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The Middle Rio Grande: Its ecology and management

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Abstract.-The Middle Rio Grande (MRG) riparian forest, or "bosque", represents the largest cottonwood gallery riparian forest in the southwestern United States. This reach of the Rio Grande extends from Cochiti Dam downstream 260 Km to San Marcial, New Mexico. It constitutes 8% of the river's total length and 34% of if its length in New Mexico. The valley traverses three major biotic communities, as defined by Brown and Lowe (1980). The MRG reach can be subdivided into 4 reaches which coincide roughly with the 4 geologic basins or "grabens" along this portion of the Rio Grande Rift. This system has been affected by man's activities throughout prehistoric and modern eras. The Rio Grande is regulated for water supply (primarily irrigation) and flood control. The effects of this interaction have contributed to the character of the riparian ecosystem in its current expressron. Over 40% of New Mexico's population lives within the MRG reach. This paper will discuss the climate, geology, hydrology, subsequent river morphology, and anthropogenic factors which contribute to the past and current expressions of the riparian habitat associated with the Middle Rio Grande.

INTRODUCTION

The Rio Grande is one of the longest rivers in North America (1900 miles). The Rio originates in the southern Rocky Mountains of Colorado, flows the whole length of New Mexico and forms the entire border between the state of Texas and the Republic of Mexico (fig. 1). The Rio is the greatest source of permanent water in the desert southwest other than the Colorado River. It is home to the largest cottonwood forest in North America, locally referred to as the "Bosque".

Human populations have increased dramatically along the Rio Grande since European settlement. Human use of water for irrigation and consumption, and human use of land for agriculture, urban centers, livestock grazing and recreation have changed Rio Grande ecosystems by altering flood cycles, channel geomorphology, upslope processes, and water quality and quantity. Such abiotic changes have influenced the biological diversity and ecological functions of the MRG, altering the distribution, structure, and composition of riparian plant and animal communities.

The Rio Grande basin above El Paso, Texas, is one of the oldest regions of agriculture in the United States. Agricultural activity extends back centuries to prehistoric inhabitants of the Rio Grande valley (fig. 2.) and includes the seventeenth and eighteenth century Pueblo Indians and Spanish colonists, and European-Americans in the latter part of the nineteenth century (Wozniak 1987). More recent history of the region involves disputes and concerns over management, irrigation, and distribution and delivery of upstream waters to downstream users in an attempt at fair sharing between concerned parties. Because of the

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long history of agricultural activity, Rio Grande water is tied to public laws governing its conveyance, storage, and use. The close connection between legislation and flow of water through the Rio Grande is largely responsible for the present physical state of the river, floodplain, and associated riparian community. Changes in the floodplain ecology probably began shortly after human settlement in the region, and change has continued relatively unabated with increasing population. (Bullard and Wells 1992).

LOCATION

The MRG is part of the larger Rio Grande fluvial system (fig. 1). The Rio Grande headwaters lie along the Continental Divide at elevations ranging from 2,440 m to 3,660 m in the San Juan Mountains of southern Colorado. The entire area of the Rio Grande drainage basin is about 470,000 sq. km of which about 230,00 sq. km. are in the United States and the remainder in Mexico (Hunt, 1974). The river flows south from Colorado through the length of New Mexico and then forms the international boundary between Texas and the Republic of Mexico. The drainage basin area above Elephant Butte is about 76,275 sq. km., including 7,615 sq. km. in the Closed Basin of the San Luis Valley in Colorado. Above Velarde the drainage basin area is about 27,325 sq. km., including the Closed Basin. The Rio Chama, one of the most important tributaries in the study area, has its headwaters in the Jemez, Conejos, and San Juan Mountains of New Mexico and Colorado. The MRG extends from Cochiti Dam downstream 260 river km (160 mi) to San Marcia1 (fig. 3). The MRG constitutes 8% of the River's total length and 34% of its length in New Mexico. The middle valley's direct drainage accounts for 7% of the total Rio Grande drainage and about half of New Mexico's direct tributary drainage.

PHYSIOGRAPHY AND GEOLOGY

Hydrologic characteristics of the Rio Grande Basin, such as infiltration, runoff, and sediment discharge, are dependent on the geology, geomorphic evolution of tributary basins and late Tertiary and Quaternary geologic and climatic history. Structural geology (such as faults and folds) of a region governs spatial and geometric relations of rock units in that region. Geologic structures and lithology influence the development of topographic features, river and tributary position, and landscape evolution. Tectonic activity can produce measurable effects on channel and sediment transport characteristics (Ouchi 1983, 1985; Schumm 1986).

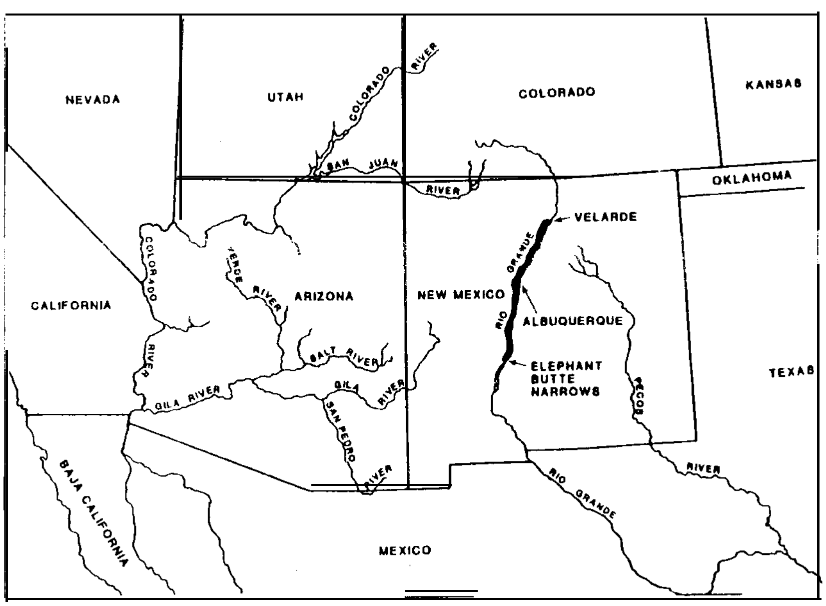

Figure 1. Middle Rio Grande study area (from Bullard and Wells, 1992).

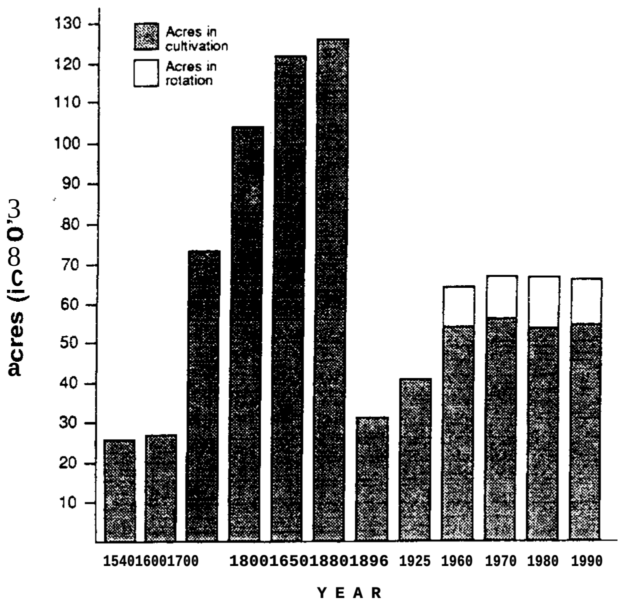

Figure 2. Historical account of acres of land under cultivation in the Middle Rio Grande Valley (acres/ 2.47=hectares) (From Crawford et al, 1993).

