than previously believed, including areas that are unsuitable for drinking.

Human activities may result in regional changes in the water cycle, water quality, and sediment transport systems (Huggett 1993). These changes are modeled at various scales, including the global and continental scales. Predictions can be made for variables such as runoff, stream discharge, soil moisture, and evapotranspiration (Huggett 1993). There is a growing, interdisciplinary interest in water resources issues that relate to sustainable development in the entire Rio Grande Basin (Gosz 1992; Crawford et al. 1993; Schmandt 1994). Those efforts include sharing scientific information and collaborative projects that will improve water and riparian area quality, as well as economic sustainability. Such partnerships, institutional cooperation, and joint decision-making are necessary to address global change issues related to climate, population, economy, the environment, and culture (Gosz 1992). In the Rio Grande Basin, total water consumption is greater than the supply. This water deficit is allowed to continue through diversion systems and groundwater mining (DuMars 1993). It is well recognized that sustainable economic development depends on efficient water use, water conservation, and water pollution control.

ARROYO DYNAMICS OF THE RIO PUERCO BASIN

Background

The Rio Puerco basin is composed of federally managed lands (FS, Bureau of Land Management, National Park Service, and Fish & Wildlife Service: 30 percent,), Indian lands (20 percent), state (10 percent), and private (40 percent) lands. This broad mosaic of ownerships and management objectives makes the Rio Puerco an excellent candidate for ecosystem management-oriented studies.

The Rio Puerco, a tributary of the Rio Grande, is one of the highest sediment-yielding streams of the United States (Aguilar et al. 1990); as much as 20 percent of the Rio Puerco's historical discharge into the Rio Grande is suspended solids (Laquer 1981). From its 19,036 km^2 drainage basin, it produces an average of 2.4 Mt./y (million metric tons per year) of suspended sediment, or an average of 130 $t/km^2/y$. Bryan and Post (1927) estimated that 500×10^6 m^3 of sediment was eroded from arroyo walls during the period 1885–1927; this translates to an average rate of 12×10^6 m^3/y or approximately 24 Mt./y based on an estimated pre-erosion sediment density of 2 g/cm^3. These calculations suggest that approximately 90 percent of the sediment mobilized in arroyo incision is redeposited within the basin; the remaining 10 percent is exported as suspended sediment load. Dortignac (1956) estimated that two-thirds of Rio Puerco's sediment was derived from arroyo deepening and widening processes, and one-third from sheet and rill erosion of hill slopes; this estimate reduces the redeposited:exported ratio further, to 93 percent:7 percent, or 13:1. Miller (1985) estimated transport rates of 500 $t/km^2/y$ in regional dune fields, which represents a surface-material mobility:average export ratio of 4:1. The Rio Puerco basin clearly exhibits high mobility of surface and near-surface sediments; the great majority of material is redistributed within the basin, but the fluvial channel system nevertheless receives and exports a significant amount of mobilized material. These have been observed and dated only on an incidental basis.

The current arroyo system developed during the latter part of the 19th century. Kirk Bryan (1925), one of the earliest students of the Rio Puerco, cited 1880 as the approximate time of erosion initiation. Sedimentation rates were particularly high during the 40 years that followed (1880–1920). Elephant Butte dam was closed in 1916. Its reservoir immediately was subjected to high deposition rates—so high that the reservoir would be filled with sediment by 2022 if early deposition rates had been sustained. This scenario is disquieting because Elephant Butte Reservoir is the primary management facility for delivery of water to the lower Rio Grande Basin in New Mexico, Texas, and Mexico. Elephant Butte Reservoir's delivery is governed by interstate compacts and by international treaty; enduring operation of the key storage and management facility is a legal, as well as a practical, necessity. The population of this area is growing rapidly, as much as 20 percent per year in selected locations, as is its dependence on reliable water supplies. While most drinking water needs are currently supplied by groundwater pumping, there is increasing concern about the quality and continuity of this source as well as its relationship to the Rio Grande.

The high sedimentation rates of the early part of this century have, fortunately, moderated. At current sedimentation rates the projected lifetime of Elephant Butte Reservoir is beyond 300 years. The Bureau of Reclamation's Albuquerque Projects Office recently (August 1, 1994) issued a "Draft Preliminary Findings Report—Rio Puerco Sedimentation and Water Quality Study" (USDI Bur. Rec. 1994) that contains an excellent review of the literature and available data. This report recommends against construction of control structures to manage sediment from the Rio Puerco, but rather recommends interagency analysis and model development to improve understanding of the system.

Table 1 summarizes published statistics on the Rio Puerco's sediment production. Some statistics cannot be compared directly because, for example, they represent different time periods. There are, nevertheless, apparent discrepancies and interpretation difficulties. For example, Bryan's estimate of a mean arroyo excavation rate of 12×10^6 m^3/y pales (by a factor of 2.5) in comparison to the Elephant Butte Reservoir's measured rate of sediment influx of 30×10^6 m^3/y during the period 1915–1925. Was Rio Puerco's erosion rate higher during the decade 1915–1925 than for the period 1885–1927? Did other tributaries contribute more than half of the sediment load during the 1915–1925 decade? Are pre-erosion sediments substantially denser than post-deposition sediments? Answers to these questions lie in field observations of the Rio Puerco Basin and of Elephant Butte Reservoir.

In-Basin Concerns

The foregoing discussion focused narrowly on sedimentary processes and on the out-of-basin effects on the Rio Grande surface water supply. There are also concerns regarding in-basin land and water resources.

While the Rio Grande channel system and Elephant Butte Reservoir accumulated large quantities of sediment, the Rio Puerco landscape lost it. The

Table 1.—Values taken from the literature indicate magnitudes of various types of mass redistributions in the Rio Puerco watershed.

	Period					
	start	end	Basin total	Units	Amount/ area	Units
Area[a]			1.9E+04	km^2		
Area			1.9E+10	m^2		
Area			1.9E+16	mm^2		
Mean water outflow	1941	1993	3.0E+07	m^3/y	1.6E-03	m^3/y
Mean water outflow	1941	1993	3.0E+16	mm^3/y	1.6	mm/y
Mean sediment outflow	1941	1993	2.3E+06	t/y	1.21E+02	$t/km^2/y$
Mean sediment outflow[b]	1941	1993	1.2E+06	m^3/y	6.1E-05	m/y
Mean sediment outflow[b]	1941	1993	1.2E+15	mm^3/y	0.061	mm/y
Arroyo excavation	1885	1927	5.0E+08	m^3	0.026	m
Arroyo excavation	1885	1927	1.2E+07	m^3/y	6.1E-04	m/y
Arroyo excavation	1885	1927	1.2E+16	mm^3/y	0.61	mm/y
Eolian movement	?	1985			500	$t/km^2/y$
Eolian movement	?	1985			250	$m^3/km^2/y$
Eolian movement	?	1985			0	mm/y
EBR sediment[b]	1915	1926	3.0E+07	m^3/y		

[a]*includes area of closed inferior drainages*
[b]*assumed density = 2,000 kg/m*^{3}

arroyos, as suggested earlier, may have lost sediment volume 10 times greater than was exported to the Rio Grande. Natural excavation of such deep grooves in the valley floors drained valley-fill aquifers and defeated extant agricultural surface-water diversions; in an apparent repetition of the demise of the settlement at Chaco Canyon, several agrarian communities abandoned the Rio Puerco basin. Sediment that remained in the basin (>90 percent of the excavated amount) has been redeposited in the lower reaches of the arroyos; vegetation has become established there and retards peak flows in the channel and further increases aggradation. Water tables rise as arroyos continue to refill with sediment. Conditions may be ripe for reinitiation of a basin-wide arroyo cycle (Gellis 1991).

What factures or combinations of factors will initiate the next cycle of erosion? What measures might be taken to ameliorate negative impact? Of measures that might be identified, which ones provide optimum benefits? What observations or monitoring would provide early warning of pending erosion? These are practical questions of concern to landowners and to land and water resource managers of the Rio Puerco and downstream areas.

Mining is a substantial activity in the Rio Puerco Basin, particularly in its southwestern quadrant. Both radioactive and toxic minerals are present in mine tailings that are exposed on the land surface. Tailings materials have episodically entered the drainage network and certainly do so on a continuous basis in a setting where surficial materials are highly mobile (Miller 1985). The presence of these materials poses both in-basin and downstream threats to water and environmental quality. In its recent study, the Bureau of Reclamation (1994) concluded: "Evidence exists that heavy metal and radionuclide contaminants are carried into the Rio Grande by the Rio Puerco. The majority of these contaminants are attached to sediment particles. It is not known whether the Rio Puerco contributes trace metals or radionuclides to the Rio Grande in quantities sufficient to cause health risks to humans or adverse ecological effects."

