STREAMFLOW AND SEDIMENT DYNAMICS OF THE MIDDLE RIO GRANDE VALLEY, NEW MEXICO, IN THE CONTEXT OF COTTONWOOD RECRUITMENT

BY

ROBERT T. MILHOUS
MARK WONDZELL
AND
AMY RITTER

Fish and Wildlife Service

U.S. Department of the Interior

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by

Robert T. Milhous
Mark Wondzell
and
Amy Ritter

U.S. Fish and Wildlife Service
National Ecology Research Center
4512 McMurry Avenue
Fort Collins, Colorado 80525-3400

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Introduction

The cottonwood gallery forests of the Middle Rio Grande floodplain in New Mexico provide important habitats for birds and other animals. Over the last century, these forests have changed significantly due to invasion of exotics such as salt cedar and Russian olive, which compete with native cottonwoods, and changes in water use both in the valley and upstream.

To successfully germinate and establish, cottonwoods require an adequate water supply, abundant sunlight, and bare, litter-free substrate. Native cottonwoods are adapted to a natural snowmelt hydrograph characterized by spring floods in late May or early June and gradually receding streamflows throughout the remainder of the summer. The natural streamflow pattern has been significantly modified by water management in the Rio Grande basin. The modified pattern is less conducive to establishment of cottonwoods than the natural pattern. In addition, exotic species now compete with native cottonwoods, and the modified flow pattern may favor these exotics.

The overall objective of this study was to investigate the possibility of enhancing cottonwood establishment and recruitment along the Middle Rio Grande through streamflow manipulation and reservoir releases. The work integrates concepts of cottonwood establishment, water resources management, and river morphology, and investigates how water management might be used to preserve and enhance cottonwood gallery forests along the river. Specific objectives of the work reported herein were to: (1) develop a technique to calculate flows that will produce channel characteristics necessary to restore and sustain cottonwood gallery forests; (2) develop a model to determine a flow pattern, or sequence of flows, that will improve the potential for cottonwood establishment and recruitment; and (3) determine if the water resources can be managed to produce the desired channel characteristics and flow pattern identified in (1) and (2).

In a review of the hydrology of the Middle Rio Grande (MRG), Bullard and Wells (1992) concluded:

> The effect of Rio Grande dams on the riparian biologic community is not well understood. Long-term discharge records exist for the Rio Grande, but the long history of streamflow regulation reduces the overall usefulness of discharge data for evaluating changes that may have occurred to the river as a result of water development projects. It seems that mean annual discharge of the Rio Grande has been more consistent, yet slightly greater, since closure of Cochiti Dam. The major problems existing for the riparian biologic systems seem to be related to the agricultural history of the Rio Grande valley, which dates back centuries, and associated legislation for control and delivery of Rio Grande water to downstream consumers. The large influx of people into the region in the mid-1800's, added to the existing Indian and Spanish population, increased the demand for water and stretched the limits of the Rio Grande in terms of water delivery and support for plant and animal communities. Diversions of water for irrigation during late summer months, when Rio Grande discharge is lowest, may at times leave the river with little or no flow.
>
> Significant changes in the riparian community were probably underway by the turn of the 19th century. When Congress authorized the Rio Grande project in 1905, change in the Rio Grande system was accelerated. Since that time the Rio Grande has been converted from an essentially natural stream to a highly modified water storage and conveyance system with extensive flood control structures (Lagasse 1980). More recent changes brought about by the efforts of the USACE, BR, BLM, AMAFCA, Interstate Stream Commission, and local irrigation districts to enhance conveyance and irrigation have probably further affected the riparian

ecology. Dams and levees have all but eliminated former seasonal floods that in the past provided nutrients and moisture to the floodplain ecosystem. Former floodplain regions have been converted to productive agricultural lands and, more recently, to urban communities. Irrigation diversions create low-flow conditions, and at times a dry river bed, in much of the reach downstream from Bernalillo. Riverside drains create hydrologic conditions that attract groundwater from the floodplains and prevent natural river losses from invading the floodplain areas. The result is a man-induced change in the river system that has created an altered floodplain ecology different, though perhaps no less viable, from the former natural condition. More stable hydrologic conditions probably exist now, in contrast to former times when seasonal high discharge events and flooding produced dynamic geomorphic changes in the channel and floodplain, but the overall affect of these changes on the riparian community is unknown.

The goal of the present study was to expand upon the conclusions of Bullard and Wells (1992) and to focus on specific concepts for managing water to preserve and enhance the cottonwood gallery forests along the Middle Rio Grande. The underlying assumption was that deliberate high flow releases from upstream impoundments would be sufficient to promote cottonwood regeneration within the active floodplain. All of the objectives presented above require this assumption to be true. Consequently the initial step in the study was to investigate the validity of this underlying assumption. This proved to be more complex and difficult than initially expected. Consequently, much of this report focuses on the results of that first step.

This report integrates concepts of cottonwood establishment, water resources management, and river morphology. The first section reviews the history and management of the floodplain and water resources in the MRG valley, and includes a description of existing flow routing models. The second section reviews vegetation information needed to evaluate the link between flows and cottonwood recruitment. The third section addresses sediment transport and sediment dynamics in the context of cottonwood establishment and the fourth analyzes the historic pattern of streamflow in relation to cottonwood establishment and applies some hydraulic models to determine the suitability of flows for cottonwood establishment. Applications of these models are described in more detail in appendices.

The MRG, as used in this report, extends from the lower end of the Taos Plateau to the headwaters of Elephant Butte Reservoir, between the U.S. Geological Survey (USGS) gages at Embudo (about 5 miles upstream of Velarde) and San Marcial (Fig. 1).

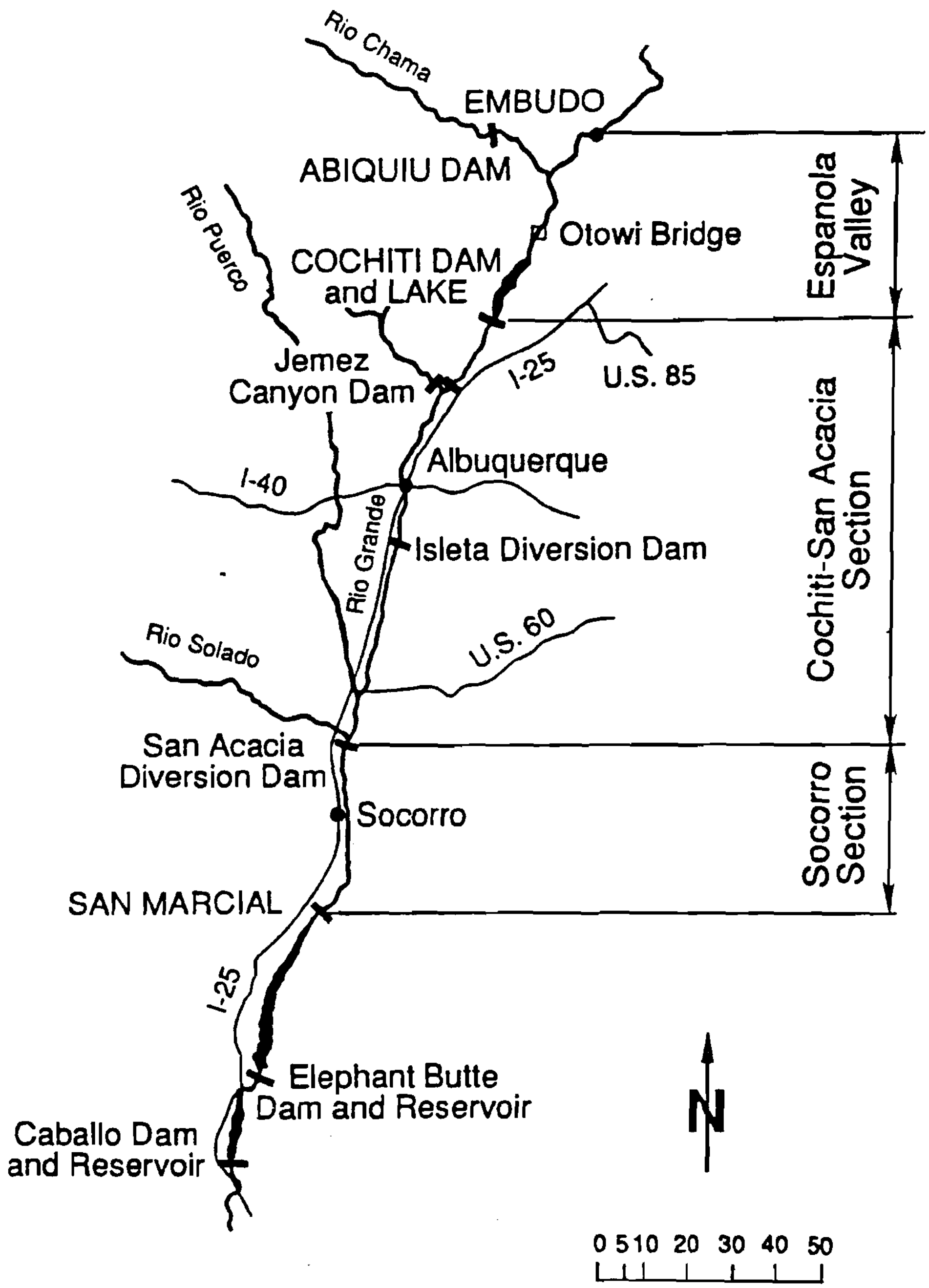


Fig. 1. Reaches, divisions, dams, and diversions along the Middle Rio Grande within the study area (from U.S. Bureau of Reclamation 1977).

Water Resources System

The MRG valley is an area of low precipitation and highly variable river flows. As a result, water has been intensely managed for many years for both irrigation and flood control. More recently, urban development has placed additional demands on the system, as have increasing environmental concerns. As a result of these demands, the Rio Grande has progressively been converted from a natural stream to a highly modified water storage and conveyance system with extensive flood control structures.

Historic development of the MRG is outlined in Fig. 2, which also includes external facilities that significantly impact the MRG. The MRG water resources system is a very complex system both physically, socially, and culturally.

The U.S. Army Corps of Engineers (1989) (USACE) provides descriptive information on the three most significant major flood events on the Rio Grande. Throughout the valley, flooding is considered to occur when flows exceed 5,000 cfs. The largest floods on record occurred in the 1920's, 1930's, and 1940's (depending on location within the valley) with flood peaks ranging from roughly 25,000 to almost 40,000 or 50,000 cfs. Little information, however, is available about historic floods in the MRG valley. The following is taken from U.S. Bureau of Reclamation (1977) (BR):

> Based on records left by a Catholic priest at Tome, New Mexico (approximately 28 river miles below Albuquerque), the peak flow of the May-June flood of 1828 is estimated to have exceeded 100,000 cfs. Newspaper accounts describe extensive damage associated with the spring floods of 1865, 1874, and 1884 (Woodson 1961). The floods of 1870, 1874, and 1890 had estimated peak discharges between 45,000 and 125,000 cfs (ASCE 1965).
>
> Other large floods include: the 64-day flood of 1920, peak discharge of 28,800 cfs; August-September flood of

?	First recorded water users were ancestors of the Pueblo Indians
1700's	Irrigation activity grew significantly
By 1870's	More than 120,000 acres were under cultivation along the middle reach of the Rio Grande
By 1913	San Luis Valley reservoirs built - Rio Grande Reservoir, Continental Reservoir, and Santa Maria Reservoir
1916	Elephant Butte Reservoir on the Rio Grande
1920's	Farmland dropped from 120,000 acres to 40,000 acres due to waterlogging
1935	El Vado Reservoir on the Rio Chama
1938	Caballo Reservoir on the Rio Grande
Early 1940's	High runoff and sedimentation reduced the Rio Grande channel capacity
Spring 1942	Elephant Butte and Caballo reservoirs are filled to capacity and spill
1950's	Groundwater use begins to deplete surface flows
1951	2,000 cfs conveyance channel from San Acacia to Elephant Butte Reservoir, 70-mile stretch
1951	Platoro Reservoir on the Conejos River
1953	Jemez Canyon Reservoir on the Jemez River
1955	22 miles of levees to protect Albuquerque and 125 miles of levees built in the middle reach
1962	Heron Reservoir on the Rio Chama
1963	Abiquiu Reservoir on the Rio Chama
1970	San Juan-Chama diversion on the Rio Chama. Diverts water from San Juan tributaries and transports it across the Continental Divide to Heron Reservoir.
1970	Galisteo Reservoir on Galisteo Creek
1975	Cochiti Reservoir on the Rio Grande
1985	Elephant Butte and Caballo Reservoirs fill to capacity

Fig. 2. Time line of water development of in the Middle Rio Grande valley.

1929 that destroyed the town of San Marcial; and the 61-day flood of 1941, peak discharge of 24,000 (U.S. Senate Document 94).

The MRG water resource system from Velarde to Elephant Butte Reservoir can be divided into three major divisions and six reaches (Fig. 1). Tributaries with drainage areas in excess of 500 mi^2 include the Rio Chama, Rio Galisteo, Jemez River, Rio Puerco, and Rio Salado; a brief description of each of these major tributaries can be found in U.S. Army Corps of Engineers (1989). The Rio Grande and its major tributaries within the project area are regulated by six main reservoirs (El Vado, Heron, Abiquiu, Jemez Canyon, Cochiti, and Elephant Butte) and many smaller ones.

In addition to natural tributary inflows to the mainstem, seven transmountain diversions (six in Colorado and one in New Mexico) deliver water to the Rio Grande. Physical location and average annual diversion quantities are summarized in U.S. Army Corps of Engineers (1989). The Rio Grande also receives water from the Closed Basin Project in the San Luis Valley, Colorado. This project pumps groundwater to the Rio Grande to help meet Colorado's delivery requirements to New Mexico, Texas, and Mexico.