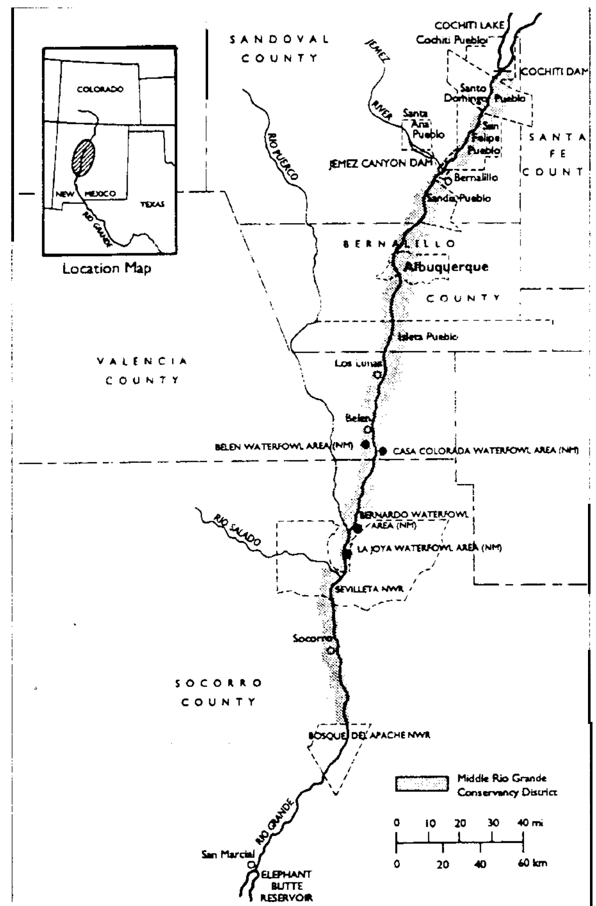

Figure 3. Setting and institutional boundaries in the Middle Rio Grande (from Crawford et al, 1993).

The location of the Rio Grande is controlled by the dominant geologic structure of the region, the Rio Grande Rift. The Rio Grande Rift is a linear topographic feature that separates the Great Plains from the Colorado Plateau (Hawley 1978) mountain ranges, which can influence weather patterns, are a direct result of geologic processes. The rift, active for at least 18 million years (Wilkins 1986), is characterized by extension, seismicity, local tectonic uplift, and volcanism (Loainski et al. 1991). The location of early trade routes was influenced by the spatial arrangement of mountain ranges that were natural barriers to travelers. Indigenous populations and early settlers in the region sought areas of suitable climate, access, and availability of water. Thus, the presence of the Rio Grande Rift has influenced human settlement patterns in the region.

The extent and type of bedrock can influence infiltration and runoff characteristics. These factors can dramatically influence tributary basin evolution, discharge characteristics, main stem flow, and main stem evolution and integration (Leopold et al. 1964; Schumm 1977; Richards 1982; Kelson 1986; Wells et al. 1987, Bullard and Wells 1992). Bedrock type influences vegetation types and densities, which in turn influence infiltration and runoff, landscape stability, soil development, and sediment supply. Soil development is important because natural, progressive changes in physical properties of soils occurring through time alter the nature of the land surface, including vegetation communities, infiltration (decreases with increasing age), erosion, and runoff and discharge.

PHYSIOGRAPHIC REGIONS

The Rio Grande basin lies in five physiographic provinces: the Coastal Plain, the Great Plains, the Basin and Range, the Colorado Plateau, and the Southern Rocky Mountains (Hunt 1974). The MRG and its tributaries are located within the latter three provinces. From about Santa Fe southward, the rift is in the Basin and Range Physiographic Province which separates the Colorado Plateau

Province to the west from the Great plains Province to the east. (Crawford et al. 1993).

The MRG valley is actually a series of basins. These grabens (depressions) formed a series of linked, but slightly offset, depositional basins, each of which contained its own ephemeral lake. Over time, the surface water eroded canyons between the intervening bedrock sills that defined the basins, integrating the area into the Rio Grande river system (Bullard and Wells 1992). The through-flowing ancestral Rio Grande drainage developed into a single river about 5 million years ago (Lozinski et al. 1991). The basins in the Middle Rio Grande are:

- Santo Domingo Basin
- White Rock Canyon to San Felipe
- Albuquerque Basin
- San Felipe to Isleta
- Belen Basin
- Isleta to San Acacia
- Socorro Basin
- San Acacia to San Marcia1

CLIMATE

The hydrology and morphology of the Rio Grande are ultimately dependent on the climate and geology of the area. An overview of these topics will create a foundation of understanding for later discussions.

The valley's climate is characterized as having moderate temperatures and being semiarid above Bernalillo to arid south of Bernalillo (Tuan et al. 1973). Temperatures increase and precipitation decreases from north to south. Annual average maximum temperatures, which usually occur in July, range from 21°C (69°F) at Cochiti Dam to 24°C (76°F) at Bosque del Apache National Wildlife Refuge (NWR). Annual average minimum temperatures (January) are about 4°C (40°F) throughout the valley. The growing season also increases southward through the valley. In Bernalillo and Albuquerque, the typical frost-free period begins in early May and extends through mid-October, lasting on average 160 days. In Socorro, the average period is 197 days, beginning in Mid-May and lasting through late October.

The Rio Grande drainage basin is located in a transitional climatic zone between the Gulf of Mexico and the Pacific rainfall provinces. Complex meteorological conditions exist in this region, and these conditions are further complicated by the orographic influence of surrounding mountain ranges and global circulation patterns.

The MRG basin has an arid to semiarid climate typical of the southwestern United States. The climate is characterized by abundant sunshine, low relative humidity, light precipitation, and wide diurnal temperature fluctuations. The average annual precipitation varies from 178 MM (7 in.) to 380 mm (15.25 in.) over two-thirds of the basin and may exceed 635 mm (25 in.) only in the high mountain areas. Winters are generally dry, and snow rarely remains on the ground at low elevations for more than 24 h. Snowfall in the high mountains composes 30-75% of the total annual precipitation; in the remainder of the basin snowfall composes less than 25% of the annual precipitation. Summer precipitation supplies almost half of the annual moisture. Most of the rain falls in brief, though sometimes intense, convective thunderstorms (fig. 4). These summer thunderstorms have a considerable moderating effect on daytime temperatures. Prevailing winds are from the southwest and typically are continuous during the spring months. Evaporation rate is high throughout the lower elevations of the basin and is highest in the southern part of the basin, where arid conditions exist.

Storms in the region are of two types; local thunderstorms that result from orographic or convective lifting, and frontal storms resulting from the interaction of two or more air masses. Generally, precipitation during storm periods lasts less that 24 h, although precipitation intensity may be extremely high at some locations within the general storm area. Precipitation periods lasting more than 24 h are generally associated with tropical disturbances related to hurricane activity in the Gulf of Mexico or in the Pacific Ocean off the west coast of Mexico.

Storms are seasonal with respect to type and magnitude. Summer months, June through August, are normally characterized by intermittent

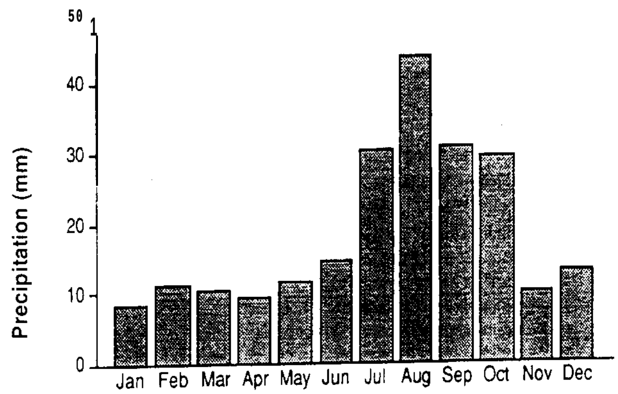

Figure 4. Monthly average precipitation distribution in the Middle Rio Grande Valley (after Crawford et al, 1993).

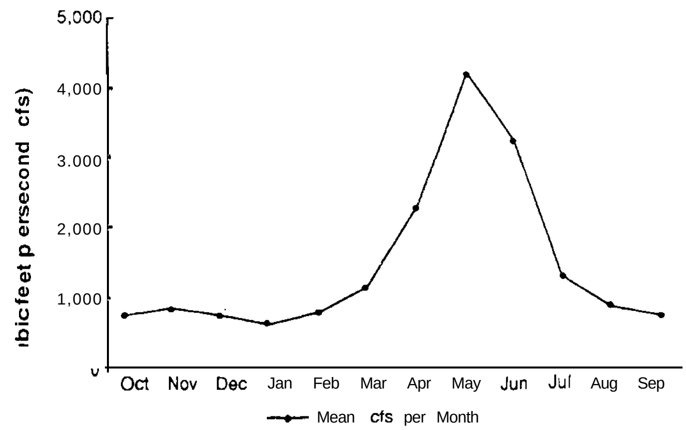

Figure 5. Mean monthly discharge in cubic feet per second (cfs) of the Rio Grande at the Otowi gauge above Cochiti Lake (U.S. Geological Survey data, 1895-l 991).

importations of tropical maritime air masses. Orographic lifting or convective action results in isolated shower activity, which is often intense but generally localized.