Research Problems

More than 1,200 technical references have been cited in a recent review of Rio Puerco literature; yet, in spite of such extensive scientific scrutiny, the cause, character, and future of erosion in the basin remain subjects of debate. Various authors have attributed arroyo incision to climatic variations or changes; to grazing; to roads and stock trails; to combinations of these factors; or to cyclic behavior of arroyo systems (coupled or uncoupled with climate variations). The ambiguity of interpretation of the prehistoric and historic record encourages study of the Rio Puerco arroyo processes through the use of numerical simulation models.

Arroyo-inducing conditions and high sediment yields are not synchronous with climate conditions owing to the critical role of vegetation as landscape armor. It takes several years for plants to succumb to stress and more for their physical soil-stabilizing structures to decompose. Other factors, such as grazing, accelerate the removal of sediment-fixing plant structures, but these also have their characteristic rates of progress. Thus, there are unknown delays between climatic causative conditions and high erosion; there are further delays (transmission times) in the channel system itself.

Conceptual Model

A simple model of influences over sediment-generating processes can be conceptualized. Hillslope conditions are interposed between major causative factors—weather and human activities—introducing characteristic time responses that delay, mask, and mix the driving signals. One could develop a model that incorporates the essentials of these dynamics in a way that allows for substantial duplication of historical observations. Such a model will be used to investigate effects that would follow different driving conditions—primarily changes in climate and human-influenced conditions such as grazing.

A structured sequence of hypotheses and tests for this project could be:

1. *Hypothesis*: A linear arroyo characterized by typical but static Rio Puerco soil, slope, and vegetation conditions exhibits repeated episodes of incision and high sediment discharge when driven with historical regional weather.
   Implications: If the hypothesis is true, then the factors of dynamic vegetation, soil disturbance, and drainage network geometry may be contributory but are not essential to the gross behavior of the arroyo system. Gross behavior of the system can be used, at least qualitatively, to investigate frequency and intensity of sediment production of the basin, including production of entrained toxic materials. If the hypothesis is false, then the effect of each of the named factors must be considered.
2. *Hypothesis*: A simple, branched arroyo characterized by typical but static Rio Puerco soil, slope, and vegetation conditions exhibits repeated episodes of incision and high sediment discharge when driven with historical regional weather.
   Implications: If hypothesis 1 was false but this hypothesis is true, then interaction among tributaries, or between tributaries and main channel, is an essential driver of arroyo instability. If the hypothesis is true, then the factors of dynamic vegetation and soil disturbance may be contributory but are not essential to the gross behavior of the arroyo system. If false, then the effect of each of these additional factors must be considered.

Development of an object-oriented arroyo dynamics process simulation model is currently underway at the TERRA laboratory (Watts et al. 1994). This model is based on geographic coverage of the Rio Puerco. The hydrologic system of the Rio Puerco is mapped from digital elevation models at 30 m resolution of the entire Basin. The resulting stream system can be analyzed automatically using geographic statistics. This allows the watershed to be analytically reduced into a combination of channel reach segments. The model being developed at TERRA treats each channnel reach as a separate object having a headwater, a right, and a left input. The system can be simulated with whatever degree of complexity is necessary by linking these objects into a simulated map of the channel system. Since the dynamics of arroyos depend on a number of features beyond simply the hydrology, each object contains geomorphic, vegetation, and other characteristics.

NUTRIENT RETENTION, STREAM METABOLISM, AND ARROYO FORMATION

The perception of streams as inanimate pipes that drain watersheds has been rejected by both hydrologists and ecologists. Streams are no longer viewed as receptacles for hillslope water; instead, groundwater and surface water fluxes are now considered interactive and hydrologically integrate hillslope and channel systems (Bencala 1993; Harvey and Bencala 1993). Solute transport in all ecosystems is tied to the movement of water. Given the advective, unidirectional transport characteristic of lotic systems, the retention of nutrients and organic matter is an insightful measure of ecosystem functioning. A suite of physical, chemical, and biological processes delays the downstream flux of nutrients, and the interplay of these factors influences the structure and functioning of stream systems. Geomorphic differences among streams can have a large impact on the retention and cycling of nutrients (Lamberti et al. 1988; Coleman and Dahm 1990; Gregory et al. 1991). In the Rio Puerco drainage, arroyo formation is an agent of geomorphic change that is of great importance to downstream environments and terrestrial systems within the catchment. In this study plan, we describe a research program to assess the influence of arroyo formation on the retention of nutrients by headwater streams of the Rio Puerco, New Mexico.

Hydrologic Retention

Stream channel complexity, as well as surface water-groundwater interactions, entrain nutrients in flowpaths that move at slower velocities than those predicted by the average advective velocity of surface flow. The resulting delay in transport is known as hydrologic retention and has been quantified using conservative hydrologic tracers (Bencala and Walters 1983; Stream Solute Workshop 1990). Analysis of tracer response in wells provides point measurements of hydrologic retention in interstitial water. Individual wells reveal the extent of penetration of surface water into the groundwater at specific locations. Average travel time to a sampling well expresses the rate of exchange between surface water and groundwater. In this manner, distribution of conservative tracers in well networks can provide a qualitative measure of hydrologic retention along a reach of stream (Triska et al. 1989, 1993).

Downstream transport of water and tracer can be simulated using numerical models to provide a quantitative measure of hydrologic retention (Bencala and Walters 1983; Stream Solute Workshop 1990; Runkel and Broshears 1991). One such approach is the One-dimensional Transport with Inflow and Storage model (OTIS) developed by Runkel and Broshears (1991). This model treats the stream as a two compartment system—a main stream channel and a transient storage zone. Transient storage reflects the temporary delay of downstream transport and includes hydrological and geomorphic features of surface and subsurface systems. The size of the storage zone can be determined by OTIS to provide a quantitative, comparative, reach-scale measurement of hydrologic retention.

Recent studies have sought to identify features of stream ecosystems that influence and organize transient storage. Surface complexities such as debris dams have been shown to increase hydrologic residence time and enhanced retention of particulate organic material (Speaker et al. 1984; Trotter 1990; Ehrman and Lamberti 1992). D'Angelo et al. (1993) examined the relationship between stream order and transient storage. They found an overall decrease in storage zone size with increasing stream order.

The interaction of surface water with groundwater also contributes to transient storage in lotic ecosystems (Bencala and Walters 1983). Surface and subsurface systems of streams are linked by vertical gradients causing groundwater discharge (upwelling) and recharge (downwelling) that result from stream bottom geometry (Vaux 1968; White et al. 1987) and hillslope-channel water interaction (Harvey and Bencala 1993). The term "hyporheic zone" refers to the subsurface component of transient storage and is defined as the region of groundwater that receives water from the above-ground channel (Triska et al. 1989). Hyporheic flowpaths have been identified as a significant source of hydrologic retention in gravel-bottom streams (Castro and Hornberger 1991; Bencala 1993).

The magnitude of subsurface storage changes with space and time. Constrained stream reaches occur when the valley floor is less than two times the active channel, reflecting geomorphic limits on the lateral extent of the fluvial system (Gregory et al. 1991). Using the above definition, D'Angelo et al. (1993) showed that transient storage was higher in unconstrained segments of a stream in the Pacific Northwest than in constrained reaches of the same stream. For a single stream reach, transient storage changes with time. For headwater streams of Appalachian (D'Angelo et al. 1991) and New Mexican (Morrice et al., in review) mountains, there is a negative correlation between discharge and hyporheic zone size.

Morrice et al. (in review) identified hydraulic conductivity as a parameter that influences hydrologic retention through its affect on surface water-groundwater exchange. Using hydrologic tracers, we compared the transient storage of three headwater streams located in catchments of contrasting geologic material and differing alluvial properties (Morrice et al. [in review], Valett et al. [in review]). The rate and spatial extent of hydrologic interaction between the streams and their alluvial aquifers decreased with decreasing alluvial hydraulic conductivity and decreasing channel complexity.

Hydrologic interaction between streams and their alluvial aquifers is heavily influenced by hydrogeologic parameters (e.g., hydraulic conductivity) and surface channel features, as well as fluvial geomorphology, including channel gradient, sinuosity, and width-to-depth ratio (Larkin and Sharp 1992). Ecological consequences of arroyo formation on headwater streams probably reflect geomorphological responses of the fluvial system. We suggest that because of its close relationship to reach complexity, hydrologic retention will be sensitive to the potential impacts of stream incision and arroyo formation.