The earliest attempts at channel stabilization were made by the Middle Rio Grande Conservancy District (MRGCD) in the early 1930's. The first levee system was completed in 1936 for the purpose of containing the river and protecting adjacent riverside drains. Most channel operation and maintenance activities, however, are the responsibility of the BR and the USACE. The BR's operation and maintenance activities are generally confined to the floodway and consist of maintenance of the cleared floodway, maintenance of the floodway channel via channel rectification and channel stabilization, and maintenance of the low-flow conveyance channels. The USACE and MRGCD, however, retain primary responsibility for levee stabilization works, rehabilitation of existing levees, and construction of new levees.

A cooperative water salvage program between the Interstate Stream Commission and the BR began in 1956 to conserve water and increase transport efficiency of the river. The program consisted of constructing pilot channels and riverside drains and clearing phreatophytic vegetation.

Reservoirs

Six major reservoirs have a significant impact on water regulation within the MRG valley (Table 1). U.S. Army Corps of Engineers (1989) provides a concise physical description of each of these reservoirs, storage capacities, authorized reservoir operations, and operational constraints as imposed by the Rio Grande compact. Bullard and Wells (1991, Appendix E) give additional comprehensive engineering design data for each of these dams. U.S. Army Corps of Engineers (1989) also provides a concise legislative history of water development in the Middle Rio Grande valley.

Table 1. *Major reservoirs and associated storage capacities in thousands of acre-feet (from U.S. Army Corps of Engineers 1989).*

Reservoir	Flood	Conservation	Recreation	Sediment	Total
Abiquiu	502	200	-	77	779
Cochiti	492	-	50	105	597
El Vado	-	180	-	-	180
Galisteo	79	-	-	9.4	89
Heron	-	401	-	-	401
Jemez Canyon	73	-	-	44	117

Cochiti, Galisteo, Jemez Canyon, and Abiquiu Reservoirs were constructed by the USACE, as part of the Middle Rio Grande Project, for the purposes of flood and sediment control. Jemez Canyon Dam, completed in 1953, was the first flood control dam uilt as part of the Middle Rio Grande Project. Located on the Jemez River 2 miles above its confluence with the Rio Grande, about 20 miles north of Albuquerque, this reservoir traps sediment and stores summer flows that would otherwise flow into the Rio Grande. Flood flows are usually evacuated as quickly as possible to provide storage for subsequent summer thunderstorms.

Abiquiu Dam and Reservoir located on the Rio Chama, began flood control operations in 1963. Abiquiu is the primary flood control structure on the Rio Chama, storing spring runoff that might otherwise flood the Rio Chama and Rio Grande valleys. Galisteo Reservoir is located on Galisteo Creek 12 miles above its confluence with the Rio Grande. The dam's uncontrolled outlet structure stores water only during periods of high runoff, and only for as long as it takes the water to flow through the outlet. Cochiti Reservoir, located approximately 35 miles upstream from Albuquerque, controls the mainstem of the Rio Grande above the middle valley. The dam was constructed for flood and sediment control; however, availability of San Juan-Chama water has allowed for a permanent pool of 50,000 acre-feet for recreation purposes. Cochiti Dam is operated in conjunction with Jemez Canyon Dam to prevent flows of the Rio Grande from exceeding channel capacity.

The other two principal reservoirs within the project area are located in the Rio Chama basin. Heron Reservoir, located on Willow Creek, a tributary to the Rio Chama, was completed in 1971 and is owned and operated by the BR. The entire capacity of this reservoir is dedicated to storing water imported to the Rio Grande basin through the San Juan-Chama project. No natural flows of Willow Creek may be stored. El Vado Reservoir, constructed in 1935, is owned by the MRGCD and operated by the BR. It is primarily used to capture surplus spring flows for future use by downstream irrigators. Recent operation, however, has focused on storing surplus San Juan-Chama water.

The San Juan-Chama Project diverts about 110,000 acre-feet annually from upper tributaries of the San Juan River in the Upper Colorado River basin. The diverted water joins the Rio Grande via the Rio Chama. The majority of the imported water is owned by the city of Albuquerque and is used to supplement the City's municipal and industrial needs, provide additional water for irrigating lands within the MRGCD, and augment or replace depleted groundwater within the Rio Grande basin. The San Juan-Chama diversion began full operation in 1970.

Diversion Structures, Canals, and Drains

There are four major diversions on the Rio Grande within the project area; Cochiti Dam, Angostura diversion dam, Isleta diversion dam, and the San Acacia diversion dam. With the exception of Cochiti, which is owned by the USACE, these diversions are owned by the MRGCD. They service MRGCD-irrigated lands, which extend along both sides of the Rio Grande from Cochiti Dam downstream to Bosque del Apache National Wildlife Refuge (NWR). Bullard and Wells (1991, Appendix E) give detailed engineering data for each of these diversions.

The MRGCD distribution and drainage system consists of diversion dams, canal headings, drainage canals, levees, and irrigation canals and ditches. The MRGCD was created in 1925 for the purposes of constructing flood control works and drainage projects, consolidating headgates, and centralizing the existing network of irrigation canals and ditches. A general description of the MRGCD distribution system is contained in Bullard and Wells (1992), and a more comprehensive description of the physical layout, including plan view maps and design capacities, is in Middle Rio Grande Conservancy District (1980).

Severe drought in the Upper Rio Grande basin in 1951 prompted emergency measures to salvage and transmit limited supplies of water downstream to Elephant Butte Reservoir. Temporary drainage channels were constructed in the summer of 1951 to provide a continuous transmission channel through the 22-mile reach above

Elephant Butte Reservoir. In December, 1951, construction of a low-flow conveyance channel began at the narrows of Elephant Butte and by May, 1954, had been completed upstream for 35 miles to the southern boundary of Bosque del Apache NWR. The floodway was cleared to a width of 1,400 feet above San Marcial and 1,000 feet below. This section went into operation while the second section was started in 1956 and constructed for an additional 40 miles upstream to San Acacia diversion dam. The floodway through this upper portion was cleared to a width of 600 feet. The entire 75-mile conveyance channel went into operation in 1959. Comprehensive historical background on construction and maintenance of the MRGCD irrigation system, diversion dams, canals, drains, low-flow conveyance channels, and levees is contained in U.S. Bureau of Reclamation (1977).

Levees

Extensive levee systems have been constructed and maintained along the MRG as part of flood control measures. The legislative history of flood control projects within the project area is detailed in U.S. Bureau of Reclamation (1977), U.S. Army Corps of Engineers (1989), and Bullard and Wells (1992), which also provides a general history of levee construction within the valley.

U.S. Army Corps of Engineers (1989) provides the most recent analysis of levee capacities at four critical reaches within the project area. They determined that minimum failure flows were on the order of 7,500 cfs along the west levee from the Corrales Siphon to the University of Albuquerque, and along both the east and west levees from the highway bridge at Isleta to the railroad bridge at Belen.

The levee system presently represents a major controlling factor in passing large flows through the MRG valley. In addition to the channel capacities cited above, Kreiner (Albuquerque District, U.S. Army Corps of Engineers; personal communication) indicated that the MRG levee capacity in the vicinity of Santa

Domingo Pueblo is currently about 5,000 cfs. He further stated that increased sediment aggradation at the upper end of Elephant Butte Reservoir has reduced channel capacity in the San Marcial reach. The USACE and BR are in the process of increasing channel capacity in these two areas.

Operation and Maintenance Activities

Operation and maintenance activities include: maintenance of cleared floodways; floodway rectification (i.e., pilot channeling); channel stabilization (e.g., jetty jack installation, riprap revetments, and groins); vegetation clearing and maintenance; and low-flow conveyance channel maintenance. Much of the following information is dated, describing completed activities through 1974 and proposed activities for the period after 1975. The information is taken from the U.S. Bureau of Reclamation's Final Environmental Impact Statement (U.S. Bureau of Reclamation 1977). According to discussions with BR staff in Albuquerque and Denver, to obtain more specific and/or current information requires a review of actual contracts and contract specifications from past channel maintenance work. Another possible source is a series of examination reports, prepared by the BR every few years, which highlight and review recent operation and maintenance activities.

The cleared floodway through the MRG valley varies in width from 150 to 2,360 feet (about 27,500 acres). Approximately half of this area is kept free of woody vegetation by river flows, the remainder by mechanical clearing. In the Española and Cochiti reaches the cleared floodway is discontinuous. Downstream from Angostura Dam the cleared floodway is continuous through the Albuquerque, Belen, Socorro, and San Marcial reaches.

The Española reach extends from Velarde to Cochiti Reservoir. Design discharge within the Española reach is 5,400 cfs. As of 1975 construction activities that would provide this capacity had not begun and the current capacity was estimated at 5,000 cfs above the Rio Chama and 8,000 cfs below. As of 1990 the designed channel capacity within the Española reach had been increased to 7,850 cfs. The BR's activities are limited to the upper 24 miles (Velarde to Otowi bridge) of this 52-mile reach. Floodway widths within this reach vary from 1,600 to 2,500 feet; the cleared floodway width varies from 350 to 450 feet. About 645 acres of vegetation were originally cleared to accommodate construction activities and flood flows. As of 1975, approximately 17 miles of channel rectification (i.e., pilot channeling and channel realignment) had been completed. Current operation and maintenance activities maintain the cleared floodway at its present width, and involve minor pilot channeling and removal of arroyo plugs. In all reaches, the cleared floodway is maintained free of woody vegetation, although herbaceous vegetation is encouraged. The goal is to maintain the current width of the cleared floodway. Generally speaking, this means that mechanical clearing is required once every 3 to 5 years, however, some reaches (e.g., Albuquerque reach) may need to be cleared annually.

The floodway from Cochiti to San Acacia (111 miles) is confined by levees and averages 1,800 feet wide. Channel work is limited to the undeveloped floodplain between the levees. The density and width of installed jetties varies according to guidelines and results of hydraulic model studies conducted by the BR. Operated in conjunction with upstream reservoirs, this channel work is intended to reverse the trend of aggradation and allow the river to degrade back to its 1936 condition.

The Cochiti reach extends from Cochiti Dam 21 miles downstream to the Angostura diversion. The BR's activities have primarily been restricted to construction and maintenance of a cleared floodway, pilot channeling, and channel stabilization. Levees in this reach are discontinuous. Floodway width varies from 230 to 4,720 feet; width of the cleared floodway varies from 150 to 1,510 feet. Approximately 3,300 jacks were installed between 1953 and 1975, occupying a total of about 55 acres of floodway. The current (1990) approach for stabilizing the river channel through this reach is to allow the river to follow a sinuous meander pattern. Sediment deposits on point bars are regraded upstream and downstream to build gradually curved banklines that are then armored with riprap.

The 38-mile Albuquerque reach extends from the Angostura diversion dam downstream to the Isleta diversion dam. The design flood capacity within the Cochiti-San Acacia reach at Albuquerque is estimated at 20,000 cfs for spring flows and 42,000 for summer flows. Width of the floodway within this reach varies from 250 to 3,020 feet; the cleared floodway varies from 170 to 1,470 feet. Between 1953 and 1975 approximately 31,200 jacks were installed, occupying about 1,800 acres of floodway. Operation and maintenance activities are primarily restricted to maintaining the cleared floodway at its present width. In this reach the cleared floodway is often mowed annually to allow passage of high flows. Pilot channeling and channel rectification work is confined to protecting existing levees and conveyance works, and removing arroyo plugs.

The 52-mile Belen reach extends from the Isleta diversion dam downstream to the San Acacia diversion dam. The width of the floodway within this reach varies from 500 to 3,060 feet; the cleared floodway width varies from 350 to 2,360 feet. Approximately 48,500 jacks were installed from 1953-1974, occupying a total of about 2,670 acres of floodway. Also located within this reach is the Bernardo Prototype Area where about 6,258 acres of floodplain were cleared from December 1963 to July 1964 to study the feasibility of removing woody vegetation for the purpose of conserving groundwater. The Bernardo Prototype Area extends upstream from the San Acacia diversion dam for 14 miles to U.S. Highway 60 near Bernardo. Other operation and maintenance activities have primarily consisted of maintaining the cleared floodway at its present width, pilot channeling, channel stabilization, and removal of arroyo plugs. Other construction activities within this reach include the Bernardo low flow conveyance channel and the Bernardo-San Acacia Conveyance and Protective works. Initially constructed in the early 1930's, the San Francisco Riverside Drain and levee was rebuilt in 1955 and used as a low flow conveyance channel, diverting all flows less than or equal to 2000 cfs. In the 1970's this channel was connected to the Bernardo-San Acacia Conveyance and Protective Works, a collection and transport system extending from south of the Rio Puerco to the San Acacia diversion dam. Today the Bernardo low-flow conveyance channel is connected with this conveyance system. Channeled flow is siphoned under the Rio Puerco and Rio Salado.

The San Acacia-Elephant Butte Division extends approximately 75 miles downstream from the San Acacia diversion dam to Elephant Butte Reservoir. The design discharge for the cleared floodway is 20,000 cfs for spring floods and 60,000 cfs for summer floods. The 46-mile Socorro reach extends from San Acacia to San Marcial. Floodway width within this reach varies from 800 to 4,900 feet. It is confined on the west by the low-flow conveyance channel levee and by valley bluffs on the east. The cleared floodway was initially cleared in 1951 and is currently maintained at its present width of 300 to 1,700 feet. The floodway channel is confined by stabilization and rectification works such as pilot channels and jetty fields. As of 1975 approximately 15 miles of pilot channels existed throughout the reach, and an estimated 13 additional miles were expected to be completed between 1975 and 1985. The entire reach, however, has essentially been pilot channeled at one time or another. Between 1953 and 1974 approximately 18,000 jetty jacks were installed occupying a total of about 400 acres within the floodway. Additional jetty fields (approximately 1,000 jacks) were expected to be installed in the reach after 1975.