Vigorous air-mass activity occurs during winter months, November through February, and is characterized by a series of cold fronts of polar Pacific air moving eastward or northeastward (Maker et al. 1972). This results in snow in the higher elevations and rain in the lower elevations. Due to the northerly path of the storms precipitation in the southern part of the basin is generally low.

The periods transitional to summer and winter (March through May and September through October) are associated with some of the largest flood-generating storms. Greater temperature differences between air masses are reflected in increased air-mass instability.

Runoff in the basin comes largely from spring snowmelt and spring and summer convective thunderstorms; it ranges from <25 mm (1 in.) to >255 mm (10 in.) in the mountains. About 70% of the runoff occurs from May to August during snowmelt and thunderstorm activity (fig. 5).

FLUVIAL CHARACTERISTICS

The physical nature of the Rio Grande, and its tributaries, varies with its position in the drainage basin. This is a direct reflection of the geology and topography of the physiographic regions traversed by the river. Gradient, channel pattern and width, discharge, and sediment load are variable throughout the length of the river. Discharge and sediment load characteristics will be discussed in more detail in separate sections.

GRADIENT OF THE RIO GRANDE

Relief is high in headwater regions, and tributary streams characteristically flow through steep canyons on their way to the San Luis Valley; gradients locally may be tens of meters per kilometer. The river has a gradient of about 0.56 m/km through the San Luis Valley. Through the Rio Grande Gorge, river slope ranges from 2.25 to >28.4 m/km. From Velarde to Cochiti Reservoir the downstream end of White Rock Canyon) river gradient is about 1.9 m/km. From below Cochiti Dam to Elephant Butte the gradient is about 0.76 m/km.

CHANNEL OF THE RIO GRANDE

The channel of the Rio Grande varies dramatically with geographic location within the river basin. Channel characteristics such as width and sinuosity are strongly influenced by position within the drainage basin and proximity to tributaries that discharge large volumes of sediment into the main stem.

The width of the Rio Grande Valley ranges from <200 m (656 ft.) in the Rio Grande Gorge to 1.5-10 km (1-6 mi) from Velarde to Elephant Butte, with the exception of White Rock Canyon and the San Marcia1 Constriction. Short canyons or narrows also exit at San Felipe, Isleta, and San Acacia at the boundaries of the sub-basins within the Rio Grande Rift The floodplain of the Rio Grande ranges from 150 m (492 FT) or less in the Rio Grande Gorge to greater than 1 km (.62 mi) in the reaches from Velarde to White Rock Canyon and from Cochiti Dam to San Acacia.

The channel is narrowest in the bedrock canyons and widest in the broad alluvial valleys downstream from Bernalillo. Generally, the channel is 60-90 m (196-295 ft) wide, flows on shifting sand and gravel substratum, and has low, poorly defined banks (Lagasse 1980). Within the MRG the floodway is largely confined between earthen levees and is cleared for much of the length, especially in urban areas and areas prone to highest aggradation. The floodplain contains a mixture of cottonwood (*Populus Fremontii*), willow (*Salix spp.*), Russian-olive (*Elaeagnus angustifolia*), and salt cedar (*Tamarix chinensis*), which together form a dense growth of riparian woodland (known as bosque), interspersed with pasture and cultivated land (Lagasse 1981). The existing contiguous bosque that abuts the Rio Grande is generally limited by the system of levees or natural bluffs where such features are present. In the southern half of the valley where the bosque is at its widest, the bosque is up to *4-5* km (2.5-3 mi) wide.

The Middle Rio Grande is slightly sinuous with straight, meandering, and braided reaches. The river is generally characterized by a shifting sandbed in the reaches and by a gravel riverbed in the Cochiti Reach. Although a perennial river, there are reaches of the Rio Grande that experience no surface flow during some summer months in dry climatic periods (Crawford et al. 1993). The 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. In some places the floodway is unstable (i.e. the channel is not confined to a fixed position). In these areas, the channel has virtually no banks, and the bed of the river is at or above the land surface outside the levees due to sediment deposition between the levees. Braided meandering patterns are especially common downstream from major sediment-supplying tributaries such as the Rio Puerco and the Rio Salado and other small, unregulated, high-sediment-discharge tributaries in the reach below Cochiti Dam.

The addition of numerous flood control and sediment control structures on the Rio Grande and tributaries has eliminated some of the problems formerly associated with flood-transported sediment discharged into the main stem. On the other hand, flood control structures have added to the problem of channel migration in some reaches of the river downstream of dams (Lagasse 1980,1981; Bullard and Wells 1992).

DISCHARGE OF THE RIO GRANDE

The Rio Grande is a perennial river that receives the majority of its discharge from late spring snowmelt and rain storms. Summer convective storms produce runoff in isolated parts of the basin, which may alter the hydrology for brief periods.

The majority of the discharge for thr MRG comes from the headwaters of the Rio Grande in Colorado and from the Rio Chama. The Rio Chama joins the Rio Grande 35 miles north of Cochiti Reservoir. The Rio Chama is assured of perennial discharge because of the San Juan-Chama Transmountain diversion (SJC) Project and dams along the Rio Chama and its tributaries (U.S. Bureau of Reclamation 1981). Average annual discharge for the Rio Grande into the Gulf of Mexico is about 9,000,000 acre-feet (Hunt 1974). The annual runoff in headwater regions ranges from 215,000 to 1,100,000 acre-feet, with and average of 660,000 acre-feet (U.S. Corps of Engineers 1989).

The Rio Grande has some of the longest stream gaging records in the United States; however, these records are not necessarily the most reliable (Bullard and Wells 1992). The Embudo gage near the southern end of the Rio Grande Gorge was installed in 1889 and has nearly 100 years of record, although not continuous. Reliability and continuity of stream gaging station data are problems throughout the United States, and The Rio Grande is no exception.

The main stem discharge of the MRG can be characterized by 10 gaging stations: Embudo upstream from Velarde, San Juan Pueblo (discontinued in 1987), Otowi Bridge near San Ildefonso, below Cochiti Dan, San Felipe, Albuquerque, Rio Grande Floodway near Bernardo, RIO Grande Floodway at San Acacia, Rio Grande Floodway at San Marcial, and below Elephant Butte Reservoir. Annual average flow at Otowi Bridge (fig. 6), is about 1,100,000 acre-feet; downstream at San Marcia1 above Elephant Butte Reservoir, the annual average flow is 745,000 acre-feet (U.S. Army Corps of Engineers 1989).

Due to extensive agricultural activity in the MRG nearly all Rio Grande water is appropriated. Releases from upstream reservoirs, under non-flood conditions, are regulated to make reservoir outflows equal to inflows in order to meet water demands. Irrigation accounts for about 90% of demands. Irrigation accounts for Rio Grande water used in the region; however, water diverted for agricultural purposes is not fully utilized. About 67% of all diverted water does not reach farmlands. This water consists of transportation losses (spills, seepage losses to unlined canals), evapotranspiration, and groundwater recharge. About 45% of all water diverted eventually returns to the river. About 33% of water diverted reaches the farms; crops use about 55% of this amount (or about 20% of the total diverted from the river). About 35% of the total diverted water is lost to evapotranspiration or groundwater recharge (U.S. Army Corps of Engineers 19793.

SEDIMENT LOAD OF THE RIO GRANDE AND TRIBUTARIES

Suspended sediment loads for the Rio Grande and tributaries are variable. These are regulated to a certain degree by flood and sediment control structures, especially in the regions above Albuquerque. Tributaries, however, can be major contributors of sediment to the Rio Grande. An increase in sediment supplied to the Rio Grande can have dramatic effects on river behavior and geomorphology both upstream and downstream (Schumm 1977; Lagasse 1980,1981).