Biological Retention

Nutrient transport in streams can also be attenuated by pathways involving biological retention. In lotic ecosystems, the competing processes of hydrologic export and biological retention are expressed in the nutrient spiralling concept (Webster and Patten 1979; Elwood et al. 1982; Newbold et al. 1983). Downstream transport adds longitudinal displacement to nutrient cycles such that they act as nutrient spirals. Comparisons of solute loads (mass transported per unit time) at successive points along a reach provides a measure of nutrient uptake or release. Ecosystem retention is then calculated as the net difference between inputs and outputs from an established reach (Grimm 1987; Stream Solute Workshop 1990; Triska et al. 1990).

Biological retention in streams can be measured in reach-scale experiments that involve the concomitant release of conservative (non-active) and non-conservative (biologically active) solutes. Uptake lengths represent the average distance traveled by a solute (*sensu* Newbold et al. 1983) and are determined from analysis of plateau concentrations of conservative and non-conservative solutes at successive points along a reach.

Hyporheic zones are historically known as habitat for unique and diverse invertebrate assemblages (for review see Williams 1984), but these groundwater/surface water mixing zones also affect stream metabolism (Grimm and Fisher 1984; Metzler and Smock 1989) and nutrient dynamics (Triska et al. 1989; Duff and Triska 1990; Hill 1990; Hendricks and White 1991). Because subsurface sediments are metabolically active, hyporheic zones may act as sources or sinks of nutrients depending on the relative magnitude of processes generating or immobilizing biologically important solutes (Triska et al. 1989; McDowell et al. 1992).

Morrice et al. (in review) and Valett et al. (in review), found that nitrate uptake length was correlated with storage zone size. Increased hydrologic exchange between surface water and groundwater promoted tighter cycling of nitrogen between surface and interstitial systems. Mixing between surface water and groundwater integrates the biogeochemistry of these regions and generates nutrient fluxes that may influence processes in both subsystems (Gibert et al. 1990; Valett et al. 1994).

Metabolism and Nutrient Cycling in Stream Hyporheic Zones

The size of the hyporheic zone and the direction and magnitude of groundwater-surface water interaction varies greatly among and within catchments, and has important implications for ecosystem metabolism and nutrient cycling. For example, Valett et al. (in review) found that interstitial dissolved oxygen concentrations were significantly correlated to the rate of exchange between surface and subsurface. This suggests that residence time in aquifer sediments governs oxygen availability and strongly influences redox potential along subsurface flow paths. Microbial respiration in groundwater proceeds through a predictable series of electron acceptors (O_2, NO_3^{-1}, Mn^{+4}, Fe_3^{+}, SO_4^{-2}, CO_2) reflecting the nature of their hydrologic supply (Chapelle and Lovely 1990). Additionally, respiration rates in stream systems (surface and subsurface) are linked to the supply of dissolved organic carbon (Dahm 1981; Kaplan and Bott 1982, 1989; Findlay et al. 1993; Vervier et al. 1993; Jones et al. [in review]) and availability of terminal electron acceptors. Since residence time affects dissolved oxygen distribution, we predict that hyporheic zones in basins with low rates of surface water-groundwater exchange will be dominated by anaerobic metabolism. In contrast, interstitial regions with high rates of surface water-groundwater exchange should be well oxygenated and dominated by aerobic processes.

Arroyo Formation and Lotic Ecosystem Functioning

Across stream systems, basin lithology influences the availability of biologically important solutes (Hynes 1975; Kruger and Waters 1983; Munn and Meyer 1990; Pringle and Triska 1991), properties of alluvial materials, sediment bed loads (Kelson and

Wells 1989), and groundwater/surface water interaction (Morrice et al. [in review]). Within catchments, nutrient retention has been shown to vary among pools, riffles, and debris dams (Munn and Meyer 1990) and is influenced by varying geomorphology within similar reach types (Coleman and Dahm 1990) and frequency of woody debris (Trotter 1990; Ehrman and Lamberti 1992). Within streams, variation in channel geomorphology influences ecosystem functioning. Just as D'Angelo et al. (1993) found lower transient storage in constrained reaches, Lamberti et al. (1988) concluded that constrained reaches were far less retentive of dissolved and particulate matter than were unconstrained reaches where channel complexity is higher.

In the semiarid southwest, stream-bed sediments of sandy-bottom streams are metabolically active (Grimm and Fisher 1984; Coleman and Dahm 1990; Valett et al. 1990) and highly mobile (Wertz 1963; Graf 1988), reflecting variable precipitation (Molles and Dahm 1990) and the influence of flash floods (Graf 1988). Under these conditions, movement of sediments may represent a significant disturbance to in-stream aquatic communities of the surface (Gray 1980; Boulton et al. 1992a) and hyporheic zone (Boulton et al. 1992b) and to ecosystem processes (Fisher et al. 1978; Grimm and Fisher 1989; Valett et al. 1994).

Mobilization of vast quantities of sediments due to arroyo formation has been a focus of concern for managing agencies in the southwestern United States (Hereford 1987; Lagasse et al. 1987; Watts et al. 1994). In New Mexico, the Rio Puerco contributes an enormous amount of sediment to the Rio Grande (and ultimately to Elephant Butte Reservoir), but Watts et al. (1994) emphasized that over 90 percent of the mobilized sediment is redeposited within the basin. Associated with convective thunderstorms, summer floods in the headwater streams of the Puerco restructure channel geomorphology, decimate benthic stream biota, and initiate stream incision and arroyo formation. In other sandy-bottom streams disturbed by flash floods, rates of ecosystem recovery are influenced by nutrient fluxes between groundwater and benthic environments (Valett et al. 1994). While arroyo formation is recognized as a critical issue for terrestrial and fluvial systems in terms of sediment erosion and transport, little is known about its local implications on biological aspects of headwater streams. Via its impacts on small-scale (e. g., 100–1000 m) stream geomorphology and its potential to disturb aquatic communities, arroyo formation may affect the rates of groundwater-surface water exchange, ecosystem metabolism, and nutrient retention in perennial headwater streams of the Rio Puerco drainage.

Research

Objectives

The structure and functioning of stream ecosystems are intimately linked to processes occurring at the watershed scale (Hynes 1975). For this reason, the biogeochemistry of streams has been used as an indicator of disturbance and successional state in adjacent terrestrial ecosystems (Likens et al. 1970; Vitousek and Reiners 1975). Cyclical arroyo formation impacts the structure and functioning of downstream reaches (e.g., Rio Grande, Elephant Butte Reservoir) and alters upland terrestrial systems, but nothing is known about its impact on the perennial aquatic habitats of headwater streams.

The general objective of this research is to determine the effect of arroyo formation on nutrient retention in headwater streams of the Rio Puerco Basin. To do this, we will interact with researchers from the Bureau of Land Management who have established study sites on a number of perennial streams near the San Pedro Wilderness in the Jemez Mountains of the Santa Fe National Forest. We will describe ecosystem structure in areas variably impacted by arroyo formation and compare nutrient dynamics in incised and unconstrained reaches. Finally, we will compare retention in these sites to a similar stream (Rio Calaveras) in the Jemez Mountains where we have studied hydrologic and biological retention and stream/groundwater interactions for the past three years (see Wroblicky et al. 1992; Morrice et al. [in review]; Valett et al. [in review]). Our current study plan includes studies of arroyo influences within single streams and comparisons of retention between an arroyo-impacted catchment and a reference catchment not impacted by arroyo formation.

Specifically, we will: (1) describe the hydrogeologic and chemical conditions of surface water and groundwater environments in headwater catchments of the Rio Puerco that are impacted by arroyo formation, (2) determine the influence of arroyo formation on the retention of water and nutrients, and (3) investigate the metabolic activity of sediments deposited in perennial reaches and imported from ephemeral tributaries (e.g., arroyos). We will pursue these objectives with three research elements: (1) structure of the groundwater/surface water interface, (2) hydrologic and biological aspects of nutrient retention, and (3) metabolism and carbon cycling in stream sediments.

Study sites

The initial phase of our research will focus on establishing study sites in perennial reaches of headwater streams that drain into the Rio Puerco near Cuba, New Mexico, on the western slopes of the Jemez Mountains in the Santa Fe National Forest. We will coordinate our efforts with ongoing research projects organized by the Bureau of Land Management focusing on headwater restoration in the Rio Puerco basin. Perennial reaches of headwater streams near the San Pedro Wilderness Area will be assessed. Potential study sites now include San Pablo Creek, the Rito Leche, and Nacimiento Creek near Señorito Canyon.