The San Marcial reach extends 29 miles from San Marcial downstream to the Narrows of Elephant Butte Reservoir. The majority of this reach is located within the spillway elevation of the reservoir; water backs up almost to San Marcial when the reservoir is full. Floodway width within this reach varies from 700 to 2,210 feet; the cleared floodway varies from 430 to 1,550 feet. Pilot channeling within this reach has usually not been necessary, and channel stabilization (i.e., jetty fields) has been limited to protecting the low-flow conveyance channel. As of

1975, approximately 7,300 jetty jacks had been installed, occupying about 190 acres of the floodway within this reach. Tremendous amounts of activity (vegetation clearing, etc.) have taken place in and around the upper end of Elephant Butte Reservoir (i.e., above the Narrows) in conjunction with reconstruction of the low-flow channel and creation of the Elephant Butte Marsh Habitat Management Area. Of the estimated 13,420 acres of woody vegetation that existed within the spillway elevation of Elephant Butte Reservoir (i.e., below San Marcial), approximately 4,155 acres were expected (in 1975) to be cleared.

To summarize, approximately 90 of the 240 river miles between Velarde and Elephant Butte Narrows have been pilot channeled. Life span of a pilot channel may be only a couple of years at best. Pilot channels are usually constructed to remove detrital and/or arroyo plugs. A pilot channel is generally excavated to a bottom width of 50 feet, and a top width of 80 feet, with approximately 63,600 cubic yards of material excavated per mile of pilot channel. The cleared floodway is maintained at its present width throughout the MRG valley. According to 1975 figures, this totals about 14,000 acres of cleared floodway. Vegetation management (i.e., clearing) serves to conserve groundwater and provide a clear path or corridor for high flows.

Clearing is usually accomplished through bulldozing, root-plowing, chaining, and mowing. According to the Environmental Impact Statement (U.S. Bureau of Reclamation 1977), some areas within the cleared floodway will need to be maintained on an annual basis while others were expected to require control once every 3 to 5 years. Jetty fields are installed to prevent damage to levees during high flows, and to stabilize new channels and other conveyance works. Jetty jacks and fields are relatively maintenance free; however, an estimated 300-600 are replaced annually due to theft or cable breakage. Tables 2 to 4 summarize channel maintenance and operation activities through 1974.

Table 2. *Jetty field construction through 1974 (after U.S. Bureau of Reclamation 1977).*

Division/ reach	Installation (year)	Number of jacks	Total acres of floodway occupied by jetty fields
Española Division			
Española reach	1956-1958	40	0
Cochiti-San Acacia Division			
Cochiti reach	1953-1974	3,265	55
Albuquerque reach	1953-1974	31,220	1,795
Belen reach	1953-1958	48,515	2,670
San Acacia-Elephant Butte Division			
Socorro reach	1951-1974	18,120	390
San Marcial reach	1951-1974	7,320	185

Table 3. *Floodway widths through 1974 (after U.S. Bureau of Reclamation 1977).*

Division/ reach	Period of clearing (year)	Floodway width (feet)	
		Cleared	Total
Española Division			
Española reach	1956-1958	350-450	1,600-2,500
Cochiti-San Acacia Division			
Cochiti reach	1953-1974	150-1,510	230-4,720
Albuquerque reach	1953-1974	370-1,470	250-3,020
Belen reach	1953-1958	350-2,360	500-3,060
San Acacia-Elephant Butte Division			
Socorro reach	1951-1974	300-1,700	800-4,900
San Marcial reach	1951-1974	430-1,550	125-190

Table 4. *Floodway rectification (i.e., pilot channeling) through 1974 (after U.S. Bureau of Reclamation 1977).*

Division/ reach	Miles of pilot channels	Estimated number of arroyo discharge points
Española Division		
Española reach	1.3	20
Cochiti-San Acacia Division		
Cochiti reach	4.0	39
Albuquerque reach	1.0	30
Belen reach	2.0	27
San Acacia-Elephant Butte Division		
Socorro reach	13.0	67
San Marcial reach	0.0	0

Operating Rules and System Models

The existing operating rules for the system are contained in descriptive form in Bullard and Wells (1991), U.S. Bureau of Reclamation (1977), and U.S. Army Corps of Engineers (1989). U.S. Army Corps of Engineers (1989) provides the best presentation of these operating rules based on simulation studies they have conducted and their implementation of the HEC-5 model. According to the Albuquerque district of the Corps of Engineers, implementation of the "rule of the river" is not entirely accurate or analytically feasible given the complex nature of these operating rules. The U.S. Army Corps of Engineers (1989) HEC-5 model currently represents the most comprehensive analysis tool for water budget accounting and reservoir forecasting within the MRG. This summary in U.S. Army Corps of Engineers (1989) includes a complete listing of model input files, reservoir operations, diversion demands. Flow inputs are monthly values derived from integrating daily flow records for the period 1967-1987 at major control points, or nodes, throughout the valley. The main gaging stations or forecast points are Del Norte, Mogote, and Platoro in Colorado; and Embudo, Otowi, and El Vado in New Mexico. Other flow inputs, diversions, losses from infiltration or evapotranspiration, precipitation, ungaged tributaries, and return flows are not accounted. The model does not attempt to re-create historical flow conditions, but rather simulates what might be expected to occur using present flow conditions under various reservoir operations.

Recent HEC-5 simulations by the USACE use the actual storage in system reservoirs as of September 30, 1988, as initial conditions. Note that current USACE simulations take advantage of "existing bugs" in the 1988 (or 1989) version of HEC-5 to more accurately incorporate operating rules outlined in the Rio Grande compact and state and federal legislation. Subsequent attempts at replicating their results (U.S. Army Corps of Engineers 1989) using more recent versions of the model have failed. Consequently the USACE continues to use the 1988/89 version of HEC-5. They do, however, intend to modify this model to include daily discharge simulations for the reach from Cochiti downstream to the sewage outfall at Albuquerque.

The USACE-Albuquerque district is also using HEC-2, a water surface profile model, to help assess the integrity of flood control levees through Albuquerque (Bernalillo to Belen) and along the low-flow conveyance channel (San Acacia to Elephant Butte Reservoir). The input data file is constructed from a series of cross sections that were digitized (by the BR) from 1984-85 aerial photography. These cross sections are located approximately every 500 feet, and HEC-2 is used to determine the levee-overtopping flow at points throughout these two reaches. Limited groundtruthing and errors and difficulties in digitizing cross sections, as evidenced by discontinuities in channel bed profiles and modeled water surface profiles requiring water to "flow uphill," have lead the BR to suspect errors in the 1984-1985 cross section data. Even so, HEC-2 can be expected to produce more or less accurate or reliable water surface elevations associated with large magnitude, low-frequency floods.

Streamflow Data

Data summaries for all USGS gaging stations on the Rio Grande and its major tributaries (Fig. 3) are contained in Appendices C and D of Bullard and Wells (1991), including location, period of record, type of gage, and average and extreme discharges for the period of record. Discharge summaries, partial duration curves for daily discharges and mean annual flows, and low and high flow frequencies for 1- to 365-day intervals are contained in Appendices J and K for the Embudo, Otowi, San Felipe, and San Marcial (both floodway and conveyance channel) gages. Bullard and Wells (1992) also provide mean annual and peak discharge hydrographs for the Embudo, Otowi, San Felipe, and San Acacia gages for the periods before and after major dam construction.

U.S. Army Corps of Engineers (1989) provides descriptive information on the three most significant flood events on the Rio Grande, as well as the standard design floods for Abiquiu, Cochiti, and Jemez Canyon reservoirs. This report also provides information on the spillway design floods for each of the reservoirs within the project area.

The MRGCD maintains daily gaging records at 15 stations within their distribution system. These records include weekly site measurements since 1975, and monthly and annual summary diversion records since 1936. These summaries contain monthly and annual diversions, main canal losses and waste, lateral delivery, lateral losses and waste, and delivery amounts to farms for each of the four reaches in the district. MRGCD staff indicated that upon written request, they would provide this data as well as maps showing the location of the 15 gaged sites. Some information on diversions and return rates is summarized in Appendix F of Bullard and Wells (1991). In addition, the U.S. Army Corps of Engineers (1989) HEC-5 model also lists assumed monthly diversion and

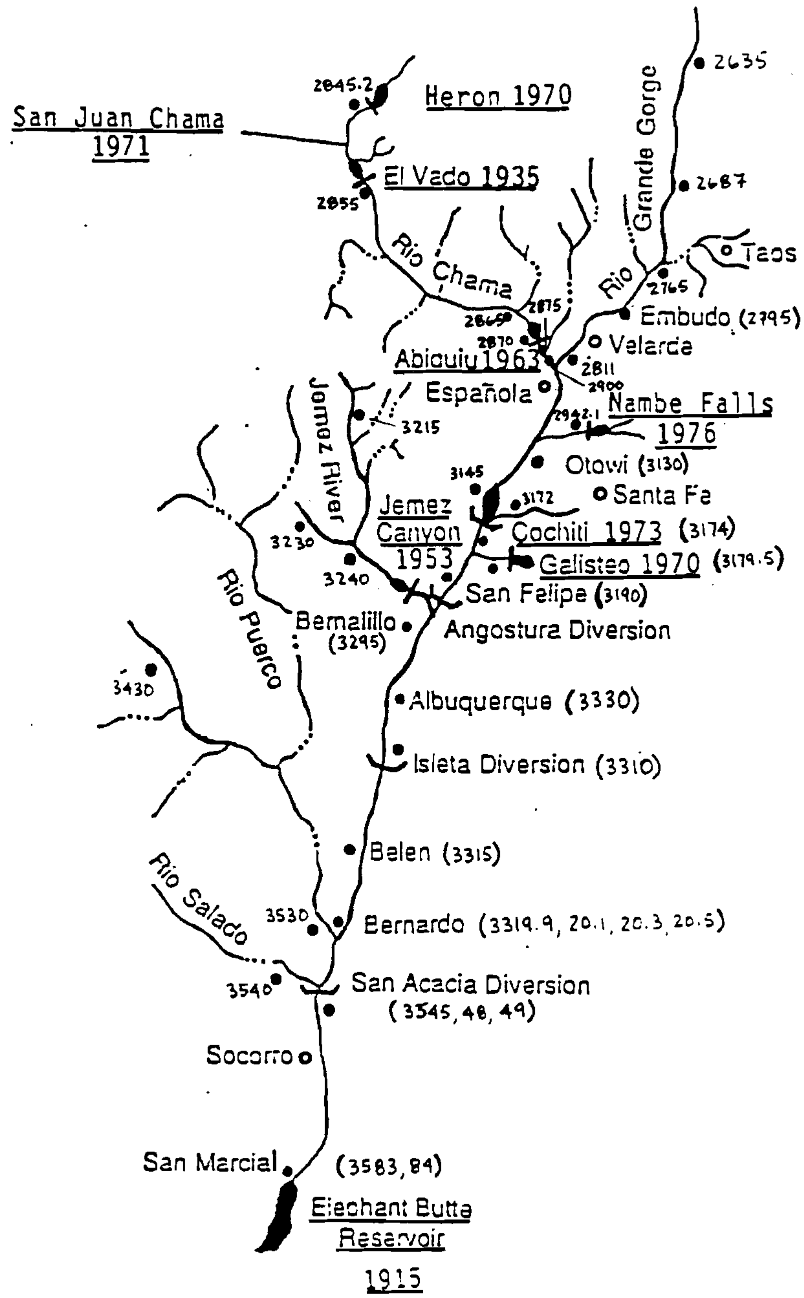


Fig. 3. U.S. Geological Survey gaging stations on the Middle Rio Grande and its major tributaries.

return flows at major points within the MRG valley. These particular estimates, as implemented within the model, were derived form historical records and a mass balance of flow data collected at gaged sites within the basin.

Variables Influencing Riparian Vegetation

Exotic Species

Comparison of existing riparian vegetation with observations of early explorers and long-time local residents suggests that significant changes have occurred throughout the MRG valley (Hansmann and Scott 1977). The most notable of these is an increase in the shrub community relative to the once expansive desert grasslands, and an increase in exotic woody species such as salt cedar (*Tamarix pentandra*, *T. chinensis*, *T. ramosissima*), Russian olive (*Elaeagnus angustifolia*), and Siberian elm (*Ulmus pumila*). These changes have been attributed to overgrazing (Hansmann and Scott 1977), changes in precipitation patterns, and construction of dams, levees, and conveyance channels (Everitt 1980).

Today, riparian woodlands (bosques) along the MRG valley are dominated by stands of cottonwood (*Populus fremontii* var. *wislizenii*), salt cedar, Russian olive, willow (*Salix exigua*, *S. goodingii*, and *S. amygdaloides*), New Mexico olive (*Forestiera neomexicana*), and seepwillow (*Baccharis salicina*). Although these and many other species are found in the valley, cottonwood, willow, salt cedar, and Russian olive are the four main species present in riparian areas (Sivinski et al. 1990). Cottonwood is found throughout the entire reach, attaining its maximum density near Albuquerque. Similarly, species of willow are abundant throughout the entire reach. By comparison, salt cedar is most abundant in the southern portion of the reach, and although it is common throughout the area, it does not attain high densities north of Bernardo (Freehling 1982). Russian olive is a major understory component throughout much of the reach, and although it appears to be more abundant in the northern half, it extends as far south as Elephant Butte reservoir.