Based upon data reviewed by Bullard and Wells (1992), the Rio Puerco which has half of the drainage area of that of the Rio Chama and the Jemez River contributes far more sediment than that of

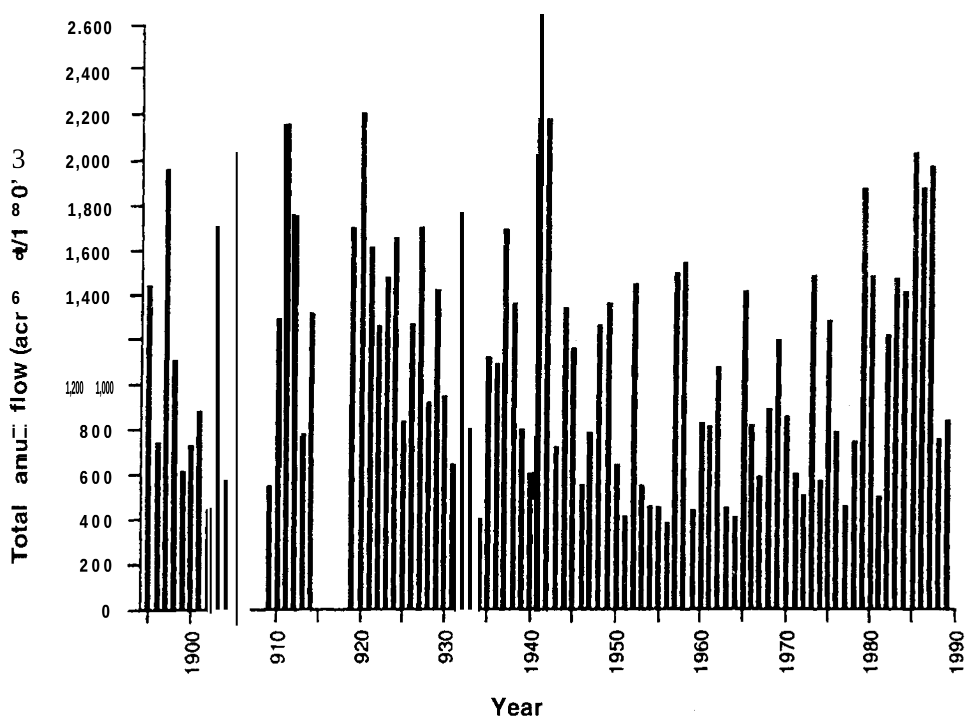

Figure 6. Total annual flow, Rio Grande at the Otowi gauge (from Allen et al, 1993).

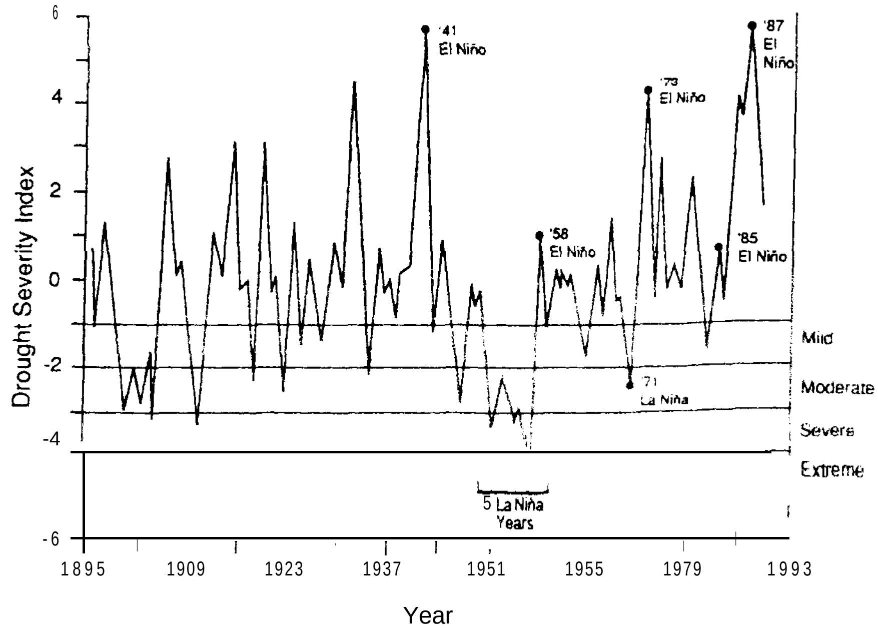

Figure 6a. Drought severity index 1895 through 1988 and El Nina and La Nina events over the past 50 years for the Middle Rio Grande Valley (after U.S. Army Corps of Engineers, 1991).

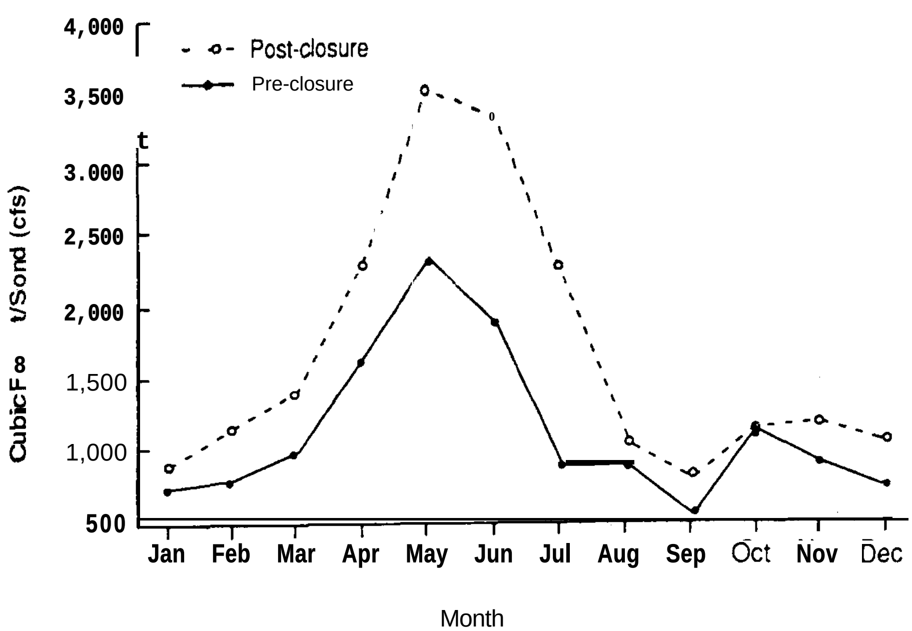

Figure 6b. Fifteen-year average of Rio Grande monthly mean discharge for pre- and post-Cochiti Dam closure periods at San Felipe gauge (from Crawford et al, 1993).

the former. The authors attribute this to the fact that the Chama and Jemez rivers are dammed and the Rio Puerco and Rio Salado are not. The conclusion is obvious and has merit. However, the rationale may be a bit misleading since the character, including soils, elevation, vegetative ground cover of the respective watersheds are not similar. Flow regimes are also very dissimilar in that the Chama is perennial, the Jemez tends to be, and the Rio Puerco lacks discharge of water or sediment for many days of the year (Heath 1983). Leopold found that 82% of the sediment transported by this tributarv occurs during events that recur about once per year (Leopold et al. 1964).

CONTAMINANTS

An additional effect related to sedimentation and river siltation is the accumulation of toxic materials in the sediments. Popp et al. (1983) and Brandvold et al. (1984) conducted studies on the sediments of the Middle Rio Grande system. Thev found that substantial quantities of cadmium, mercury, lead, uranium, and pesticides (18 different concentrations ranging from undetectable to >500 micrograms per liter are being transported by the Rio Grande and deposited in Elephant Butte Reservoir. These materials are primarily bound to sediment, although an unknown amount of cycling from sediments to the water column occurs in the reservoir (Bullard and Wells 1992).

ANTHROPOGENIC FACTORS

Some references have already been made to the anthropogenic factors that have played a role in creating the riparian habitat as currently evidenced by the “bosque” found within the MRG. These structural changes and dewatering combined with the abiotic features previously discussed combine to create a highly modified and controlled system.

Although there is no evidence of any major climatic changes within the past 5,000 years (Cully 1977), there are indications of climatic variability (fig 6a).

The river has been a focus of human settlement and development since prehistoric times. This section addresses the hydrologic resource trends from about 5,000 years ago up to the present. Generally the MRG was a braided, slightly sinuous aggrading river with a shifting sand substrate. In the past, as now, the slope of the riverbed decreased from north to south and tributaries’ contributions of water and sediment were important in defining the river’s local and overall morphology.