Structure of the groundwater/surface water interface

Initial field sampling will be aimed at characterizing the hydrogeologic and biogeochemical conditions of surface and groundwater environments in our study streams. Using standard methods modified for use in sandy-bottom streams, we will analyze hydrogeologic properties (e.g., vertical hydraulic gradients, alluvial hydraulic conductivity) and the distribution and concentration of biologically important (e.g., redox-sensitive) solutes at the benthic/hyporheic interface. We will compare biogeochemical structure of incised and unconstrained reaches and the physical-chemical conditions of saturated sands entering the main channel from ephemeral tributaries (e.g., arroyos). Results from these surveys will be used to identify characteristic reach types and locate sites for experimentation (see below).

Hydrologic and biological aspects of nutrient retention

Rivers and streams are "open" ecosystems, dominated by physical transport of nutrients across upstream and downstream boundaries. The downstream flow of water accounts for the vast majority of the input and output of materials for a reach of stream or river (Cummins et al. 1983; Grimm 1987). Retention integrates the processes that retard the movement of nutrients out of an ecosystem and is defined as the difference between inputs and outputs over a designated time period (e.g., retention = [nutrients in—nutrients out]/time). Biological activity entrains nutrients in plant and animal biomass, reducing the movement across the downstream boundary. This is a significant component of nutrient retention in streams. Similarly, nutrients may enter volumes of water moving much slower than the main current. Pools, eddies, backwaters, and flowpaths routing surface water through the near-stream groundwater system are features of streams that result in hydrologic retention. We will investigate the influence of arroyo formation on the hydrologic and biological retention of NO_3-N. We focus on NO_3-N because it is the predominant form of plant-available nitrogen in streams and because nitrogen is the nutrient commonly limiting biological processes in southwestern streams and rivers (Grimm and Fisher 1986).

This research element addresses the impacts of arroyo formation on hydrologic and biological mechanisms of nutrient retention. We will compare transient storage and nutrient uptake lengths within individual streams and compare results to those already analyzed for a nearby reference stream (Rio Calaveras, Jemez Mountains, New Mexico) to investigate the influence of arroyo formation on nutrient retention.

Question 1: How does arroyo formation influence hydrologic retention in headwater streams of the Rio Puerco Basin?

Hypothesis 1: Decreased channel complexity and deposition of silt in the beds of arroyo-cut streams results in decreased hydrologic retention.

Predictions: (1) Transient hydraulic storage will be lower in reaches where arroyo formation has impacted the stream channel through incision and/or deposition of fine-grained sediments. (2) Average values for transient storage in Rio Puerco headwaters will be less than in the reference stream (Rio Calaveras).

Alternatively, sediment deposition may provide extensive sand bars and channel storage that promotes subsurface flow and hydrologic retention.

Tests: After identifying geomorphic reaches associated with arroyo formation, we will compare the transient storage of incised (or constricted) reaches with intact reaches of greater channel complexity. Bromide will be used as a biologically and chemically conservative solute to be injected into the surface waters of all study reaches. Bromide transport will be simulated by a one-dimensional transport with inflow and storage computer model (OTIS, Runkel, and

Broshears 1991). Transient storage size (As) is a parameter of the OTIS model that is widely accepted as a measure of hydrologic retention, and will be determined and compared among reaches and streams. Comparison of As among reach types will assess the extent and variation in transient storage with the Rio Puerco headwaters. Comparisons with past injections in the reference stream will be used to test the prediction that arroyo-impacted streams have less transient storage.

Increased hydrologic retention results in longer contact time between water and microbial communities of benthic and hyporheic habitats. Our past research has shown that uptake lengths (the average downstream distance a molecule of nitrate travels in solution before being entrained by biological processing) and transient storage are closely related (Valett et al. [in review]).

Question 2: How does arroyo formation affect the retention of NO_3-N in headwater streams of the Rio Puerco Basin?

Hypothesis 2: Disturbance in the form of scouring during elevated flow and instability of sediments at base flow maintains lower biological activity in the stream channel resulting in reduced nitrate retention in streams affected by arroyo formation.

Predictions: (1) Uptake lengths for NO_3-N will be greater in streams heavily impacted by arroyo formation (e.g., longer uptake lengths will occur in the Rio Puerco headwaters compared to the reference stream). (2) Uptake lengths will be longer in constrained (incised) reaches compared to unconstrained reaches.

Tests: Uptake length for NO_3-N will be determined from experiments in which nitrate is injected with a conservative tracer (Tests for Hypothesis 1, above). Calculated uptake lengths will be compared among study streams (Rio Puerco streams vs. Rio Calaveras) and designated reaches (constrained vs. unconstrained) to assess differences in biological nutrient retention.

Metabolism and carbon cycling in stream sediments

This research element focuses on carbon cycling and the rates and nature of metabolic processes in the sediments of arroyo-impacted streams and associated shallow groundwater systems. Convective thunderstorms and intermittent flows in arroyo tributaries are expected to result in the importation of fine-grained sediments that are low in organic matter content. This research element addresses the intensity of biological activity and the implications of hydrologic exchange between surface and interstitial zones on the metabolism of saturated sediments in headwater streams of the Rio Puerco.

Question 3: What is the influence of arroyo formation on aquatic microbial processes that cycle carbon?

Hypothesis 3a: Because of low organic matter content and frequent disturbance, metabolic demand of stream sediments will be low compared to the hydrologic supply of oxygen, promoting aerobic metabolism in the hyporheic zone.

Prediction: (1) Stream sediments will be low in organic matter (e.g., < 1 percent by weight). (2) Porewater will be well oxygenated. (3) Metabolic activity in sediment will occur aerobically.

Hypothesis 3b: Grain size and other alluvial properties of imported sediments will result in low rates of exchange between oxygenated surface water and metabolically active subsurface regions resulting in anaerobic metabolism and nutrient transformations in stream bed sediments.

Prediction: (1) Alluvial hydraulic conductivity will be low (e.g., less than 1×10^{-5} cm/s) in reaches containing imported sediments. (2) Interstitial water will be anoxic. (3) Metabolic activity in sediments will be anaerobic.

Tests: Sediment cores will be used for measures of respiration, after which sediments will be analyzed for organic matter content. Evolution of CO_2 and O_2 consumption will be used to differentiate between aerobic and anaerobic metabolism in sediment cores. Oxygen concentration in interstitial spaces and alluvial properties will be measured in accordance with Research Element I.

Climatic factors that will be investigated include intense, sustained, or repeated La Niña (dry-winter) conditions and Gulf moisture (intense summer precipitation) conditions. Models will be used to simulate conditions and effects of climate, land use, and vegetation condition on sheet and rill erosion and on arroyo sediment dynamics. The studies have practical application for evaluating water quantity risks imposed on the Elephant Butte Reservoir, located downstream on the Rio Grande from the confluence of the Rio Puerco, and other reservoirs in similar geoclimatic settings. Elephant Butte Reservoir has historically suffered high rates of sedimentation; if these were to recur, then the utility of the dam as the major controlling structure for release of water to the lower Rio Grande (Texas and Mexico) would be impaired. These studies also have practical application to evaluation of water quality risks because toxic and radioactive mine tailings are copious in parts of the basin; their entrainment in sediments may adversely affect water and riparian habitat downstream. Although these studies focus principally on sedimentary processes, they will provide information that benefit the integrated management of the Rio Puerco and Rio Grande ecosystems. Issues as broad as the health of the bosque or wetland forests, the water supplies of El Paso and Albuquerque, and the general economy of the Rio Grande border region may eventually be related to these analyses.

REFERENCES

Aguilar, R.; Francis, R.E.; Stout, P.J. 1990. Erosion/depositional cycles reflected by relict soil horizons, Rio Puerco watershed. Agronomy Abstracts.

American Public Health Association. 1992. Standard methods for the examination of water and wastewater, 18th ed. Amer. Water Works Assoc. 1106 p.

Andrade Jr., E.R.; Sellers, W.D. 1988. El Niño southern oscillation phenomenon and the Sevilleta Long-Term Ecological Research Site. Unpublished manuscript available from Department of Biology, University of New Mexico, Albuquerque, NM. 16 p.

Baldwin, B. 1963. Part 2, Geology. In: Spiegel, Zane, and B. Baldwin. Geology and Water Resources of the Santa Fe Area, New Mexico. U.S. Geological Survey Water-Supply Paper 1525. 21–89 p.

Baltz, E.H. 1978. Resume of Rio Grande Depression in North-Central New Mexico. In: Guidebook to Rio Grande rift in New Mexico and Colorado, compiled by Hawley, J.W. New Mexico Bureau of Mines and Mineral Resources, cir. 163. 210–228 p.