Campbell and Dick-Peddie (1964) observed changes in vegetation on the Rio Grande above the headwaters of Elephant Butte reservoir, and attributed these differences to climatic differences between the areas above and below the reservoir. According to Campbell and Dick-Peddie (1964), and references therein, the area near Socorro corresponds closely with the northern boundary of the Chihuahuan desert, as evidenced by substantial changes in the upland vegetation above and below the Rio Puerco-Rio Grande confluence. Such obvious changes are not as readily apparent in the phreatophytic communities.

Campbell and Dick-Peddie (1964) classified the phreatophytic vegetation below Elephant Butte Reservoir as being composed of screwbean mesquite (*Prosopis pubescens*) and salt cedar, with salt cedar becoming more dominant in the northern part. Above Elephant Butte, salt cedar is eventually replaced by cottonwood or cottonwood and Russian olive. In cottonwood stands that had not been recently disturbed they found little salt cedar, however, adjoining areas and open areas within cottonwood stands contained salt cedar.

Because salt cedar and Russian olive have become a permanent fixture in the riparian community, it has become the goal of several federal, state, and private organizations to maintain cottonwood as the dominant canopy species and to maintain the few remaining plant associations that are composed of native species. To do so requires a complete understanding of the ecology, life history characteristics, and water requirements of these species. The following briefly outlines some of the current knowledge about these two exotic species.

Salt cedar was introduced into the United States in the mid- to late 1800's as an ornamental in California, and later as an erosion control agent in New Mexico (Robinson 1958). Salt cedar was first reported in New Mexico in 1915 by Wooton and Standley who mention the plant as "often escaped" (Robinson 1965). By the late nineteenth and early twentieth centuries it had escaped cultivation and become naturalized in the Southwest (Robinson 1965). As reported by Kerpez and Smith (1987), Everitt (1980) and Larner et al. (1974) attributed the rapid spread of salt cedar in the United States to reservoir construction and altered natural flows, which provided numerous suitable seed beds. Graf (1978) indicated that the most dramatic change in the fluvial landscape of the Colorado plateau was in the riparian vegetation; islands, bars, and beaches along major water courses that were once sparsely vegetated are now covered by dense thickets of salt cedar. In Arizona and New Mexico, fluvial landscapes are often dominated by broad alluvial valleys, which are often covered by salt cedar thickets of several thousand hectares. These thickets often result in constricted channels and lower water tables.

Turner (1974) described salt cedar as a facultative phreatophyte; that is, it does not necessarily depend on available ground water to survive. Campbell and Dick-Peddie (1964) found dense stands of salt cedar growing where the water table was 1.5 to 6 meters below the surface. In places where the water table was less than 1.5 m from the surface, plants branched profusely below ground and did not form dense stands. They also found areas flooded during the growing season to have a higher density of salt cedar than areas having an early spring flood and a limited supply of groundwater throughout the growing season. Horton and Campbell (1974) found that in areas where the water table was more than 6 m deep, salt cedar formed an open shrubland with 4.5-6 m between individual plants. They attributed the survival of these individuals to available rainfall and bank storage of floodwaters.

Salt cedar flowering and seed dispersal often occurs in pulses (Warren and Turner (1975). Observations by John Taylor (U.S. Fish and Wildlife Service, Bosque del Apache NWR; personal communication) over the last 5 years (1987-1991) suggest that the seed dispersal/germination window for salt cedar extends from April to September with the strongest pulse occurring in early May and another in late June or early July. Similar observations along the Gila and San Pedro Rivers indicate that salt cedar often has multiple flowering and seed dispersal pulses throughout an extended dispersal/germination window that often lasts from April/May to October (Warren and Turner 1975). Seed production from a single mature salt cedar may be as high as 500,000 seeds per year (Tomanek and Ziegler 1962).

Once wetted, fresh seeds usually germinate within 24 hours (Horton et al. 1960). Slowly receding water levels along river or reservoir banks create optimum seedbeds for germination, but survival requires several months without subsequent flooding. Seedlings require saturated soils throughout the first 2-4 weeks and usually do not survive more than 1 day without moist soil. Consequently, synchronous timing of seed dispersal and moisture availability is critical to successful germination and establishment (Warren and Turner 1975). Salt cedar seedlings can survive submergence for several weeks, but are easily uprooted by even weak currents (Kerpez and Smith 1987). However, prolonged inundation (i.e., long-term submergence) will often kill salt cedar. Wiedemann and Cross (1978) found that a 28-month period of submergence killed 99% of all salt cedar, but only 28% had died after 17 months. However, mortality increased to 77% when the mature salt cedar had previously been "mechanically manipulated." Warren and Turner (1975) found that 70 days of inundation killed almost all salt cedar. They observed seedlings ranging from 4-12 weeks old that had been submerged 1-6 weeks; all ages survived 1 week and only the 12 week old plants survived 6 weeks. Those plants with shoots extending above the water surface had the highest chance of survival; those able to withstand the deepest root crown submergence were also those tall enough to extend above the water surface.

Salt cedar is very drought tolerant. It is capable of dropping its leaves, halting growth and withstanding lengthy droughts. It can also withstand high concentrations of dissolved solids and very saline conditions. It is very resilient to fire. In the absence of frequent flooding, salt cedar communities burn every 16-20 years (Kerpez and Smith 1987). Fires prevent most stands from either reaching maturity or persisting as mature communities (Ohmart and Anderson 1978). Salt cedar is seldom killed by fire and often grows back vigorously after a burn (Kerpez and Smith 1987). Consequently, native riparian vegetation, which is not adapted to fire, is usually replaced by salt cedar after a burn (Horton 1977).

Phenological observations of cottonwood, willow, and salt cedar by Campbell and Dick-Peddie (1964), suggest that development of floral and vegetative parts is approximately 20 days later at Albuquerque than at El Paso, and that variations in local moisture conditions affect the development time as much as 5 days when comparing streamside cottonwoods to those located on drier sites.

The introduction and spread of Russian olive to and throughout southwestern watersheds is poorly documented. Christensen (1963) reported the species as being naturalized and commonly cultivated in central Utah by 1924. According to Freehling (1982), one of the first mentions of Russian olive in the Rio Grande watershed in New Mexico was by Garcia (1903), who identified it growing in southern New Mexico near Mesilla Park. Freehling (1982) further mentions that Wooton and Standley (1915) reported its cultivation in several places throughout the state. Van Cleave (1935) identified it as a conspicuous component of riparian vegetation fringing the edges of lakes and swamps in the MRG valley. By 1960, Russian olive had become an integral part of riverside woodlands throughout the MRG valley (Campbell and Dick-Peddie 1964).

Russian olive is well adapted to a range of environmental conditions and grows equally well beneath cottonwood canopies, in open areas, and among pure stands of salt cedar (Campbell and Dick-Peddie 1964). It thrives under a wide range of light, soil, and moisture conditions, growing equally well in water-logged river bottoms where the water table is within 2 feet of the surface and in areas that experience significant drought (Borell, no date). Russian olive grows well in a variety of soils, and can withstand flooding, silting, and saline conditions; however, it grows best in good soil with light salt and alkali content (Borell, no date). Russian olive flowers in late spring usually in June. Fruits ripen during the summer (August through October), and the ripe fruits and seeds are dispersed throughout the fall and winter (U.S. Forest Service 1974). Some of the fruits, however, may even remain on the trees until spring.

Cottonwood fruits ripen beginning about the time leaves reach full size (about 4-6 weeks after flowering), and dispersal takes place a few weeks after ripening. In the vicinity of Albuquerque, flowering dates are from April to May and seed ripening and dispersal dates are usually June-July (U.S. Forest Service 1974). John Taylor (U.S. Fish and Wildlife Service, Bosque del Apache NWR; personal communication) suggests that seed ripening and dispersal begins in May and peaks in mid-June.

Many riparian species are adapted to hydrographs dominated by spring snowmelt. The short-lived, water-dispersed seeds of most riparian species depend on a seed dispersal window coinciding with the peak annual discharge so that newly germinated seedlings have a chance to become established before the next flood. Changes in the timing of the peak discharge or multiple peaks may favor species with broader seed dispersal and germination windows. The introduction, rapid spread, and naturalization of exotic species such as salt cedar and Russian olive within the Middle Rio Grande valley during the last 80 years may be related to reservoir construction and altered streamflows (Larner et al. 1974; Everitt 1980), and the extensive disturbance associated with levee-drain construction during 1925-1935 (Sivinski et al. 1990).

Water Quality Factors

As indicated earlier, salt cedar is less dominant north of Albuquerque and relatively scarce throughout the Española valley; in contrast, salt cedar almost completely dominates the near-river riparian zone below La Joya. The decline in salt cedar in the north is probably not climate related because large, healthy stands of salt cedar are found in the Grand Valley of Colorado. Field observations and discussions with local biologists suggest that competition between cottonwood, Russian olive, and salt cedar varies along the river. One hypothesis is that changes in salinity may alter the relative competitiveness of the three species.

Figures 4 and 5 indicate a definite increase in the conductivity (a surrogate for salt concentration) of the Rio Grande in the downstream direction. Other data suggest the increase is partly due to irrigation return flows from the central portion of the MRG, but mostly due to salt delivered to the Rio Grande by the Rio Puerco. Dissolved constituents also vary along the river (Fig. 6). The dissolved constituents were not measured for the Albuquerque gage. Calcium is the major cation in the upper reach, whereas sodium is the major cation in the lower reach. The significance of the change in constituents is not known at this time. Changes in cations cause changes in soil characteristics, which could influence the relative competitiveness of salt cedar.

Although higher salt concentrations may favor salt cedar in the lower reaches of the Middle Rio Grande, data taken at the Albuquerque and San Marcial floodway gages show that the average specific conductance has either remained the same or decreased slightly since the 1960's (Figs. 7 and 8). Changes in water quality since 1960 thus probably do not account for declines in cottonwoods and increases in salt cedar over this time period.

Changes in the Cottonwood Forests

Photographs in an article on the San Felipe Pueblo (Strong 1979) suggest that in 1899 cottonwood forests were located away from the river, with the largest trees at the outer edge of the floodplain. The same pattern is seen today along the Green River and Gunnison Rivers, where the largest cottonwoods are on the outside edge of the second bench of the riparian zone, some distance from the main channel. This is in contrast to the present Rio Grande where cottonwood stands are often located close to the river. A sketch map in an article on the history of Pueblo-Spanish relationships (Simmons 1979) suggests that in the 1740's cottonwood bosque was an important part of the riparian landscape above the Rio Puerco, but may not have been as important below the Rio Puerco. It is the present day reach below the Rio Puerco where salt cedar is most abundant.

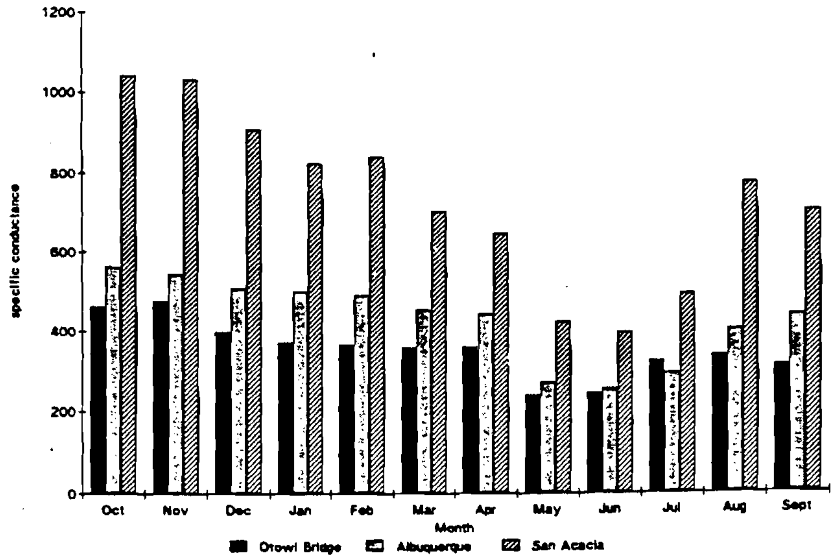


Fig. 4. Specific conductance in the Middle Rio Grande for water year 1975.

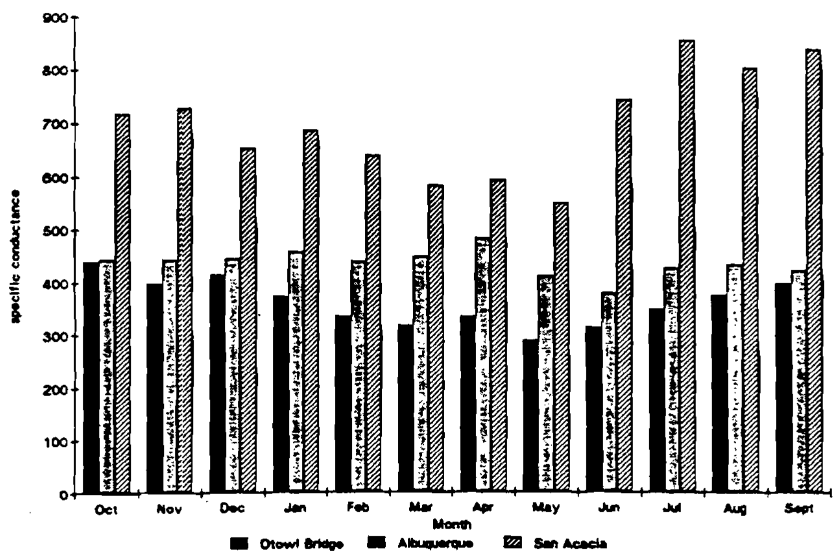


Fig. 5. Specific conductance in the Middle Rio Grande for water year 1990.