Because there were no diversions and because of the relative hydrologic stability of the system, Crawford et al. believe that the Rio Grande generally supported perennial flows. Exceptions could have occurred during periods of prolonged drought and would have been more prevalent farther downstream. With no water regulation, the river’s hvdrograph would have reflected the seasonal events of snowmelt runoff and summer/ fall precipitation (Fig. 6; note that these river discharge records do not reflect “natural” flows because upstream storage and diversions were alreadv in place during the period of record, but thev do indicate the general shape of the hydrograph).

The total flow in the MRG also fluctuated from vear to vear in response to annuai climatic variability. Figure 6 graphs the total annual Rio Grande flows at the Otowi gauge above Cochiti over the past 100 vears (fig. 6). Although these data also include the effects of human water management practices, they too are indicative of this annual variability. Figures 6a and 6b show temporal climatic variability and the effects of Cochiti Dam on the mean discharge respectively.

As human settlement and irrigated agriculture expanded in the middle vallev and upstream in the upper Rio Grande Basin, more irrigation water was diverted from the river reducing total river discharges. The further downstream one proceeded in the system, the less water there was. Prior to the construction of storage and flood control facilities, diversions from the Rio Grande and some of its tributaries were limited to the growing season. Other seasonal flows, peak runoff, and precipitation flows were not affected. By 1913, storage reservoirs in the headwaters of the Rio Grande had been built, and in 1935 the MRGCD completed El Vado Reservoir on the Rio Chama (Shupe and Folk-Williams 1988). These facilities began to take peaks off of some of the high river discharges and to increase the duration of lower flows. The expansion of these reservoirs and the addition of the flood and sediment control dams and reservoirs further accentuated this trend.

Other water management facilities have influenced the hydrology of the MRG. The 120 km (75 mi) long Low Flow Conveyance Channel, its downstream half operational in 1954 and its full length completed in 1959, reduced flows in the river channel in the Cicero Reach. The San Juan-Chama Project, completed in 1971, imports up to 110,000 acre-feet of San Juan River water from the Colorado River Basin to the Rio Chama/Rio Grande basins, 69,100 acre-feet of which is delivered to or through the middle valley. The effect of this importation has been to increase mean daily flows. In addition, the City of Albuquerque's annual treated wastewater discharge into the Rio Grande is currently about 60,000 acre-feet (R. Hogrefe, pers. comm in Crawford et al. 1993).

In all discussions regarding river morphology, it is important to recognize the differences within spatial and temporal scales. To describe a river system as being in a state of dynamic equilibrium (or energy balance) does not mean that it is static. To the contrary, this equilibrium results from a collection of processes that are by definition predicated on change. For example, even during periods when the entire river system is considered to be in a state of dynamic equilibrium, changes constantlv occur in subareas as small as the outside band of a meander, or as large as manv river kilometers upstream and downstream from a tributary inflow. Likewise, this state of dvnamic equilibrium can accommodate climatic deviations from the norm distinguished between natural and human-caused perturbations. The geomorphic processes triggered in response to a change in magnitude or duration of a variable, regardless of the cause, will be the same (Leopold et al. 1964; The river constantlv adjusts, always trying to establish a new equilibrium between its discharge and sediment load (Bullard and Wells 1992).

Prior to measurable human influence on the system, up to the 14th century (Biella and Chapman 1977), the river was a perennially flowing, aggrading river with a shifting sand substrate. As stated, its pattern was, as a rule, braided and slightly sinuous. The river would freely migrate across the floodplain, the extent being limited only by the valley terraces and bedrock outcroppings. The Rio Grande's bed would aggrade over time; then, in response to a hydrologic event or series of events, it would leave its elevated channel and establish a new course at a lower elevation in the vallev. This process is called river avulsion (Leopold et al. 1964). Although an aggrading svstem, the Rio Grande was in a state of dvnamic equilibrium, providing periods of stabilitv that allowed riparian vegetation to become established on riverbends and islands alternating with periods of instabilitv (e.g. extreme flooding) that provided. bv erosion and deposition, new locations for riparian vegetation.

The earliest phase of significant water development activities (from about A.D. 1400 through the early part of this century) progressively decreased river flows as irrigated agriculture increased. More influential on the morphology of the river, however, was the increased sediment deposition into the ecosystem resulting from land-use activities in the watershed. When coupled with natural climatic variability, the net effect was to accelerate the raising (aggregation) of the riverbed and , accordingly, the frequency of overbank flooding and the river avulsion. The channel configuration, while still braided and sinuous, began to broaden and became shallower. Because the increasing rapiditv of channel movement, riverbanks and islands were as a rule less stable. This likelv contributed to an increased frequency of floods. Between 1822 and 1941, a total of 46 moderate floods was recorded along the reach (Crawford et al. 1993). During nonflood periods, diminished river flows caused the active channel to retreat to fewer, narrower channels within the wide and shaiiow sandv riverbed.

During the next phase of human interaction with the river, from the mid-1920's through 1950, a system of levees were constructed to constrain the river to a single floodwav through portions of the middle valley. Concurrently, water diversions in the middle vallev and upstream in the Rio Grande Basin increased.-This had the net effect of further accelerating channel aggradation, especially in those areas where levees concentrated the deposition of sediment in the floodway.

In the contemporary phase of human water management beginning in the early 1950's, the sediment and flood control structures constructed in the upper portion of the MRG valley accelerated the reversal of channel aggradation in the Cochiti and Albuquerque reaches. The lowering riverbed is resulting in a more incised and sinuous single-channel river (see Fig. 7 for a visual example in the Belen Reach). This process becomes less pronounced with downstream distance from Cochiti and Jemez Dams. With reduction of the peak flows, where unregulated tributaries and arroyos such as Calabicillas Arroyo discharge into the Rio Grande, adequate flows are not available to transport the sediment. Sediment deltas are more persistent; they reduce river gradient upstream (tending to increase aggradation) and increase the gradient downstream (tending to reduce aggradation).

The channel modification process, described above, immediately affected the river's channel morphology. To increase the water delivery efficiency and flood flow capacity within the floodway the BOR initiated a river channel maintenance program in 1953. This included Bank stabilization, river training, sediment removal, and vegetation control. Although the techniques have evolved over the years, the program continues. Within the stabilized floodway, reaches of the MRG have been straightened, the irregularity of the channel width has been reduced, and the riverbanks have been stabilized.

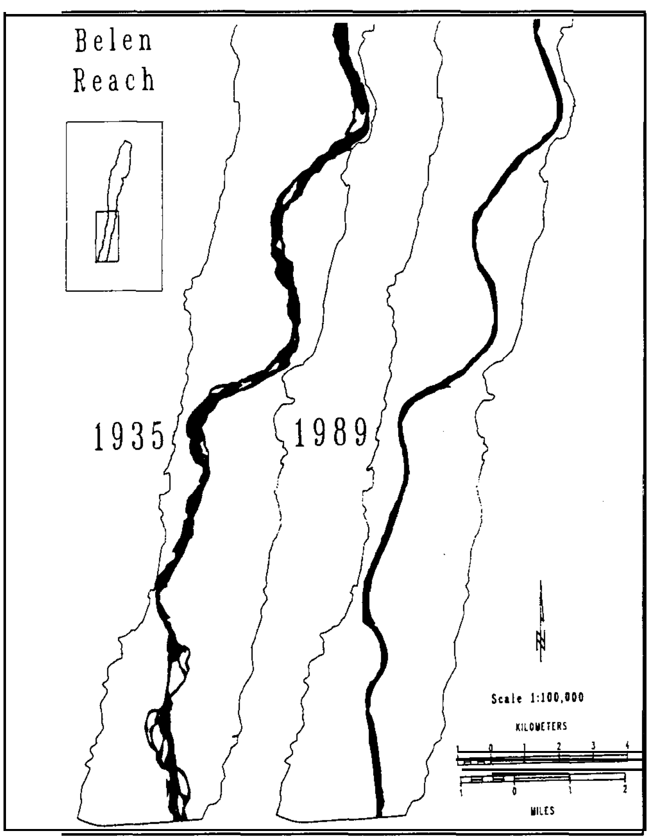

Figure 7. Changes from braided to single channel, 1935-89, portions of Belen Reach, Middle Rio Grande (from Crawford et al., 1993).