Bencala, K.E. 1984. Interactions of solutes and streambed sediments 2. A dynamic analysis of coupled hydraulic and chemical processes that determine solute transport. Water Resources Research. 20: 1804–1814.

Bencala, K.E. 1993. A perspective on stream-catchment connections. Journal of the North American Benthological Society. 12: 44–47.

Bencala, K.E.; Walters, R.A. 1983. Simulation of solute transport in a mountain pool-and-riffle stream: a transient storage model. Water Resources Research. 19: 718–724.

Betancourt, J.L.; Pierson, E.A.; Rylander, K.A.; Fairchild-Parks, J.A.; Dean, J.S. 1993. Influence of history and climate on New Mexico Piñon-Juniper Woodlands. pp. 42-62. IN: Aldon, E.F.; Shaw, D.W., (ed) Piñon-Juniper Ecosystems for Sustainability and Social Needs.

Bingham, G.E.; Kluzek, E.; Lamaye, A.S.; Riley, J.P. 1995. A nested model chain between GCM scale and river flow: A testbed for vegetation, erosion, and water yield scaling studies. Preprint, American Meteorological Society, Conference on Hydrology, Jan 15–20, 1995. Dallas, TX.

Boulton, A.J.; Peterson, C.G.; Grimm, N.B. 1992a. Stability of an aquatic macroinvertebrate community in a multiyear hydrologic disturbance regime. Ecology. 73: 2192–2207.

Boulton, A.J.; Valett, H.M.; Fisher, S.G. 1992b. Spatial distribution and taxonomic composition of the hyporheos of several Sonoran Desert streams. Archiv fur Hydrobiologie. 125: 37–61.

Bretschko, G.; Leichtfried, M. 1987. The determination of organic matter in river sediments. Archiv fur Hydrobiologie. 68: 403–417.

Bruning, J.E. 1973. Origin of the Popotosa Formation, North Central Socorro County, New Mexico (Ph.D. dissertation). New Mexico Institute of Mining and Technology. 132 p.

Bryan, K. 1925. Date of channel trenching (arroyo cutting) in the arid Southwest. Science. 62: 338–344.

Bryan, K. 1938. Geology and ground-water conditions of the Rio Grande Depression in Colorado and New Mexico. In: (U.S.) Natural Resources Committee, Regional Planning part VI-The Rio Grande Joint Investigations in the Upper Rio Grande Basin in Colorado, New Mexico, and Texas, 1936–37: U.S. Government Printing Office, Vol. 1. 197–225 pp.

Bryan, K.; Post, G.M. 1927. Erosion and control of silt on the Rio Puerco, New Mexico. October, 1927. Report of the Chief Engineer, Middle Rio Grande Conservancy District, Albuquerque, NM. 174 p.

Bryson, R.A.; Hare, F.K. 1974. Climates of North America. World survey of climatology, Vol. 11, Elsevier Science Publishers B.V., Amsterdam.

Castro, N.M.; Hornberger, G.M. 1991. Surface-subsurface water interactions in an alluviated mountain stream channel. Water Resources Research. 27: 1613–1621.

Chapelle, F.H; Lovely, D.R. 1990. Rates of bacterial metabolism in deep coastal-plain aquifers. Applied and Environmental Microbiology. 56: 1865–1874.

Chapin, C.E.; Seager, W.R. 1975. Evolution of the Rio Grande rift in the Socorro and Las Cruces areas. In: New Mexico Geological Society Guidebook,

26th Field Conference, Las Cruces, New Mexico, 1975. 297–321 pp.
City of Albuquerque. 1994. Reduce Your Use: Save Our Water. City of Albuquerque.
Coleman, R.L.; Dahm, C.N. 1990. Stream geomorphology: effects on periphyton standing crop and primary production. Journal of North American Benthological Society. 9: 293–302.
Crawford, C.S.; Cully, A.C.; Leutheuser, R.; Sifuentes, M.S.; White, L.H.; Wilber, J.P. 1993. Middle Rio Grande Ecosystem: Bosque Biological Management Plan. U.S. Fish and Wildlife Service, Albuquerque, NM.
Cummins, K.W.; Sedell, J.R.; Swanson, F.J.; Minshall, G.W.; Fisher, S.G.; Cushing, C.E.; Peterson, R.C.; Vannote, R.L. 1983. Organic matter budgets for stream ecosystems: problems in their evaluation. In: J.R. Barnes and G.W. Minshall, editors. Stream Ecology, Plenum Publishing Corporation. 299–353 pp.
Dahm, C.N. 1981. Pathways and mechanisms for removal of dissolved organic carbon from leaf leachate in streams. Canadian Journal of Fisheries Aquatic Sciences. 38: 68–76.
Dahm, C.N.; Molles, M.C. 1992. Streams in semiarid regions as sensitive indicators of global climate change. In: P. Firth and S. Fisher, eds. Troubled waters of the greenhouse Earth. Springer-Verlag, New York, NY. 240–260 pp.
Dahm, C.N.; Moore, D.I. 1994 The El Niño southern oscillation phenomenon and the Sevilleta Long-Term Ecological Research Site. Unpublished manuscript available from Department of Biology, University of New Mexico, Albuquerque, NM. 16 p.
D'Angelo, D.J.; Webster, J.R.; Benfield, E.F. 1991. Mechanisms of stream phosphorus retention: an experimental study. Journal of North American Benthological Society. 10:225–237.
D'Angelo, D.J.; Webster, J.R.; Gregory, S.V.; Meyer, J.L. 1993. Transient storage in Appalachian and Cascade mountain streams as related to hydraulic characteristics. Journal of North American Benthological Society. 12: 223–235.
D'Arrigo, R.D.; Jacoby, G.C. 1991. A 1000-year record of winter precipitation from nothwestern New Mexico, USA: a reconstruction fom tree-rings and its relation to El Niño and the Southern Oscillation. The Holocene. 1: 95–101.
Denny, C.S. 1940. Tertiary Geology of the San Acacia Area, New Mexico. Journal of Geology. Vol. 48. 73–106 pp.
Diaz, H.F. 1991 Some Characteristics of wet and dry regimesin the contiguous United States: implications for climate change detection efforts. In: Schlesinger, M.E. (ed) greenhouse-gas-induced climatic change: a critical appraisal of simulations and observations. Elsevier Science Publishers B.V., Amsterdam. 269–296 pp.
Diaz, H.F.; Holle R.L.; Thorn Jr., J.W. 1985. Precipitation trends and water consumption related to population in the Southwestern United States, 1930–83. American Meteorological Society, Boston, MA. J. Climate and Applied Meteorology, Vol. 24, No. 2: 145–153.
Dickenson, R.E.; Errico, R.M.; Giorgi, F.; Bates, G.T. 1989. A regional climate model for the Western U.S. Clim Change. 15:383–422.
Diniz, E.V. 1984. Quality of urban runoff in Albuquerque, NM. pp. 93–102 In: W.J. Stone, ed. Selected paper on water quality and pollution in New Mexico. NM Bureau of Mines and Mineral Resources Hydrologic Report 7. NM Institute of Mining and Technology, Socorro, NM.
Dorroh Jr., J.H. 1946. Certain hydrologic and climatic characteristics of the Southwest. University of New Mexico Publications in Engineering No. 1, University of New Mexico Press Albuquerque, NM. 64 p.
Dortignac, E.J. 1956. Watershed resources and problems of the Upper Rio Grande Basin. USDA, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
Duff, J.H.; Triska, F.J. 1990. Denitrification in sediments from the hyporheic zone adjacent to a small forested stream. Canadian Journal of Fisheries and Aquatic Sciences. 47: 1140–1147.
DuMars, C.T. 1993. Institutional and legal responses to global climate change in the Upper Rio Grande Basin. In: Ballentine and Stakhiv, eds. Proceedings of the first national conference on climate change and water resources management. U.S. Army Corps of Engineers IWR Report 93-R–17, Alexandria, VA. II–3 to II–22 pp.
Ehrman, T.P.; Lamberti, G.A. 1992. Hydraulic and particulate matter retention in a 3rd-order Indiana stream. Journal of the North American Benthological Society. 11: 341–349.
Ellis, S.R.; Levings, G.W.; Carter, L.F.; Richey, S.F.; and Radell, M.J. 1993 Rio Grande Valley, Colorado, New Mexico, and Texas. American Water Resources Association. Paper No. 93132. Water Resources Bulletin. Vol 29, No. 4: 617–648.
Elwood, J.W.; Newbold, J.D. O'Neill; R.V.; and W. Van Winkle. 1982. Resource spiraling: an operational

paradigm for analyzing lotic ecosystems. In: T.D. Fontaine III, and S.M. Bartell, editors. Ann Arbor Science Publishers.