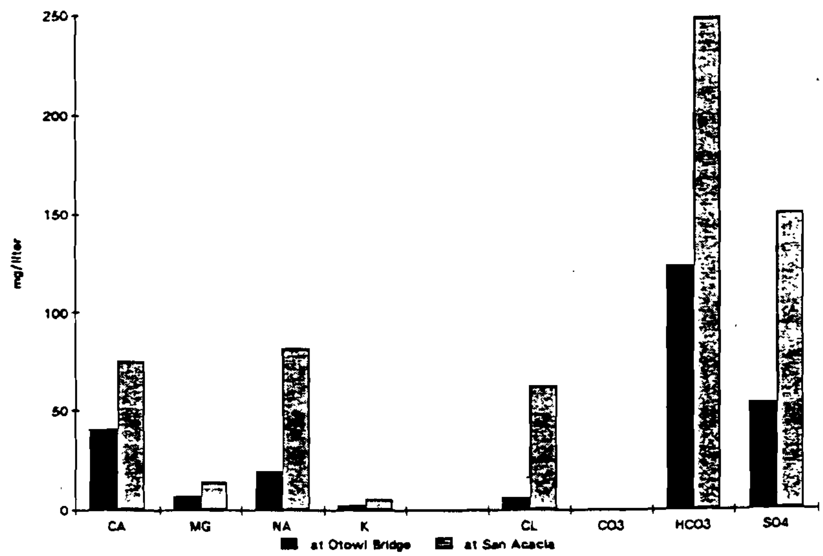


Fig. 6. Major constituents of dissolved solids in the Middle Rio Grande. Data for Otowi bridge were obtained on August 22, 1990, and for San Acacia on September 6, 1990.

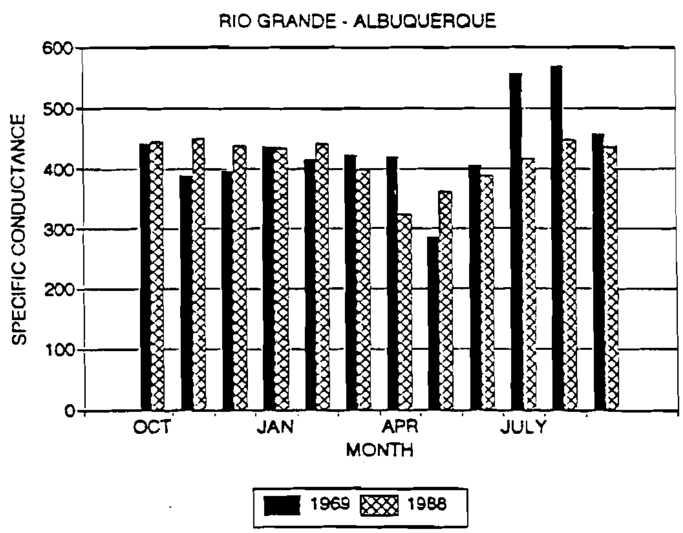


Fig. 7. Specific conductance measured at the Albuquerque gaging station.

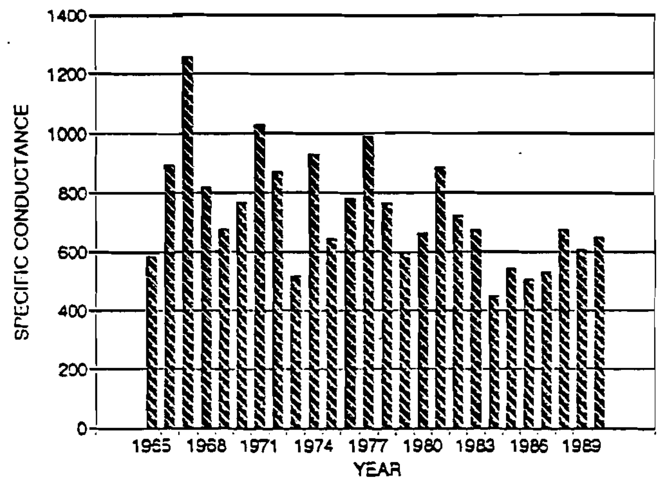


Fig. 8. Specific conductance measured at the San Marcial floodway gaging station.

Another factor is that many of the present dense stands of cottonwood are growing among the numerous jetty jacks located along the river (Fig. 9).

As a result of these observations we attempted to find information on cottonwood stands prior to the 1930's, when the first airphotos are available. The effort was not intensive because of manpower limitations; only information available in Colorado was reviewed. Photographs obtained from the USGS were of some help in determining the nature of the pre-1930's cottonwood forest.

Fig. 9. Cottonwoods growing among jetty jacks at a site just downstream of the Santa Fe railway bridge at Belen (September 1991).

The USGS photographs available were taken in 1905 near the present San Acacia diversion dam. On July 28, 1992, comparison photos were taken from approximately the same location. A comparison of the photographs shows a dramatic increase in riparian vegetation adjacent to the San Acacia diversion dam (Figs. 10 and 11). In addition, salt cedar is present today but was absent in 1905.

Information on the age of existing cottonwood trees along the MRG may help in understanding the dynamics of these stands. During the week of July 27, 1992, increment cores were taken from cottonwoods at several sites on the Bosque del Apache NWR (Ritter 1993). Within each stand, one representative tree was selected at random and sampled. Where possible, trees were excavated and sampled at the root flare. Larger trees, however, were usually

1905

1992

Fig. 10. Comparison of a 1905 view of the San Acacia dam site looking downstream to the view in 1992.

1905

1992

Fig. 11. Comparison of a 1905 view of the San Acacia looking northeast to the view in 1992.

not excavated and therefore were sampled as near the ground surface as possible. Several of these trees may have been buried at least 3 feet below the current ground surface; consequently tree ages should be viewed as only rough estimates of establishment dates.

Cottonwoods sampled on the west side of the conveyance channel were approximately 40 years old, which is about the age of the conveyance channel. Airphotos for the 1940's show that the river once covered those locations. A cottonwood located on the west bank of the river between the levee and jetty fields was 30 years old, which corresponds approximately to the time that the jetty jacks were installed. This area was part of the riverbed in 1949 but some trees can be seen in 1962 photos. This tree may therefore be slightly older than 30 years. At the same site, a cottonwood approximately 18 years old was sampled on the east side of the jetty jacks. This location is a fresh bar in the 1973 aerial photos and is fairly well vegetated in the 1989 aerial photos. Therefore this age seems fairly accurate.

Another cottonwood sampled close to the levee was at least 25 years old, again corresponding to installation of the jetty jacks. There are trees in this location in the 1962 and 1973 aerial photos, but the site is probably a bar in the 1949 aerial photos. The photos therefore indicate that this tree is between 30 and 43 years old. However, a high flow in 1967 (peak flow of 6,160 cfs at the San Marcial gage downstream; the highest flow between 1962 and 1972) could also have established this tree.

A cottonwood sampled 25 feet west of the river bank was 15 years old. This age seems fairly accurate since the 1972 aerial photo shows no trees in this location. In 1972, the river was approximately 900 feet east of its present position.

Two trees from a site covered by the river in a 1972 aerial photo were approximately 9 years old. Here, a line of older cottonwoods extends across a field between two bends in the river parallel to an unvegetated flood channel. The line of cottonwoods is presently west of the river, but in 1973 it was immediately adjacent to the channel.

The lateral migration of the river in the past allowed for periodic establishment of cottonwood trees. However, the river has been stabilized by the conveyance channel, channelization, levees, jetty jacks, and the construction of Cochiti Reservoir. Presently, the Rio Grande meanders only within its riverbed. Many young cottonwoods, 1 to 2 years old, were seen on the river bank, sand bars, and point bars. These trees will probably not survive because they are vulnerable to subsequent high flows. Very few young trees were found a "safe" distance from the river bank.

River Morphology Investigations

The form of riparian cottonwood forests is strongly influenced by river morphology and the interaction of sediment and water. In the MRG important changes have also been caused by construction of diversion works, levees, dams, conveyance canals, and drains. This section examines channel change in the MRG.

Two reaches along the MRG in New Mexico were examined. Reach 1 extends from San Felipe to Albuquerque. Levees on both sides constrict movement of the river to a defined channel of approximately 1,500 feet in Albuquerque. U.S. Geological Survey gaging stations at San Felipe (08319000) and Albuquerque (08330000).

The second reach extends from near San Antonio to below the Bosque del Apache NWR (approximately 10 river miles). A conveyance channel parallels the river through the reach; other ditches and drains are also present. The San Marcial gage (08358400) is located at the downstream end of the reach.

San Felipe to Albuquerque Reach

Most of the work done in the San Felipe to Albuquerque to reach was in the southern portion between Bernalillo and Albuquerque. Planform changes between 1935 and 1989 were investigated for a reach from Los Griegos to Albuquerque, a distance of approximately 10 river miles. This reach is bounded on both sides by levees which restrict and limit movement of the river to a zone approximately 1,500 feet wide in the vicinity of Albuquerque. Figures 12 and 13 compare the Rio Grande planform in 1935 and 1989 near Los Griegos and Albuquerque. In addition, these figures also show locations of cottonwood groves. The streambed in 1989 was much straighter and narrower than in 1935. The river is no longer able to move as freely as it used to because of the levees. In 1935 the river also had a much wider floodplain than in 1989. The 1989 floodplain has been overgrown with riparian vegetation.

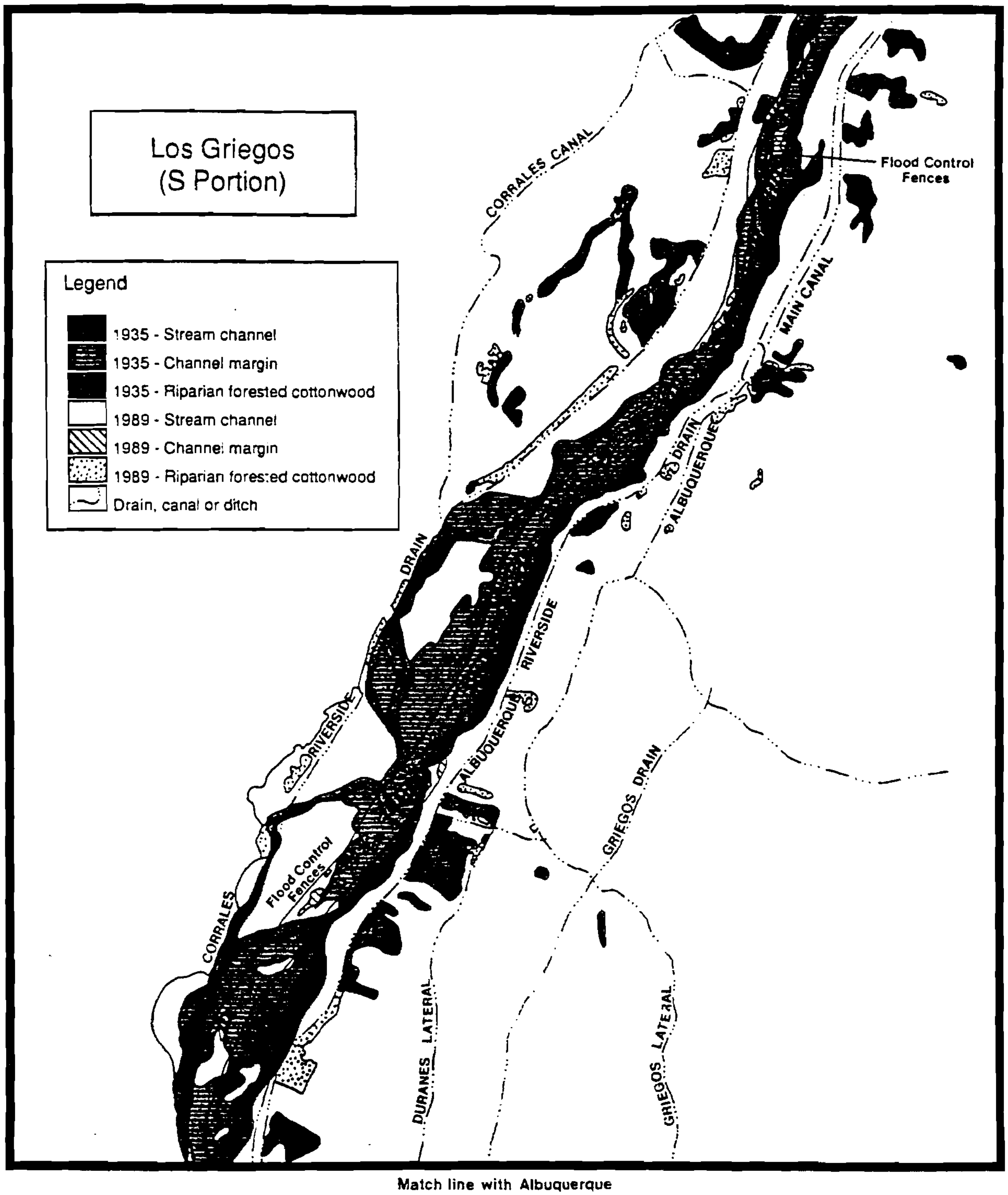


Fig. 12. Comparison of the planforms of the Rio Grande in the Los Griegos area in 1935 and 1989.