INSTITUTIONAL INFRASTRUCTURE

The waters of the Rio Grande are managed by an interwoven fabric of federal, state, interstate, and international water laws, agreements, and regulations. The fabric defines how water is released through the system, influencing not only the quantity of water, but often the timing of the releases as well. The following are the principal management components.

THE TREATY OF 1906 - Provides for the annual delivery of 60,000 ac/ft to Mexico. Prompted by the Reclamation Act of 1902 and the resulting study identifying construction of Elephant Butte Dam which was authorized in 1905 and completed in 1916.

THE RIO GRANDE COMPACT - Initiated in 1923 and agreed upon in 1929, approved by Congress in 1939, allocates Rio Grande water between the states of Colorado, New Mexico, and Texas via a complex set of delivery schedules that relate runoff volumes to delivery obligations at set river index points. In normal years New Mexico must assure delivery of 60% of the flow passing Otowi gage reaches Elephant Butte Reservoir which is the delivery point for Texas' allocation. In wet years the percentage is 80%. The Compact also provides rules for accruing and repaying water credits and debits, water storage restrictions, and operation of reservoirs. The compact does not affect obligations to Mexico or to Indian tribes (Shupe and Folk-Williams 1988).

MIDDLE RIO GRANDE CONSERVANCY ACT 1923 - Formed the Middle Rio Grande Conservancy District in 1925 in response to decrease in productive, irrigated farmland and increased flooding along the MRG. Channel Aggradation, flooding, and waterlogging of arable lands resulted from Rio Grande water infiltrating the groundwater system of the lower, surrounding floodplains. This resulted in a dramatic decrease in productive farmland from 50,000 ha to 16,000 ha by 1925 (Nanninga 1982). From 1925 to 1935 the MRGCD constructed, operated, and maintained four major diversions dams (Cochiti, Angostura, Isleta, and San Acacia), two canal headings, and many miles of drainage canals, river levees, and main irrigation canals (fig 8). Initial flood control structures were 2.5 m spoil levees that paralleled the Rio with a mean channel width of 450 m. From 1951 to 1977 a system of Kellner jetty fields was installed along the MRG to protect levees and to aid in flood control and channel stabilization.

In recognition of continued flooding and sedimentation problems on the MRG, the COE and BOR jointly prepared the "Rio Grande Comprehensive Plan". The COE's portion of the plan provided Jemez Canyon Dam in 1953, Abiquiu Dam and Reservoir in 1963, Galisteo Dam in 1970, and Cochiti Dam and Reservoir in 1973. The system consisting of Abiquiu, Jemez Canyon, Galisteo, and Cochiti dams and the levees along the Rio Grande provides flood control and protection for the MRG valley (Lagasse 1980).

El Vado Reservoir on the Rio Chama was proposed by the MRGCD in 1928, providing irrigation water and flood control to the MRG. Under an agreement with the Department of Interior, El Vado also provided irrigation water to the A Indian pueblos in the area (Cochiti, Isleta, San Felipe, Santa Ana, and Santo Domingo). The dam was completed in 1935 and rehabilitated in 1958. Operating responsibility was transferred to BOR in 1956.

FLOOD CONTROL, DIVERSION PROJECTS, AND PUBLIC LAWS

CABALLO DAM, located 27 km below Elephant Butte Dam, was authorized in 1933. This provides flood control for El Paso and the Juarez Valley. It is managed by both the BOR (conservation operations), and the International Boundary and Water Commission (IBWC) (flood control).

PLATORO DAM AND RESERVOIR, on the Conejos River in Colorado, was authorized in 1940 for conservation and flood control and completed in 1951.

FLOOD CONTROL ACT OF 1948 authorized construction of Jemez Canvon Reservoir and the low-flow convevance channel from San Acacia to Elephant Butte Reservoir. It also authorized the

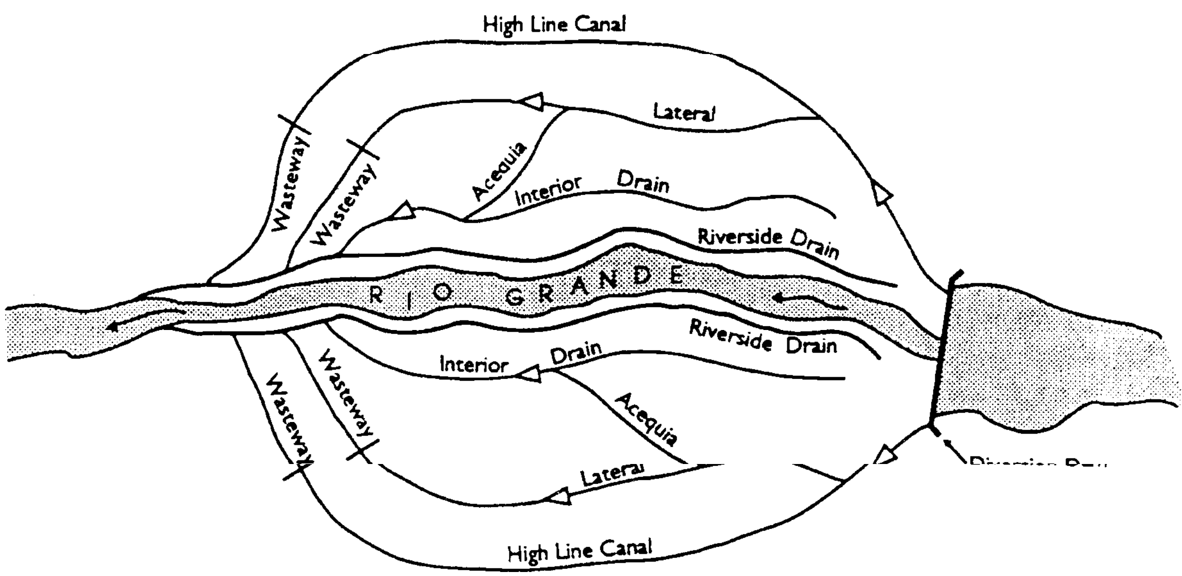

Figure 8. Schematic map of an irrigation network on the Middle Rio Grande (Bullard and Wells, 1992).

BOR to maintain the Channel of the Rio Grande from Velarde to Caballo Reservoir to accommodate flows of about 5,000 CFS.

The Low Flow Conveyance Channel is used to transfer water through its 82 km length more efficiently during periods of low flow, which minimizes water losses to infiltration and phreatophytes. The low-flow conveyance channel is normally operated to convey the entire flow in the Rio Grande up to about 2,000 cfs; when flows exceed about 2,000 cfs, the remainder is carried by the natural channel. Water is also allowed to flow in the natural channel when the silt load is high.

FLOOD CONTROL ACT OF 1960 - The Flood Control Act of 14 July 1960 (PL48-645) contains the criteria governing operations of the four Middle Rio Grande Project flood control reservoirs: Jemez Canyon, Abiquiu, Cochiti, and Galisteo. Portions of the operating criteria include:

- The reservoirs are operated only for flood control.
- Cochiti spring outflow will be at the maximum rate of flow without causing flooding of leveed protected areas.
- Provided there is at least 212,000 ac ft of storage available for regulation of summer floods and inflow is less than 1500 cfs, no water will be withdrawn from storage in Cochiti Reservoir.
- Jemez and Galisteo will be managed during July through October to only handle summer floods.
- All Reservoirs will be evacuated by March 31, each year.
- When it benefits Colorado or New Mexico in Compact, deliveries of a flow of 10,000 cfs is authorized through the Albuquerque reach.
- No departure from the foregoing schedule is allowed without consent of the Rio Grande Compact Commission.
- In the event of an emergency, the COE must advise the Compact Commission in writing, and the foregoing rules of operation may be suspended during the period of emergency.

SAN JUAN-CHAMA TRANSMOUNTAIN DIVERSION PROJECT - 1963 - The SJC Project imports water from the San Juan River basin (in the Colorado River basin). This water is not subject to Rio Grande Compact, and can thus be used for beneficial use (COE 1989). Annual diversion of about 110,000 ac ft is authorized. The imported water is stored and released at Heron Reservoir. This water is allowed to be used for municipal, irrigation, domestic, and industrial purposes, and to provide recreation and fish and wildlife benefits.