Findlay, S.; Strayer, D.; Goumbala, C.; Gould, K. 1993. Metabolism of stream water dissolved organic carbon in the shallow hyporheic zone. Limnology Oceanography. 38: 1493–1499.

Fisher, S.G.; Gray, L.J.; Grimm, N.B.; Busch, D.E. 1978. Temporal succession in a desert stream ecosystem following flash flooding. Ecological Monographs. 52: 93–110.

Fitzsimmons, J.P. 1955. Geomorphology of South - Central New Mexico. In: New Mexico Geological Society 6th Field Conference, South-Central New Mexico. 105–107 pp.

Fitzsimmons, J.P. 1959. The structure and geomorphology of West-Central New Mexico. In: New Mexico Geological Society 10th Field Conference. 112–116 pp.

Flemming, C.A.; Trevors, J.T. 1990. Factors influencing respiration data in freshwater sediments. Hydrobiologia. 192: 205–214.

Gellis, A. 1991. Decreasing trends of suspended sediment concentrations at selected streamflow stations in New Mexico. Proceedings of 36th Annual New Mexico Water Conference, Nov. 7–8, 1991. New Mexico State University Water Resources Research Institute (WRRI) Report No. 265: 77–93.

Gibert, J.; Dole-Olivier, M.J.; Marmonier, P.; Vervier, P. 1990. Surface water-groundwater ecotones. In: R.J. Naiman and H. Decamps, editors. The ecology and management of aquatic-terrestrial ecotones. Man and the Biosphere Series. Vol 4. UNESCO and The Parthenon Publishing Group, Park Ridge, New Jersey. 199–225 pp.

Giorgi, F.; Broudeur, C.; Shields, C.; Bates, G.T. 1994. Regional climate change scenarios over the United States produced with a nested grid regional climate model. Journal of Climate. 7: 375–399.

Gosz, J. 1992. Rios Initiative. Congressional briefing on the Rio Grande Basin. University of New Mexico, Albuquerque, NM.

Graf, W.L. 1988. Fluvial processes of dryland rivers. Springer-Verlag, New York, NY. USA.

Gray, L.J. 1980. Recolonization pathways and community development of desert stream macroinvertebrates. Dissertation. Arizona State University, Tempe, AZ. USA.

Gregory, S.V.; Swanson, F.J.; McKee, W.A.; Cummins, K.W. 1991. An ecosystem perspective of riparian zones. Bioscience. 41: 540–541.

Grimm, N.B. 1987. Nitrogen dynamics during succession in a desert stream. Ecology. 68: 1157–1170.

Grimm, N.B.; Fisher, S.G. 1984. Exchange between interstitial and surface water: implications for stream metabolism and nutrient cycling. Hydrobiologia. 111: 219–22

Grimm, N.B.; Fisher, S.G. 1986. Nitrogen limitation potential of Arizona streams and rivers Journal of the Arizona-Nevada Academy of Science. 21: 31–43.

Grimm, N.B.; Fisher, S.G. 1989. Stability of periphyton and macroinvertebrates to disturbance by flash floods in a desert stream. Journal of the North American Benthological Society. 8: 293–307.

Happ, C.C. 1948. Sedimentation in the Middle Rio Grande Valley, New Mexico. Geological Society of America Bulletin Vol. 59. 1191–1216 pp.

Harvey, J.W.; Bencala, K.E. 1993. The effect of streambed topography on surface-subsurface water exchange in mountain catchments. Water Resource Research. 29: 89–98.

Hawley, J.W.; Haase, C.S. 1992. Hydrogeologic framework of the Northern Albuquerque Basin: Socorro, New Mexico Bureau of Mines and Mineral Resources, Open-File Report 387.

Hawley, J.W.; Love, D.W. 1981. Overview of geology as related to environmental concerns in New Mexico. In: New Mexico Geological Society, Special Publication No. 10. 1–10 pp.

Hawley, J.W.; Love, D.W. 1991. Quaternary and Neogene landscape evolution: a transect across the Colorado Plateau and Basin and range provinces in West-Central and Central Mexico. In: Field Guide to Geologic Excursions in New Mexico and Adjacent Areas of Texas and Colorado. New Mexico Bureau of Mines and Mineral Resources. Bulletin No. 137. New Mexico Institute of Mining and Technology. 105–148 pp.

Heath, D.L. 1983. Flood and recharge relationships of the Lower Rio Puerco. In: New Mexico Geological Society Guidebook 34. 329–337 pp.

Hendricks, S.P.; White, D.S. 1991. Physicochemical patterns within a hyporheic zone of northern Michigan river, with comments on surface water patterns. Canadian Journal of Fisheries and Aquatic Sciences. 48: 1645–1654.

Hereford, R. 1987. Sediment-yield history of a small basin in southern Utah, 1937–1976: Implications for land-management and geomorphology. Geology. 15: 954–957.

Hill, A.R. 1990. Groundwater flow paths in relation to nitrogen chemistry in the nearstream zone. Hydrobiologia. 206: 39–52.

Huggett, R.J. 1993. Modelling the human impact on nature: systems analysis of environmental problems. Oxford University Press, Oxford. 202 p.

Hynes, H.B.N. 1975. The stream and its valley. Verhandlungen Internationale Vereinigung Limnologie. 19: 92–99.

Jacobi, G.Z.; Smolka, L.R. 1984. Reconnaissance survey of Bluewater Creek, Cibola County, June 20–21,1983. EID/WPC–83/10. Environmental Improvement Division, Santa Fe, NM. 9 p.

Jones, J.; Fisher, L S.G.; Grimm, N.B. [In review]. Vertical hydrologic exchange and hyporheic metabolism in a Sonoran Desert stream. Submitted to Ecology.

Kaplan, L.A.; Bott, T.L. 1982. Diel fluctuations of DOC generated by algae in a piedmont stream. Limnology and Oceanography. 27: 1091–1100.

Kaplan, L.A.; Bott, T.L. 1989. Diel fluctuations in bacterial activity on streambed substrata during venal algal blooms: effects of temperature, water chemistry, and habitat. Limnology and Oceanography. 34: 718–733.

Kelly, V.C. 1977. Geology of Albuquerque Basin, New Mexico. New Mexico Bureau of Mines and Mineral Resources, Memoir No. 33. New Mexico Institute of Mining and Technology Socorro, New Mexico. 60 p.

Kelly, Vincent C. 1952. Tectonics of the Rio Grande Depression of Central New Mexico. In: Guidebook of the Rio Grande Country, Central New Mexico, Third Field Conference, October 3–5, 1952. New Mexico Geological Society. 93–103 pp.

Kelson, K.I.; Wells, S.G. 1989. Geologic influences on fluvial hydrology and bedload transport in small mountainous watersheds, northern New Mexico, USA. Earth Surface Processes and Landforms. 14: 671–690.

Kiladis, G.N.; Diaz, H.F. 1989. Global climatic anomalies associated with extremes of the Southern Oscillation. Journal of Climate. 2: 1069–1090.

Kruger, C.C.; Waters, T.F. 1983. Annual production of macroinvertebrates in three streams of differing water quality. Ecology. 64: 840–850.

Lagasse, P.F. 1981. Geomorphic response of the Rio Grande to dam construction. New Mexico Geological Society, Special Publication No. 10, 1982. 27–46 pp.

Lagasse, P.F.; Schall, J.D.; Peterson, M.F. 1987. Erosion risk analysis for a southwestern arroyo. Journal of Urban Planning and Development. 113: 37–39.

Lamberti, G.A.; Gregory, S.V.; Ashkenas, L.R.; Wildman, R.C.; Steinman, A.D. 1988. Influence of channel geomorphology on retention of dissolved and particulate organic matter in Cascade Mountain streams. In: D.L. Abell, editor. Proceedings of the California riparian systems conference, Davis, California. General Report PSW–110, Berkeley, CA. 33–39 pp.

Laquer, Frederic C. 1981. A survey of the trace metal distribution in water and suspended sediment in the Rio Grande, Rio Puerco, and Rio Salado in central New Mexico. Socorro, New Mexico: New Mexico Institute of Mining and Technology. M.S. thesis.

Larkin, R.G.; Sharp Jr., J.M. 1992. On the relationship between river-basin geomorphology, aquifer hydraulics, and ground-water flow direction in alluvial aquifers. Geological Society of America Bulletin. 104: 1608–1620.