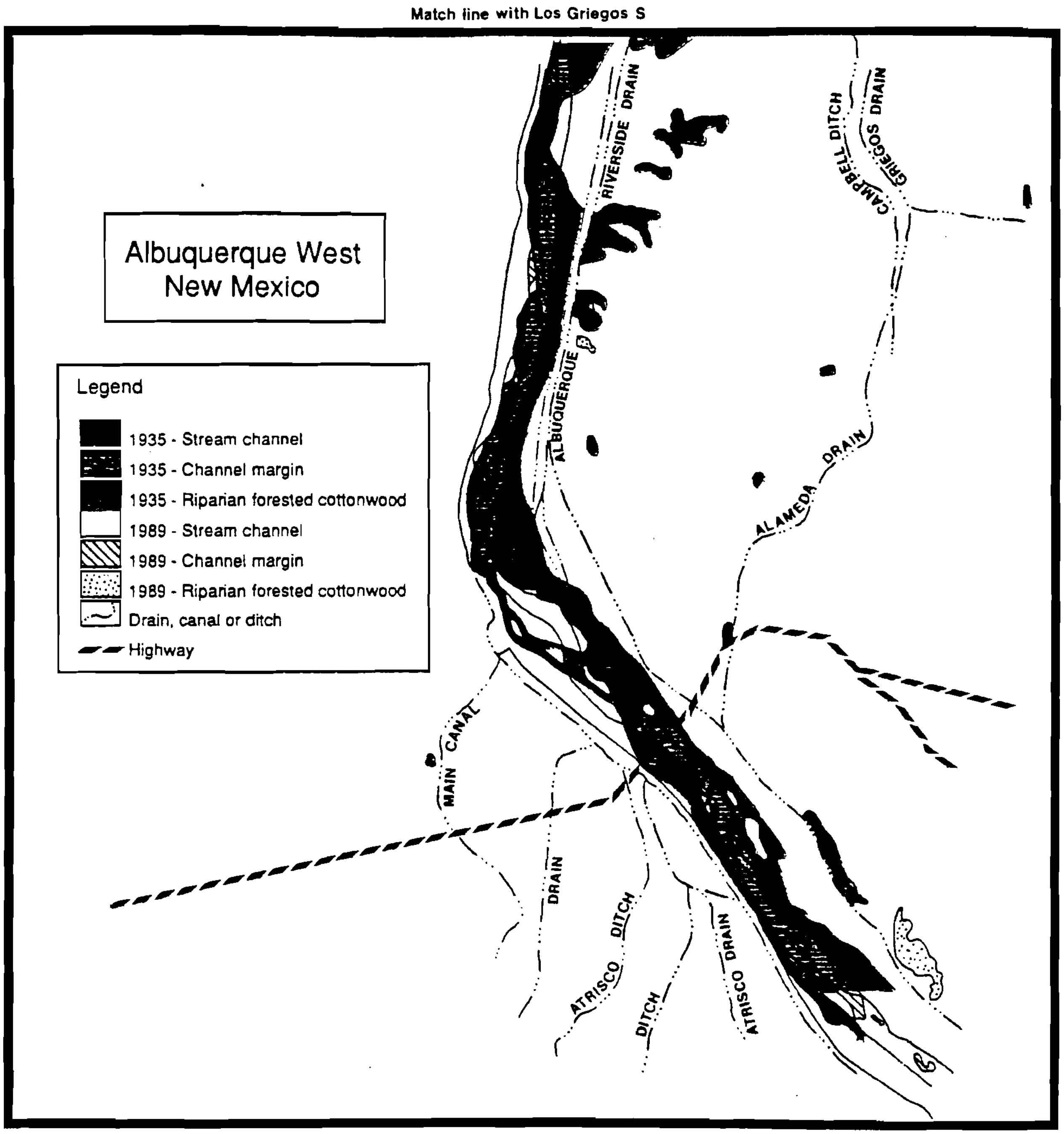


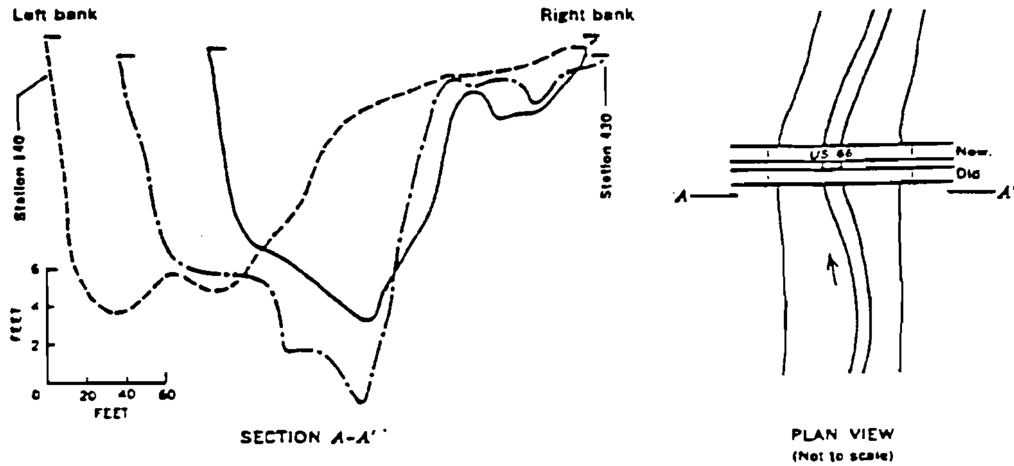
Fig. 13. Comparison of the planform of the Rio Grande in the Albuquerque area in 1935 and 1989.

The Rio Grande is a braided sandbed river. Without the levees the river would be very migratory in nature. Figure 14 illustrates lateral and vertical changes in the river near Old Town, Albuquerque, for a period in 1942 and 1948 (Culbertson et al. 1967). Note, however, that this figure describes a channel that no longer exists because of channel stabilization works.

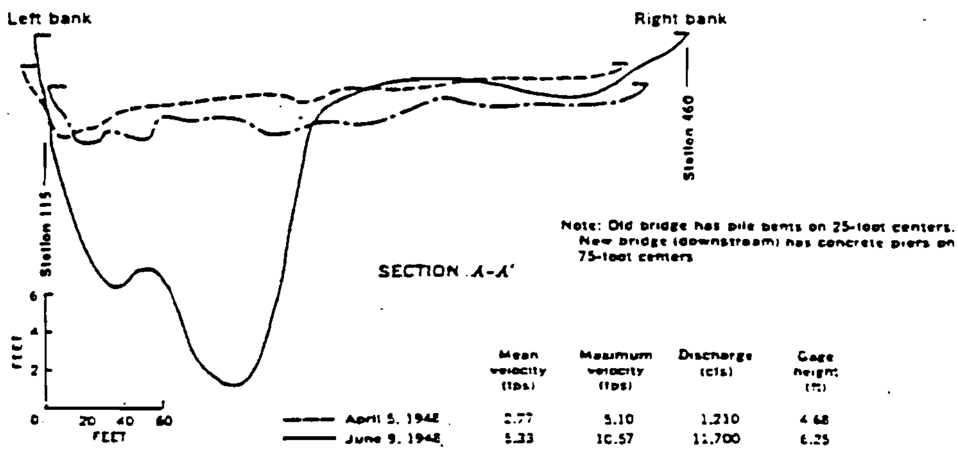
Three major reservoirs have impacted flows of both sediment and water in the San Felipe to Albuquerque reach: Jemez Canyon Dam on Jemez Creek starting in 1953, Abiquiu Dam on the Rio Chama starting in 1963, and Cochiti Dam on the main stem of the river starting in 1973. All three have the primary purposes of controlling sediment flows and flood flows in the MRG.

According to Lagasse (1981), Rittenhouse (1944) found the sources of channel and floodway sediments in the Albuquerque area were 21% to 39% from Jemez Creek, 3% to 8% from Galisteo Creek and the Santa Fe River, and 11% to 37% from the Rio Grande above Cochiti. Lagasse also reports that Jemez Canyon Dam had a trap efficiency as low as 40% prior to 1979. The river channel was stabilized in the late 1950's and early 1960's. Consequently, construction activities causing significant changes in sediment and flood flows started in 1953 and continued through 1974.

Mean annual discharge of the Rio Grande has been impacted by evaporation from reservoir pools, transbasin diversions into the Rio Grande basin, and changes in consumption within the basin (Fig. 15). However, these impacts are minor relative to the impacts on peak flows and sediment flows (Figs. 16 and 17).



	Mean velocity (fps)	Maximum velocity (fps)	Discharge (cfs)	Gage height (ft)
April 6, 1942	3.85	8.82	6,930	4.87
May 2, 1942	3.44	7.94	8,490	4.37
May 15, 1942	4.85	11.33	13,900	5.09



	Mean velocity (fps)	Maximum velocity (fps)	Discharge (cfs)	Gage height (ft)
April 5, 1948	2.77	5.10	1,210	4.68
June 9, 1948	5.33	10.57	11,700	6.25
June 28, 1948	2.80	4.91	1,250	3.48

Fig. 14. Shift of the thalweg and local scour during flood flows, Rio Grande at Albuquerque, New Mexico.

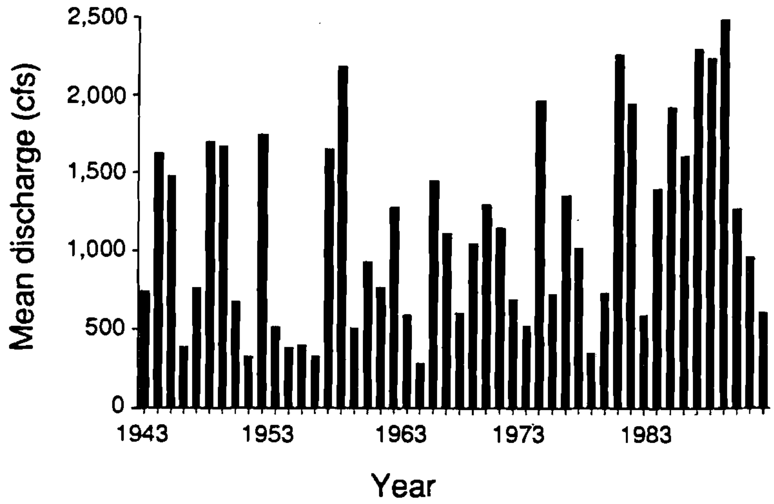


Fig. 15. Mean annual discharge of the Rio Grande at Albuquerque, New Mexico, water years 1943-1990.

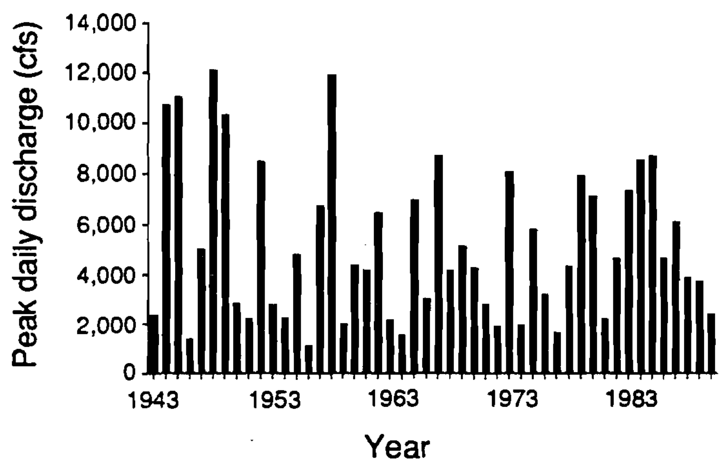


Fig. 16. Peak discharge of the Rio Grande at Albuquerque, New Mexico, water years 1943-1990.

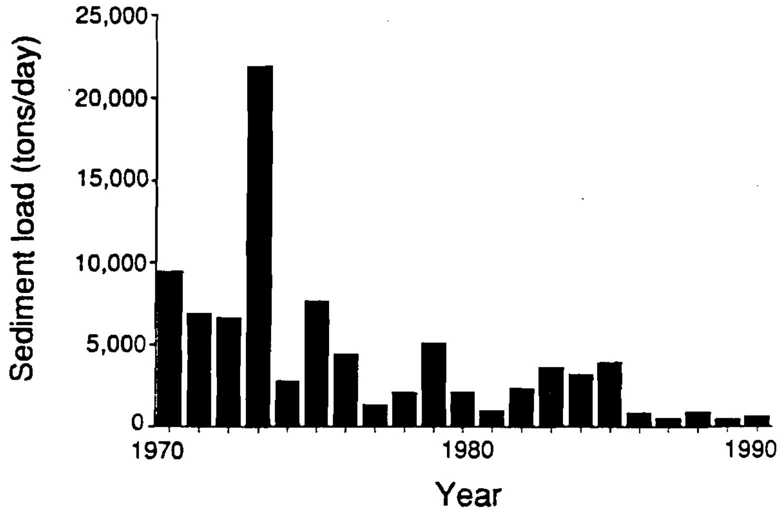


Fig. 17. Measured sediment load for the Rio Grande at Albuquerque, New Mexico, water years 1970-1990.

A reduction in peak flows can cause a significant reduction in sediment transport capacity. The same volume of water can transport quite different quantities of sediment. Suppose the volume of water (V_w) is

$$V_w = Q * t$$

where Q is the discharge and t is the time. Suppose further the sediment transport load (Q_s) is related to the discharge using the equation

$$Q_s = A * Q^{2.0}$$

where A is a constant and 2.0 is a common power term for sediment load in a stream.

The volume of sediment transported (V_s) in time t is

$$V_s = Q_s * t = A * t * Q^{2.0}$$

Suppose we have the same volume of water in twice the time; the new sediment volume transported (V_{sn}) is

$$V_{sn} = A * (2t) * (Q/2)^{2.0}$$

$$= 0.5\ (A\ t * Q^{2.0})$$

$$= 0.5 * V_s$$

This logic leads to a sediment transport capacity index (STCI) for a time period of n days of the form

$$STCI = \left(\sum_{i=1}^{n} (Q^B)/(QREF^B) \right) / n$$

where Q is the daily discharge, QREF is an arbitrary reference discharge, B is a coefficient, and n is the number of days in the period.

The sediment transport capacity index presented above is useful when considering the transport of sand. For a reach with significant gravel substrate the index should be written as

$$STCIG = \left(\sum_{i=1}^{n} ((Q - QCRT)^B)/(QREF^B) \right) / n$$

where QCRT is a critical discharge based on the size of the gravel and the nature of the river.