ALBUQUERQUE METROPOLITAN ARROYO FLOOD CONTROL AUTHORITY (AMAFCA) - Following several large, damaging floods east of the Rio Grande in urban Albuquerque in 1955, 1961, and 1963 AMAFCA was created in 1963 to address and alleviate the problems of urban flooding from unregulated ephemeral tributaries. A series of concrete lined drainage structures were constructed from arroyos at the foot of the Sandia Mountains and feed into the Rio Grande.

THE CLOSED BASIN PROJECT - The Closed Basin Project in Colorado was authorized by PL 92-514 in 1972. The purpose is to help Colorado meet its required deliveries to New Mexico, and to help all three Rio Grande Compact States meet their delivery requirement to Mexico. The closed basin Project'was justified and funded 100% by the federal government on the basis of honoring the Treaty of 1906. The project consists of 170 salvage wells that remove groundwater from the unconfined aquifer in the Closed Basin and discharge the water into the Rio Grande. The water would normally be consumed by evapotranspiration. Approximately 60,000 to 140,000 ac ft of water is delivered to the Rio Grande at rates up to 140 cfs when fully operational.

CURRENT HYDROLOGIC REGIME AND ITS EFFECTS ON THE RIPARIAN VEGETATION

Present conditions in the Rio Grande include levees, dams, and channelization. Cochiti Dam has had a major impact on the river and riparian zone below it by reducing peak flows and sediments in the system (fig. 6b). The timing and duration of releases of peak flows may not be suitable for germination and establishment of native species (Fenner et al. 1985, Szaro 1989). In contrast to unmodified riverine systems (fig. 9), levees have restricted the lateral movement of the river, and channelization has occurred along some reaches (fig. 10). The consequence of all these actions for native riparian vegetation, once areas have become vegetated, is a drastic reduction in numbers of sites and opportunities for further recruitment.

Probably as a result of the construction of Cochiti Dam, the northern reaches (Cochiti and Albuquerque) of the Middle Rio Grande are now degrading. Because sediments are trapped at the dam, released waters have high potential for erosion and the channel is deepening. Vegetation is stabilizing the riverbanks, enhancing the narrowing and deepening of the channel. Comparison of 1935 and 1989 aerial photos indicates that the riverine, or river channel portion of the MRG , has been reduced by 49% (8,920 ha [22,032 ac] in 1935 to 4,347 ha [10,736 ac] in 1989 (fig. 7). For native riparian plant species, there is little or no recruitment, except for banks and bars adjacent to the

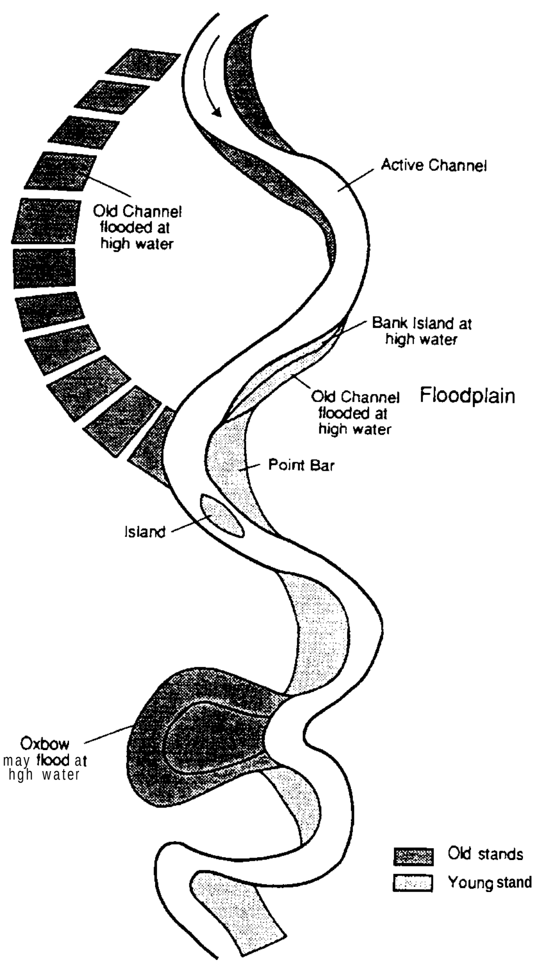

Figure 9. Zones of cottonwood and other riparian species establishment along an unmodified river (Crawford et al, 1993).

main channel of the river that are exposed after high flows. These areas may be scoured by the next high flows and are often subject to mowing to maintain the floodwav. This lack of recruitment is a consequence of the presence of existing riparian vegetation and the absence of high magnitude flows to remove established vegetation and create barren areas tor colonization.

In the southern reaches (Belen and Socorro) of the MRG, large amounts of sediment are introduced into the svstem at the confluence of the Rio Puerco and Rio Salado (Lagasse 1980). Some areas are without levees, and waters spread out here and deposit sediments. In these reaches, decreases in peak flows prevent sediments in the channel from being moved downstream. At the southern end of the MRG, Elephant Butte Dam has caused the base elevation to rise upstream enhancing deposition, channel widening, river braiding, and aggrading in some areas. Sediment deposition creates substrate for recruitment of native cottonwoods and willows and introduced salt cedar.

Much of the riparian zone along the MRG is dominated by cottonwood trees, which form a sparse to dense canopy cover along the river. In the understory, native species include the shrub coyote willow, seepwillow, false indigo bush, New Mexico olive, and others. Introduced species have become increasingly important in numbers, frequently becoming dominant species in the understorv and occasionallv in the canopy. In the northern reach, the major introduced species in Russian olive. In the south (below Bernardo), salt cedar is prevalent in the understory, and it also forms large monotypic stands along the river and adjacent floodplain. Other introduced species (e.g. Siberian elm, tree-of-heaven, china-berry tree, mulberry, and black locust) are found in the bosque, mostly along levee roads and in other disturbed communities now dominated by native species. These exotics have the potential for becoming the primary species there through time.

Six structural types of plant communities were recognized by Hink and Ohmart (1984) (fig.11), based on the overall height of the vegetation and the amount of vegetation in the understory or lower layers. Type I had vegetation in all layers, with trees 15-18 m ((50-60 ft) high. Type I areas were mostly mixed to mature age class stands dominated by cottonwood/coyote willow, cotton-