Latif, M.; Barnett, T.P.; Cane, M.A.; Flugel, M.; Graham, N.E.;. von Storch, H.; Xu, J-S; Zebiak, S.E. 1994. A Review of ENSO prediction studies. Climate Dynamics. 9: 167–179.

Lee, R.; Cherry, J. 1978. A field exercise on groundwater flow using seepage meters and min-piezometers. Journal of Geological Education. 27:6–10.

Likens, G.E.; Bormann, F.H.; Johnson, M.M.; Fisher, D.W.; Pierce, R.S. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook Watershed Ecosystem. Ecological Monographs. 40: 23–47.

Love, D.W.; Hawley, J.W.; Young, J.D. 1983. Preliminary report on the geomorphic history of the Lower Rio Puerco in relation to archeological sites and cultural resources of the Hidden Mountain Dam Site. In: Inventory survey of the Lower Hidden Mountain flood-pool, Lower Rio Puerco Drainage, Central New Mexico: Tularosa, NM, Human Systems Research. 21–65 pp.

Luce, C.H.; Kluzek, E.; Bingham, G.E. 1995. Development of a high resolution climatic data set for the Northern Rockies. In: Tinus, Richard W., tech ed. Interior west global change workshop. RM-GTR-262. Fort Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station.

McDowell, W.H.; Bowden, W.B.; Asbury, C.E. 1992. Riparian nitrogen dynamics in two geomorphologically distinct tropical rain forests watersheds: subsurface solute patterns. Biogeochemistry. 18: 53–75.

Maciolek, J.A. 1962. Limnological analyses by quantitative dichromate oxidation. Research Report No.

60, United States Fish and Wildlife Service, Washington, D.C.

Mearns, L.O; Giorgi, F.; McDaniel, L.; Shields, C. [In press]. Analysis of daily variability of precipitation in a nested regional climate model: comparisons with observations and doubled CO_2 results. Global and Planetary Change.

Metzler, G.M.; Smock, L.A. 1989. Storage and dynamics of subsurface detritus in a sand-bottomed stream. Canadian Journal of Fisheries and Aquatic Sciences. 47: 588–594.

Miller, J.R. 1985. Sediment storage, transport, and geochemistry in semiarid fluvial and eolian systems: applications to long-term stability and potential dispersal pattern of uranium tailings in the Grants mineral belt, New Mexico. Albuquerque, NM: University of New Mexico. M.S. Thesis. 160 p.

Molles Jr., M.C.; Dahm, C.N. 1990. A perspective on El Niño and La Niña: global implications for stream ecology. Journal of the North American Benthological Society. 9: 68–76.

Molles, M.C.; Dahm, C.N.; Crocker, M.T. 1992. Climatic variability and streams and rivers in semiarid regions. In: R.D. Roberts and M.L. Bothwell, eds. Aquatic ecosystems in semi-arid regions: implications for resource management. N.H.R.I. Symposium Series 7, Environment Canada, Saskatoon. 197–202 pp.

Morrice, J.A.; Valett, H.M.; Dahm, C.N.; and Campana, M.E. [In review]. Alluvial characteristics, groundwater-surface water exchange and hydrologic retention in headwater streams. Submitted to Limnololgy and Oceanography.

Munn, N.L.; Meyer, J.L. 1990. Habitat-specific solute retention in two small streams: an intersite comparison. Ecology. 71: 2069–2082.

Newbold, J.D.; Elwood; J.W.; O'Neill, R.V.; Sheldon. A.L. 1983. Phosphorus dynamics in a woodland stream ecosystem: a study of nutrient spiralling. Ecology. 64: 1249–1265.

NM Environmental Improvement Division. 1982. Work Element 4.1., Irrigated Agriculture. NMEID, Santa Fe, NM. 8 p.

NM Water Quality Control Commission. 1992. Water quality and water pollution control in New Mexico.

NM Water Quality Control Commission. 1992. NMED/SWQ–92/1. NM Water Quality Control Commission, Santa Fe, NM. 289 p.

NM Water Quality Control Commission. 1991. Water quality standards for interstate and intrastate steams in NM. NMWQCC, Santa Fe, NM. 49 p.

Pierce, S.T. 1989. Intensive water quality survey of the Rio Grande from Angostura to U.S. 85 Bridge, Sandoval and Bernalillo Counties, NM, July 25–28, 1988. EID/SWQ–88/6. NM Environmental Improvement Division, Santa Fe, NM.

Popp, C.J.; Brandvold, D.K.; Brierly, J.A.; Scott, N.J.; Gloss, S.P. 1980. Heavy metals and pesticides in water, sediments and selected tissue samples of aquatic life in the Middle Rio Grande Valley of New Mexico. Final Report Project EPA-E4W7–06–072. University of New Mexico, Albuquerque, NM. 206 p.

Popp, C.J.; Hawley, J.; Love,D.; Dehn, M. 1988. Use of radiometric (Cs–137, Pb–210), geomorphic, and stratigraphic techniques to date recent oxbow sediments in the Rio Puerco Drainage, Grants uranium region, New Mexico. Environmental Geology Water Science. (11)3: 253–269 pp.

Popp, C.J.; Laquer, F. 1980. Trace metal transport and partitioning in suspended sediments of the Rio Grande and tributaries in Central New Mexico. Chemosphere. Vol. 9. 89–98 pp.

Potter, D.U. 1984a. Rio Grande water quality survey (August 28 -September 4, 1984) in response to a sewer line break at Tijeras Arroyo on August 25, 1984. EID/SWQ–84/9. Environmental Improvement Division, Santa Fe, NM. 27 p.

Potter, D.U. 1984b. Intensive survey of the Rio Grande upstream and downstream from the City of Albuquerque Wastewater Treatment Facilities, March 21–22, 1984. EID/SWQ–84/5. Environmental Improvement Division, Santa Fe, NM. 10 p.

Potter, D.U. 1984c. Summary of water quality data collected on the Rio Grande, November 1 through February 21, 1984, during the construction of Albuquerque's WWTP No. 2 (AO, Docket No. VI–83–744, issued by EPA for Oct. 1-May 15, 1984. EID/SWQ–84/4. Environmental Improvement Division, Santa Fe, NM. 33 p.

Potter, D.U. 1985a. Loading effects of the Española, Santa Fe and Los Alamos County wastewater treatment facilities on Cochiti Reservoir. Phase II: Nutrient Loading Calculations for April 1984 -March 1985 and Final Project Summary. EID/SWQ–85/4. Environmental Improvement Division, Santa Fe, NM. 85 p.

Potter, D.U. 1985b. Reconnaissance Survey of Las Huertas Creek near Placitas in Sandoval Co., NM, June 25–26, 1985. Data file 85–35–07. NM Environmental Improvement Division, Santa Fe, NM.

Potter, D.U. 1986. Loading effects of the Albuquerque wastewater treatment facilities on Elephant

Butte Reservoir, Sierra County, Water Years 1976–1985. EID/SWQ–86/9. NM Environmental Improvement Division, Santa Fe, NM. 81 p.

Potter, D.U. 1987a. Intensive water quality survey of the Jemez River and its tributaries in Sandoval County, August 3–6, 1987. EID/SWQ–87/11. NM Environmental Improvement Division, Santa Fe, NM. 59 p.

______________. 1987b. Intensive water quality survey of the Rio Grande in Socorro County, June 8–11, 1987. NM Environmental Improvement Division (EID/SWQ–87/7), Santa Fe, NM. 70 p.

Potter, D.U. 1988. Intensive water quality survey of Las Huertas Creek. NM Environmental Improvement Division, Santa Fe, NM.

Potter, D.U.; Tague, D.F. 1986. Intensive survey of the Rio San Jose, Cibola County, NM, May 20–21, June 17–18, and July 8–9, 1986. EID/SWQ–88/6. NM Environmental Improvement Division, Santa Fe, NM. 58 p.

Pringle, C.M.; Triska, F.J. 1991. Effects of geothermal groundwater on nutrient dynamics of a lowland Costa Rican stream. Ecology. 72: 951–965.

Revelle, R.R.; Waggoner, P.E. 1989. Effects of climatic change on water supplies in the western United States. In: D.E. Abrahamson, ed., The challenge of global warming. Island Press, Washington, D.C. 151–160 pp.

Ropelowski, C.F.; Halpert, M.S. 1986. North American precipitation and temperature patterns assoicated with El Niño/Southern Oscillation (ENSO). Montly Weather Review. 114: 2352–2362.

Ropelowski, C.F.; Halpert, M.S. 1987. Global and regional scale precipitation patterns assoicated with El Nino/Southern Oscillation (ENSO). Montly Water Review. 115: 1606–1626.