The value of B is usually 2.0 unless there is a specific reason to select some other value (Milhous 1992b). The use of 2.0 is based on review of a number of discharge versus sediment load relations. The range in B is considerable. If a discharge versus sediment load function is available, the B from that relation could be used.

The reservoirs constructed in the Middle Rio Grande valley have reduced both the sediment supply (Fig. 17) and the sediment transport capacity. The time series of the annual sediment transport capacity index calculated using the streamflows for the Albuquerque gage is shown in Fig. 18. The reference discharge is 2,000 cfs and the power coefficient (B) is 2.0. A discharge versus total sediment load relation for the Albuquerque gage is shown in Fig. 19. A regression analysis of the data results in the equation

$$Q_{ts} = 0.029*(Q^{1.66})$$

where Q is the discharge and Q_{ts} is the total sediment load. Analysis of the data indicates the power term in the equation above could be 2.0 with a 15% chance that the assumption of 2.0 is in error.

Calculated sediment loads were used to develop the above equation, whereas the data in Fig. 17 represent measured sediment load. The difference between these two quantities is small for many streams, but for the Rio Grande it is significant (Fig. 20) with measured annual sediment yield often 70% to 80% of the total load.

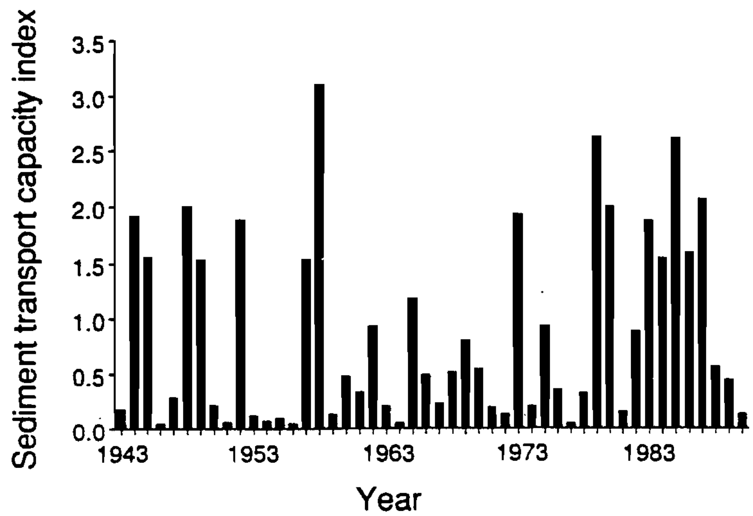


Fig. 18. Sediment transport capacity index for the Rio Grande at Albuquerque, New Mexico, water years 1943-1990. (Reference discharge of 2,000 cfs and critical discharge of zero.)

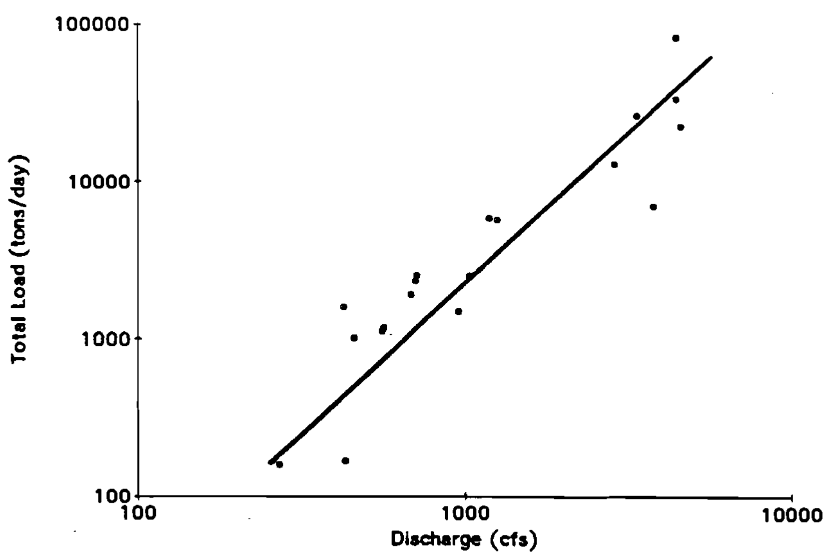


Fig. 19. Discharge versus total sediment relation for the Rio Grande at Albuquerque, New Mexico, water year 1975.

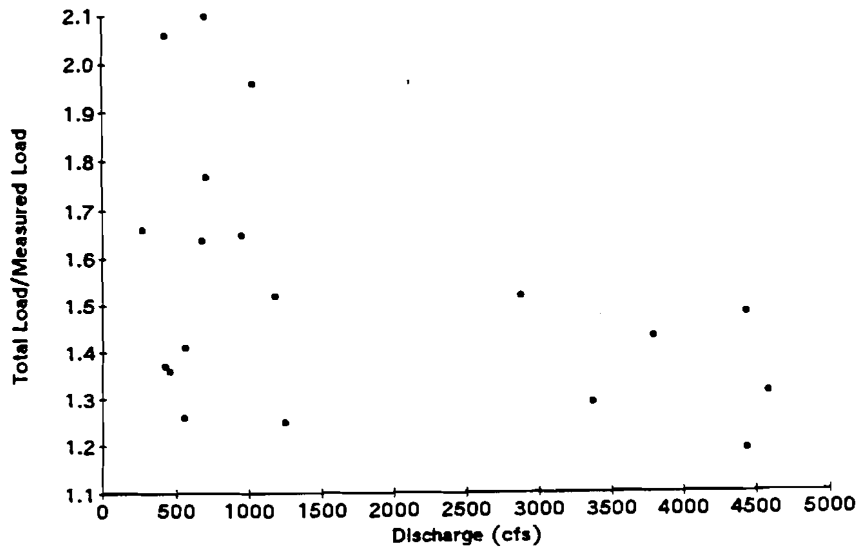


Fig. 20. Ratio of total sediment load to measured sediment load versus discharge for the Rio Grande at Albuquerque, New Mexico, water year 1975.

The annual sediment transport capacity index time series (Fig. 18) suggests that the river still has considerable capacity to transport sediment, but the measured sediment load data (Fig. 17) indicate a significant reduction in yield. A graph of sediment yield versus sediment transport capacity index indicates that the reservoirs have reduced yield significantly (Fig. 21). This also should have resulted in a reduction in bed elevations, which Lagasse (1981) indicates is the case for the period up to 1980, except where base level is controlled by a structure or by gravel deposited in the channel.

Figure 22 shows temporal changes in water surface elevation for two flows. Water surface elevations were determined using a stage-discharge relation derived from annual peak flow data. Degradation has probably continued to occur in the Albuquerque area.

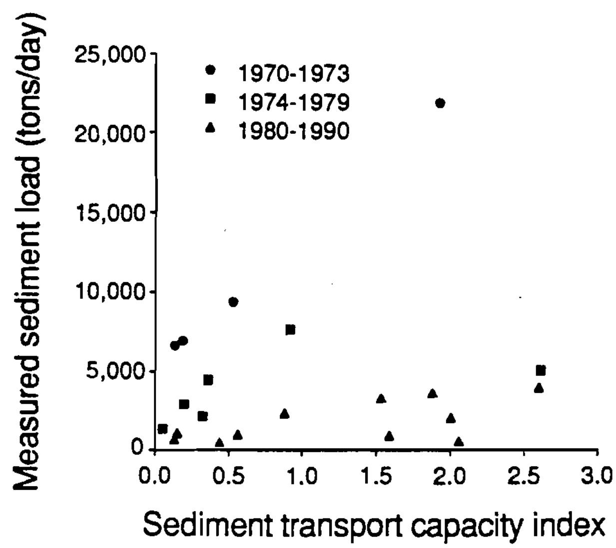


Fig. 21. Relation between measured sediment load and sediment transport capacity index for the Rio Grande at Albuquerque, New Mexico, water years 1970-1990.

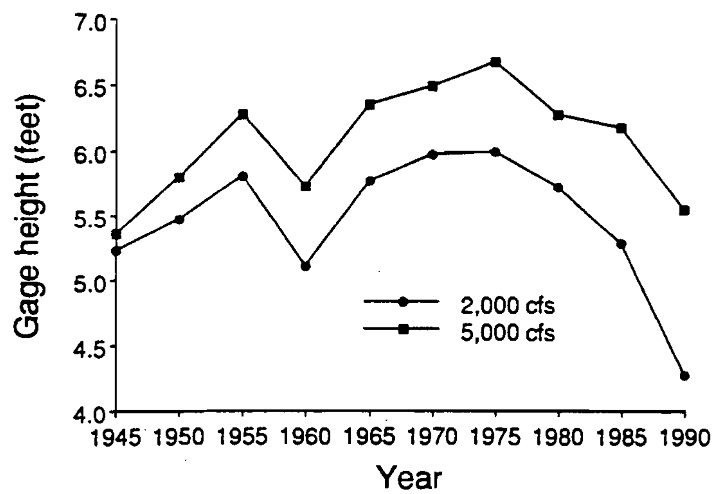


Fig. 22. Change in gage height at the Albuquerque, New Mexico, station between 1945 and 1990.

The Rio Grande below Cochiti does have gravel in the sediment and gravel is deposited in the Rio Grande by tributary streams. To investigate the change in capacity of the river to move gravel, a sediment transport capacity index for gravel was used. Data in Mengis (1980) were used to estimate the critical discharge (6,000 cfs), based on depths and velocities at selected cross sections in the Albuquerque area and a gravel size of 2.5 cm.

The capacity to transport gravel has been eliminated except in very wet years (Figs. 23 and 24). Because gravel is found in the sediment we would expect the bed to become paved and the larger material transported to the channel by tributaries to cause nick points (Lagasse 1981). If the period from 1931 to 1990 is considered, the loss of gravel transport capacity may be even more important. Reservoirs have caused part of this change, but part could also be a result of the same climatological processes that have been suggested to have changed the sediment regime in the Paria River (Graf et al. 1991).

Bosque del Apache Reach

The reach is located along the Bosque del Apache NWR south of San Antonio and is approximately 10 river miles long. Irrigation ditches and drains are common in this reach; the most notable is a low-flow conveyance channel and levee that parallel the west bank of the river along the entire reach. A major component of the study in this second reach was to investigate and understand the link between stream morphology, channel dynamics, and cottonwood establishment.

There have been very significant changes in the location of the riverbed and thalweg between 1935 and 1989 (Fig. 25). The 1989 channel is much straighter and narrower than the broad, meandering, braided channel of 1935. The river is not as confined as in the reach near Albuquerque because flows have been reduced considerably by the conveyance channel.

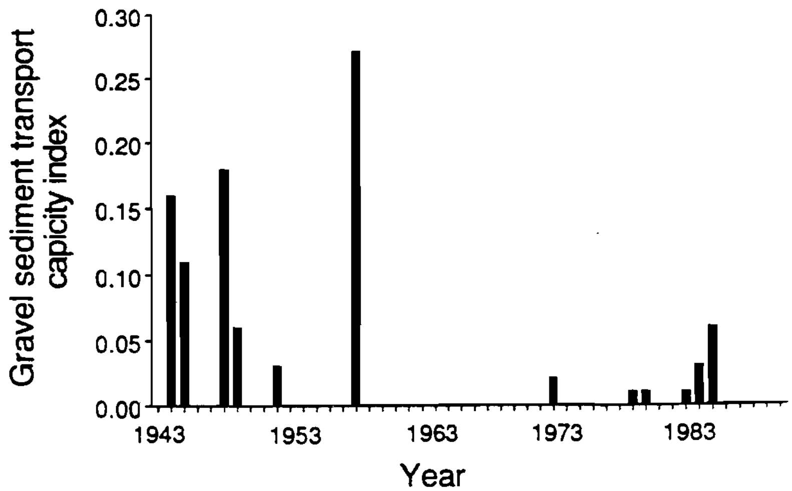


Fig. 23. Gravel sediment transport capacity index for the Rio Grande at Albuquerque, New Mexico, water years 1943-1990. (Reference discharge of 2,000 cfs and critical discharge of 6,000 cfs.)

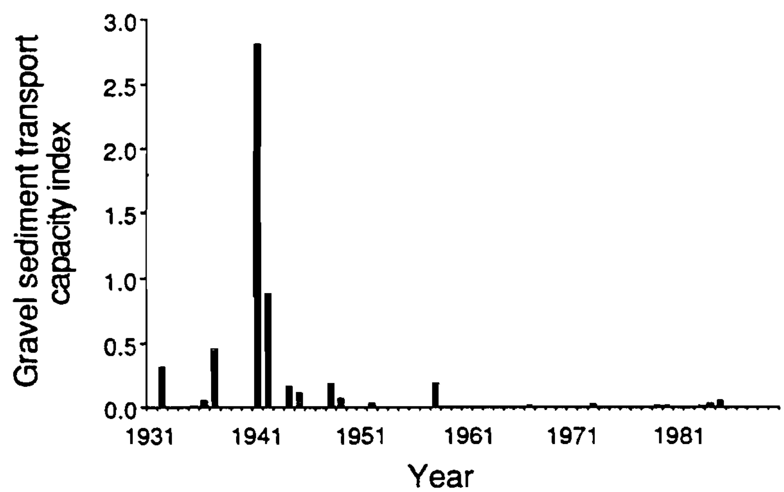


Fig. 24. Gravel sediment transport capacity index for the Rio Grande at San Felipe, New Mexico, water years 1931-1990. (Reference discharge of 2,000 cfs and critical discharge of 6,000 cfs).