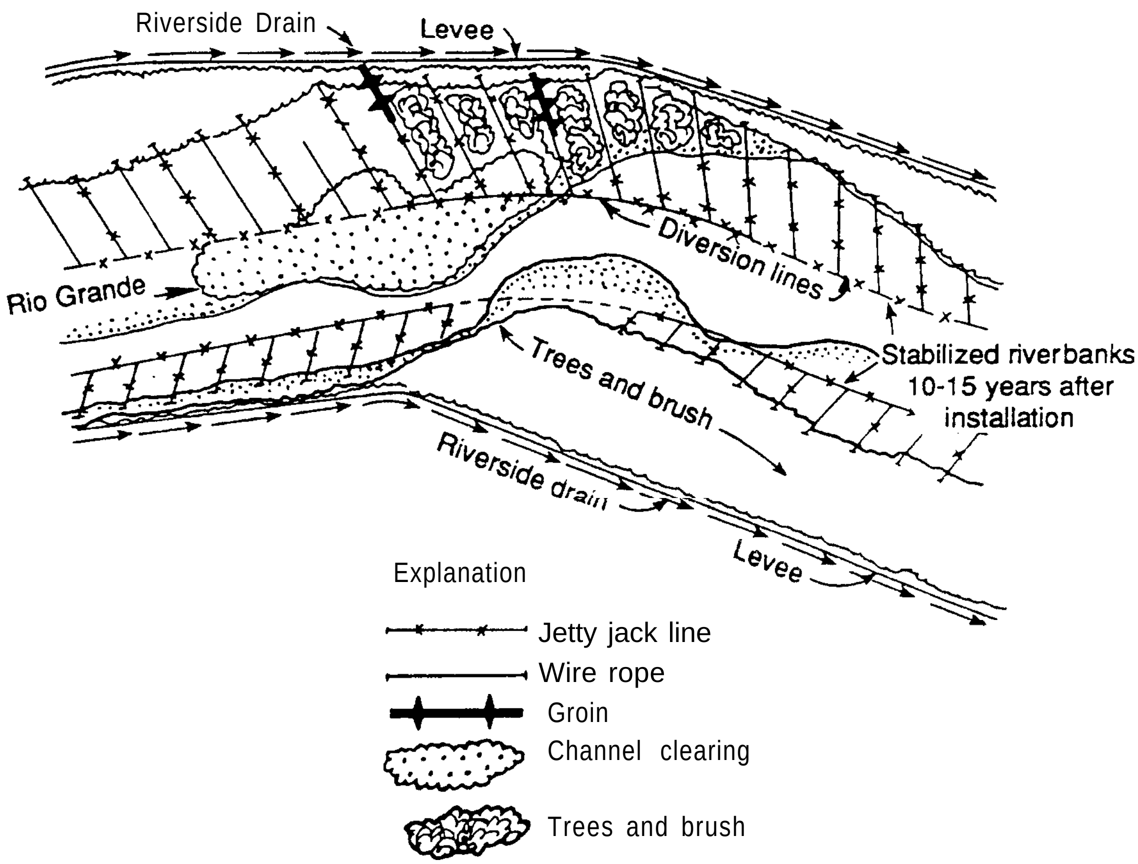

Figure 10. Channel stabilization works on the Middle Rio Grande (after Bullard and Wells, 1992).

wood/Russian olive, and cottonwood/juniper. Type II areas consisted of mature trees from 15 to 18 m (50-6- ft) with a sparse understory. Intermediate age stands of cottonwood trees with a dense understory were classified as Type II, while similarly aged trees with open understory were called Type IV. Type V was characterized by dense vegetation up to about 4.6 m (15 ft) often with dense grasses and annuals. Type VI had low, often sparse vegetation, typical of sandbars with cottonwood, willow, and other seedlings. This type also included sparsely vegetated drains.

Hink and Ohmart (1984), described three cottonwood-dominated community types based on the overstory species and on the type and abundance of the understory species. The cottonwood/coyote willow community, cottonwood/Russian olive, and cottonwood/juniper found in the northern reach. New Mexico olive, false indigo bush and other species were also found.

Other plant communities also occurred in the study area (Hink and Ohmart 1984). Russian olive occurred along the river channel in narrow, 15-60 m (50-200 ft wide bands. Cattail marshes, dominated by cattails with some bulrush and sedge, are found in areas that are inundated or have a high water table. Wet meadows with saltgrass and sedges were also designated as marsh communities. In the southern reach, salt cedar was the primary component of the plant community almost to the complete exclusion of other species.

Hink and Ohmart (1984) also delineated sandbars in and adjacent to the river, and the river channel. Most of the sandbars were bare, but some had developed vegetation consisting of grasses, forbs, cottonwood and willow seedlings, and other species. Many of these bars were scoured during each year's high fiows. If not removed by scouring, vegetation in these locations is periodically mowed by the BOR to keep the floodway clear.

While the structure and diversity of native plant communities appear to be significant to the diversity of species in animal communities, introduced plant species that have become naturalized in the

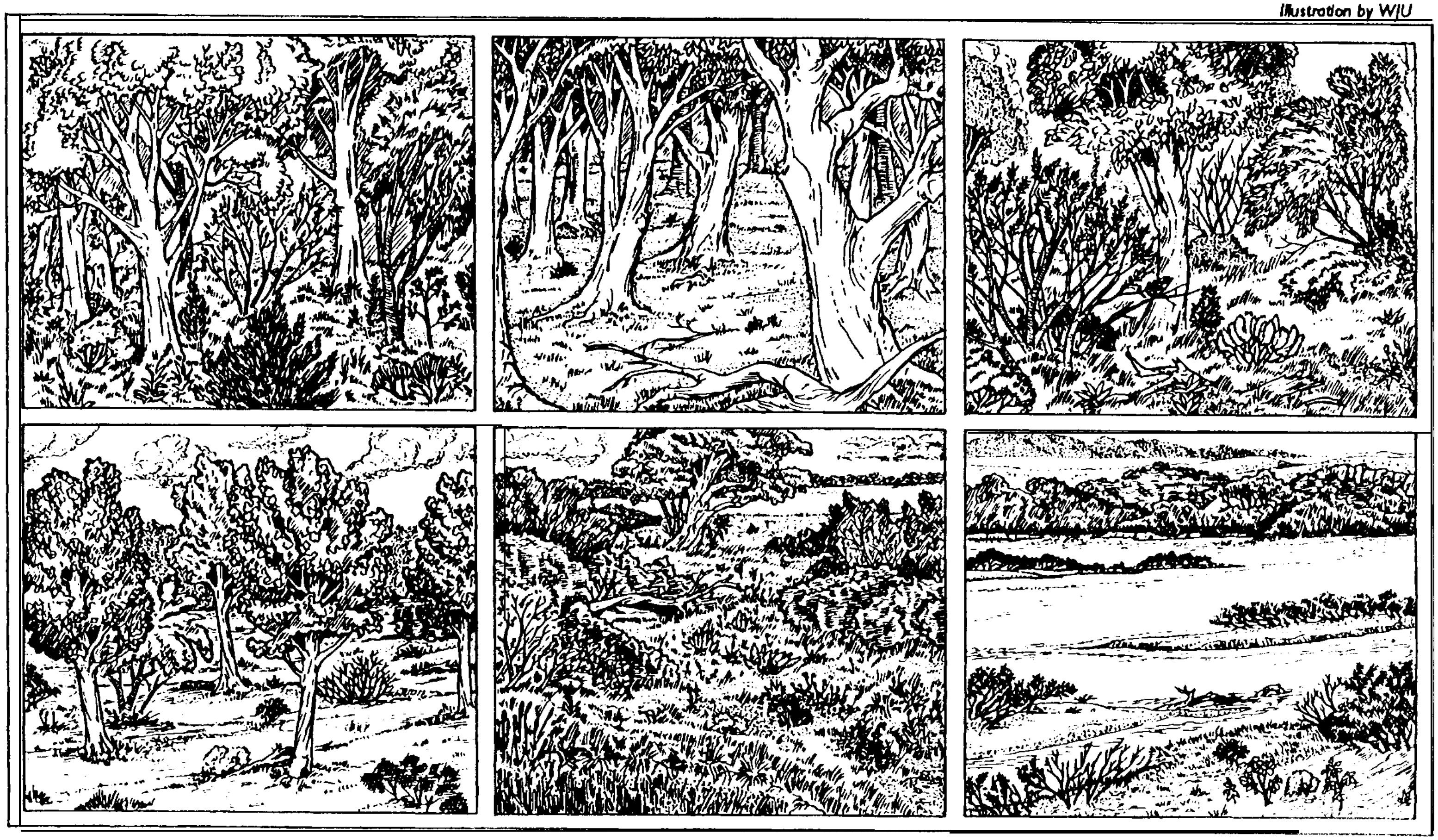

Figure 11. Vegetation structural types I-VI, Middle Rio Grande riparian zone (after Hink and Ohmart, 1984).

region also provide shelter and sometimes food. The fruits of the Russian olive, a species which is prominent in the community types in the northern reach of the MRG, appear to be a significant part of the diet for some resident, migrant, and breeding bird species. Salt cedar found throughout the study area but particularly abundant in the southern portion, provides cover for birds and mammals and habitat for many insect species (Hink and Ohmart 1984).

CONCLUSION

The MRG has been the center of considerable activity by man for over 10,000 years. Until only recently man's activities have not had a significant impact on the character of the riparian area adjacent to the Rio Grande in this vicinity. With advent of irrigation, control structures such as levees and Jetty Jacks, water diversions and control structures such as Cochiti Dam, the hydrograph and subsequent river morphology have been dramatically altered. This alteration in flow regimes and channel configuration continues to have ramifications and effects upon the native flora and fauna of the MRG.

ACKNOWLEDGMENTS

Much of what is contained in this paper comes directly from primarily two documents which I highly recommend to the reader. The first "Hydrology of the Middle Rio Grande from Velarde to Elephant Butte Reservoir, New Mexico" by Bullard and Wells 1992. The second indispensable document is the Middle Rio Grande Bosque Biological Management Plan, Crawford et al. 1993. The Figures have been taken from the Bosque Biological Management Plan, Crawford et al. 1993.

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