Runkle, R.L; Broshears, R.E. 1991. One-dimensional transport with inflow and storage (OTIS): A solute transport model for small streams. CADSWES Technical Reports: 91–01.

Sanchez, Blane. 1994. Pueblo of Isleta, Isleta, NM.

Schmandt, J. (ed.). 1993. Water and Development: The Rio Grande/Rio Bravo. Houston Advanced Research Center, Center for Global Studies, Houston, TX.

Schmandt, J. (ed.). 1994. Uniting the Basin: the Rio Grande/Rio Bravo sustainable development conference. Houston Advanced Research Center, Woodlands, TX.

Shepherd, R.G. 1976. Sedimentary processes and structures of ephemeral stream point bars, Rio Puerco near Albuquerque (abs): Geological Society of America Abstracts with Programs 8, No. 6, 1103 p.

Slavin, P.J. 1991. Summary of recent work on the geomorphology of the Upper Rio Puerco. In: Field guide to geologic excursions in New Mexico and adjacent areas of Texas and Colorado. New Mexico Bureau of and Mineral Resources. Socorro, NM. 171–172 pp.

Speaker, R.W.; Moore, K.; Gregory, S.V. 1984. Analysis of the process of retention of organic matter instream ecosystems., Verhandlungen Internationale Vereinigung Limnologie. 22: 1835–1841.

Stone, W.; Minnis, M.; Thompson, S.; Nunn, S.C. 1991. The Rio Grande Basin. In: Stone, ed. The Rio Grande Basin global climate change scenarios. WRRI Report No. M24, Water Resource Research Institute, Las Cruces, NM. 17–26 pp.

Stream Solute Workshop. 1990. Concepts and methods for assessing solute dynamics in stream ecosystems. Journal of North American Benthological Society. 9:95–119.

Tague, D.F.; Drypolcher, A. 1979. Pollutant loads in stormwater runoff from Albuquerque, NM. Environmental Improvement Division, Santa Fe, NM. 45 p.

Tremback, C.J.; Tripoli, G.J.; Arritt, R.; Cotton, W.R.; Pielke, R.A. 1986. The regional atmospheric modeling system—RAUS. Proc. Conf. Development and Applications of Computer Techniques to Environmental Studies. P. Zannetti, Ed. Computational Mechanics Publications, Boston. pp. 601–607.

Thorn, C.R.; McAda, D.P.; Kernodle, J.M. 1993. Geohydrologic framework and hydrologic conditions in the Albuquerque Basin, Central NM. U.S. Geological Survey. Water Resources Investigations Report 93–4149, Albuquerque, NM. 106 p.

Thornthwaite, C.W.; et al. 1942 Climate and accelerated erosion in the arid and semi-arid Southwest, with special refernce to the Polcca Wash Drainage Basin. USDA Technical Bulletin No. 808. Washington, D.C.

Triska, F.J.; Kennedy, V.C.; Avanzino, R.J.; Zellweger, G.W.; Bencala, K.E. 1989a. Retention and transport of nutrients in a third-order stream in northwestern California: channel processes. Ecology. 70: 1877–1905.

Triska, F.J.; Kennedy, V.C.; Avanzino, R.J.; Zellweger, G.W.; Bencala, K.E. 1990. *In situ* retention-transport responses to nitrate loading and storm discharge in a third-order stream. Journal of the North American Benthological Society. 9: 229–239.

Triska, F.J.; Duff, J.H.; Avanzino, R.J. 1993. Patterns of hydrological exchange and nutrient transformation in the hyporheic zone of a gravel-bottom stream: examining terrestrial-aquatic linkages. Freshwater Biology. 29: 259–274.

Trotter, E.H. 1990. Woody debris, forest-stream succession, and catchment geomorphology. Journal of the North American Benthological Society. 9: 141–156.

USDI, Bureau of Reclamation. 1994. Summary of findings, Rio Puerco, NM.

U.S. Geological Survey. 1992. National Water Summary 1990–91—Stream Water Quality: New Mexico. U.S. Geological Survey Water Supply Paper 2400. USGS, Albuquerque, NM.

Valett, H.M.; Fisher, S.G.; Stanley, E.H. 1990. Physical and chemical characteristics of the hyporheic zone of a Sonoran Desert stream. Journal of the North American Benthological Society.

Valett, H.M.; Fisher, S.G.; Grimm, N.B.; Camill, P. 1994. Vertical hydrologic exchange and ecological stability of a desert stream ecosystem. Ecology. 75: 548–560.

Valett, H.M; Morrice, J.A.; Dahm C.N.; Campana, M.E. [In review]. Parent lithology, groundwater/surface water exchange, biogeochemistry, and nitrate retention in headwater streams. Submitted to Limnololgy and Oceanography.

Vaux, W.G. 1968. Intergravel flow and interchange in water in a streambed. Fisheries Bulletin. 66: 479–489.

Vervier, P.; Dobson, M.; Pinay, G. 1993. Role of interaction zones between surface and ground waters in DOC transport and processing: considerations for river restoration. Freshwater Biology. 29: 275–284.

Vitousek, P.M.; Reieners, W.A. 1975. Ecosystem succession and nutrient retention: an hypothesis. Bioscience. 25: 376–381.

Waite, D.A., et al. 1972. Rio Puerco Special Project Evaluation Report 1242.3: Santa Fe, NM. U.S. Department of Interior, Bureau of Land Management. 35 p.

Ware, J.A. 1984. Man on the Rio Grande: introduction and overview. In: New Mexico Geological Society Guidebook, 35th Field Conference, Rio Grande Rift: Northern New Mexico. 271–273 pp.

Watts, R.D.; Fox, D.G.; DeCoursey, D.; Goonan, T. 1994. Arroyo dynamics of the Rio Puerco Basin. TERRA Work Plan, Draft Document.

Webster, J.R.; Patten, B.C. 1979. Effects of watershed perturbation on stream potassium and calcium dynamics. Ecological Monographs. 19: 51–72.

Wertz, J.B. 1963. Mechanisms of erosion and deposition along channelways. Journal of the Arizona Academy of Science. 2: 146–163.

Wierenga, P.J.; Duffy, C.; Senn, R.; Gelhar, L.W. 1981. Impacts of irrigated agriculture on water quality in the Rio Grande below Albuquerque, NM. Department of Agronomy, New Mexico State University, Las Cruces, NM. 135 p.

White, D.S.; Elzinga, C.H.; Hendricks, S.P. 1987. Temperature patterns within the hyporheic zone of a northern Michigan river. Journal of the North American Benthological Society. 6: 85–91.

Williams, D.D. 1984. The hyporheic zone as habitat for aquatic insects and associated arthropods. In: V.H. Resh and D.M. Rosenberg, editors. The Ecology of Aquatic Insects, Prager Press, New York, NY. 430–455 pp.

Wilson, D.B.; Babcock, P.D. 1979. Nitrogen and phosphorus compounds in the Middle Rio Grande. Engineering Experiment Station. New Mexico State University, Las Cruces, NM. 62 p.

Wilson, D.B.; Tague, D.F.; Snavely, M.; Babcock, P. 1984. Nitrogen/phosphorus transport in the Rio Grande. In: W.J. Stone, ed. Selected papers on water quality and pollution in New Mexico. NM Bureau of Mines and Mineral Resources Hydrologic Report, Socorro, NM. 119–134 pp.

Winter, T.C.; LaBaugh, I.W.; Roseburg, D.O. 1988. The design and use of a hydraulic potentiomanometer for direct measurement of differences in hydraulic head between groundwater and surface water. Limnology and Oceanography. 33: 1209–1214.

Woodson, R.C.; Martin, T.J. 1963. The Rio Grande Comprehensive Plan in New Mexico and its Effects on the River Regimen Through the Middle Valley. Proceedings of the Federal Interagency Sedimentation Conference, Jackson, Mississippi.

Wroblicky, G.J.; Campana, M.E.; Valett, H.M.; Morrice, J.A.; Henry, K.S.; Dahm, C.N.; Hurley, J.V.; Noe, J.M. 1992. Remote monitoring of stream hyporheic zones with inexpensive pressure transducer-data acquisition systems. In: J.A. Stanford and J.J. Simons, editors. Proceedings of the first international conference on ground water ecology. American Water Resource Association Technical Publication Series, Bethesda, MD. 267–277 pp.

Young, J.D. 1982. Late Cenozoic Geology of the Lower Rio Puerco–Valencia and Socorro Counties, New Mexico. M.S. Thesis. New Mexico Institute of Mining and Technology. 126 pp.