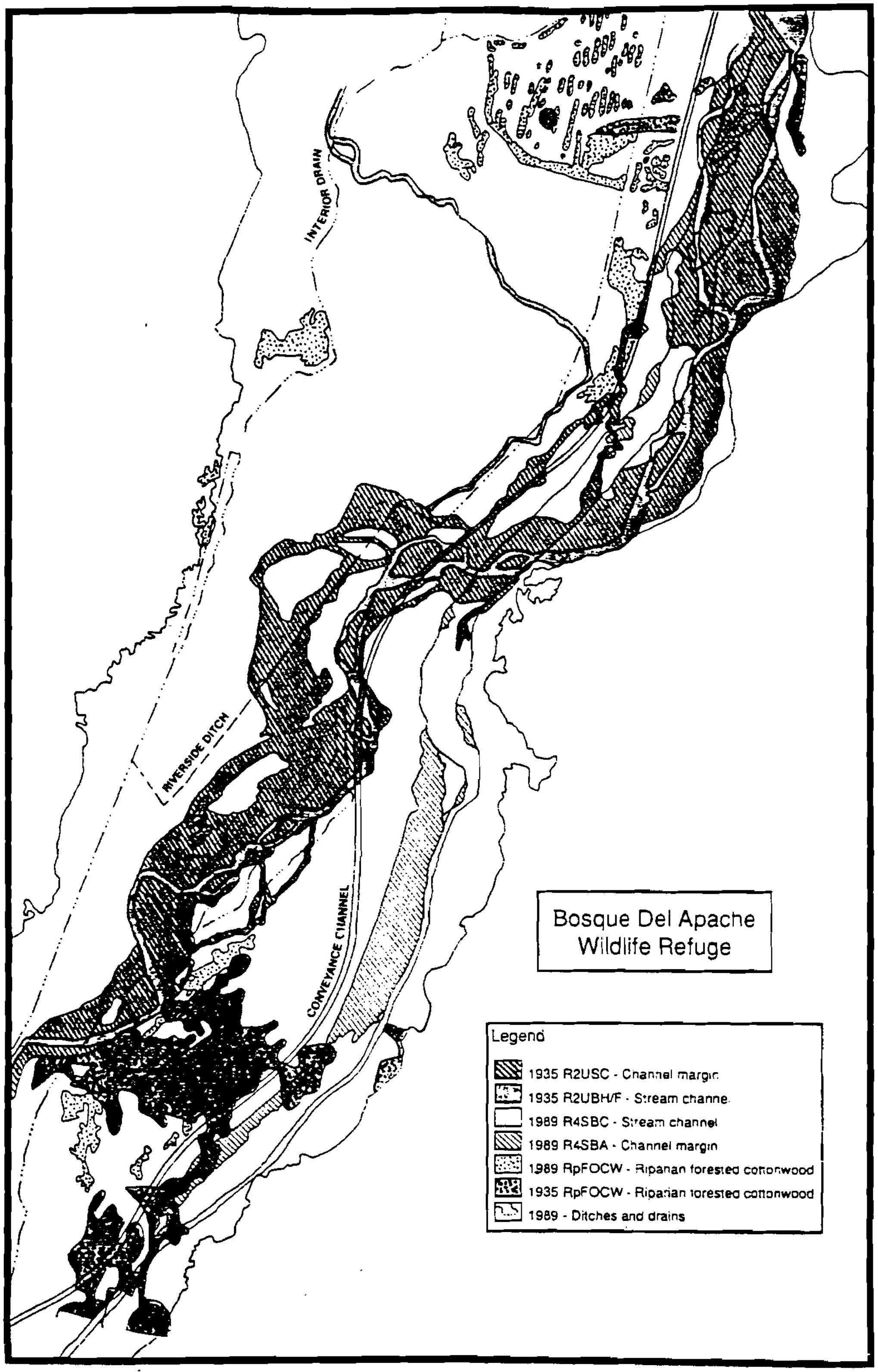


Fig. 25. Comparison of the planforms of the Rio Grande in the Bosque del Apache reach in 1935 and 1989.

Airphoto mosaics of the Bosque del Apache NWR reach in the years 1949, 1962, 1972, and 1973 were examined for changes in planform (Ritter 1993). There was very little change in planform from 1935 to 1942. The planform changed considerably from 1942 to 1962 due to the construction of the conveyance channel during the 1950's. In addition, approximately 18,000 jetty jacks were installed for channel stabilization between 1953 and 1974. The river was straightened and traces of the old riverbed can be seen where the river used to flow. The conveyance channel and the straightening can be seen in the 1962 mosaic. The lower section of the reach meandered in 1962 and 1972 but was straightened by 1989. In general, from 1962 to 1989 the riverbed in this reach changed very little due to the conveyance channel, channelization activities, and jetty jack installation. The 1989 floodplain supports abundant and dense stands of riparian vegetation that were not visible in earlier photos.

The same processes described for the San Felipe to Albuquerque reach are also occurring downstream to San Marcial, but the reduction in sediment yield is not as dramatic as occurred near Albuquerque. Analysis of peak flow data indicate that the river was degrading slowly until an increase in storage in Elephant Butte Reservoir caused a backwater effect and resulted in significant aggradation.

Cottonwood Establishment Investigations

Four numerical approaches were used to investigate the potential for cottonwood establishment: analysis of peak flows, establishment indices, a cell-based establishment model, and hydraulic simulations of conditions necessary for establishment. Each technique links streamflow to one aspect of the riparian vegetation, namely cottonwood establishment.

Analysis of Peak Flows

Cottonwood establishment requires a clean, moist substrate during the time the seeds are viable, followed by flows that do not destroy the young seedlings. We assumed that clean substrate results if flows cover an area at some time between April 1 and July 15. We also assumed that seedlings survive if the flows during the rest of the water year and during the next establishment period are less than the establishment flow. If the flows during the rest of the water year or during the following establishment period are greater than the establishment flow, the establishment index is zero.

First, we examined peak flows in the Albuquerque area. The nearest gage with more than 50 years of record is located at San Felipe (Fig. 26). Peak flows during the last 15 years were lower than the peak flows for the 15 years beginning in 1927.

Howe and Knopf (1991) collected data on cottonwood ages at three sites (near Bernalillo, at Albuquerque, and near Belen) along the Rio Grande (Fig. 27). Trees near Bernalillo were younger than those at the other two sites. The ages in Fig. 27 should not be taken as absolute because of uncertainties in aging cottonwood. There is no clear relationship between age of the trees as determined by Howe and Knopf and the peak discharge measured at San Felipe.

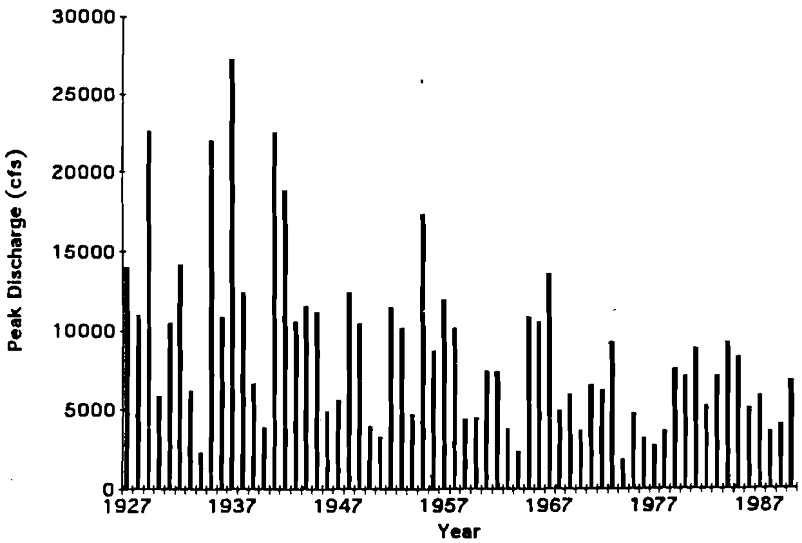


Fig. 26. Instantaneous peak flows at San Felipe, New Mexico, water years 1927-1990.

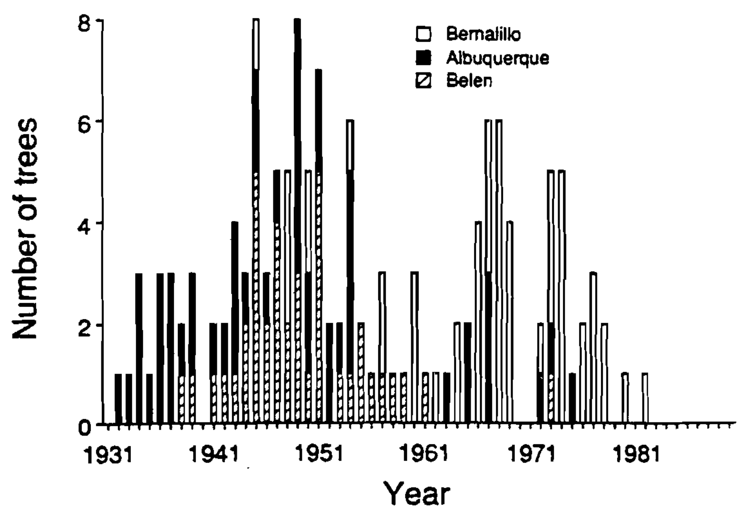


Fig. 27. Establishment dates for cottonwood trees along the Middle Rio Grande. Data from Howe and Knopf (1991).

One possible cause of a reduction in cottonwood establishment is that reservoirs have delayed peak flows. Timing of the peaks relative to July 15 is given in Fig. 28 for the flows used in Fig. 26. The only anomaly is for water year 1974, when the high flow occurred in the fall and was the lowest of record. Figure 28 suggests that changes in the timing of peak flows have probably not caused a reduction in the establishment of cottonwood seedlings.

Peak flows during entire water years (October 1 through September 30) were used in Figs. 26 and 28. However, peak flows needed for scour should occur between April 1 and July 15. Peak daily flows during this period are given in Fig. 29, which is similar in general form to Fig. 27.

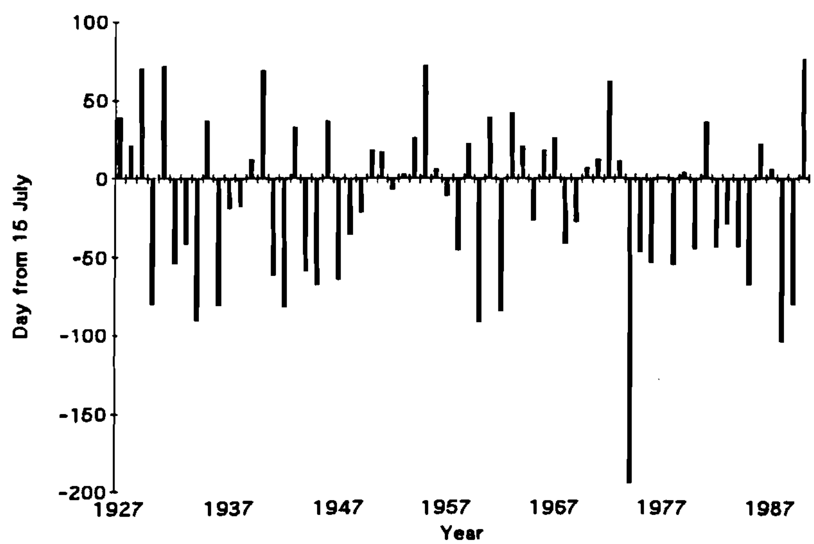


Fig. 28. Timing of peak flows at San Felipe, New Mexico, water years 1927-1990. Negative numbers are days before July 15 in each water year; positive numbers are days after July 15.

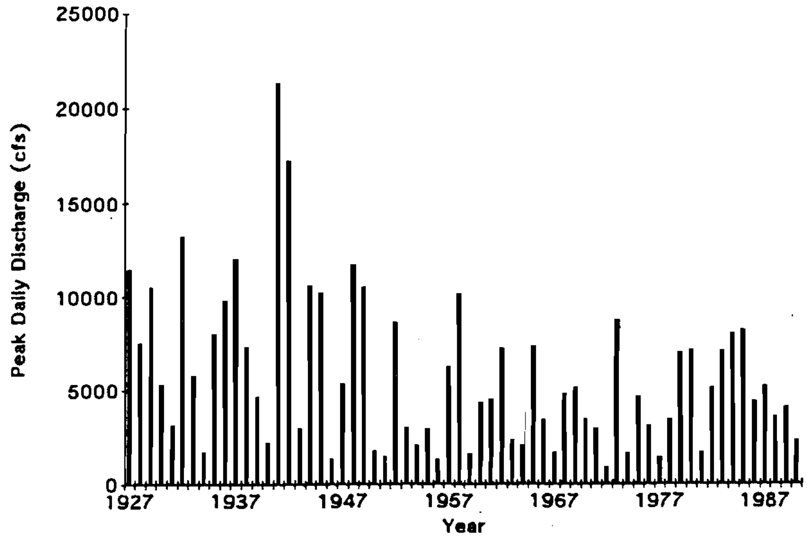


Fig. 29. Maximum daily flows during period April 1-July 15 for the Rio Grande at San Felipe, New Mexico, water years 1931-1990.

Establishment Indices

A better idea of effective peak flows may be obtained by examining the maximum daily streamflows during the establishment period that were not exceeded in the rest of the same water year or the following water year. For the data from the gage near San Felipe the results are given in Fig. 30. The data suggest cottonwood should have been able to establish throughout the period of record. Figure 27 indicates that was the case.

A problem with an index based only on maximum flows is that the area of bars and floodplain prepared for establishment is not considered (Milhous 1992a). An index that accounts for area assumes that the width of a river can be calculated by the simple power law

$$W = A*(Q^B)$$

where W is width, Q is stream flow, and A and B are constants.

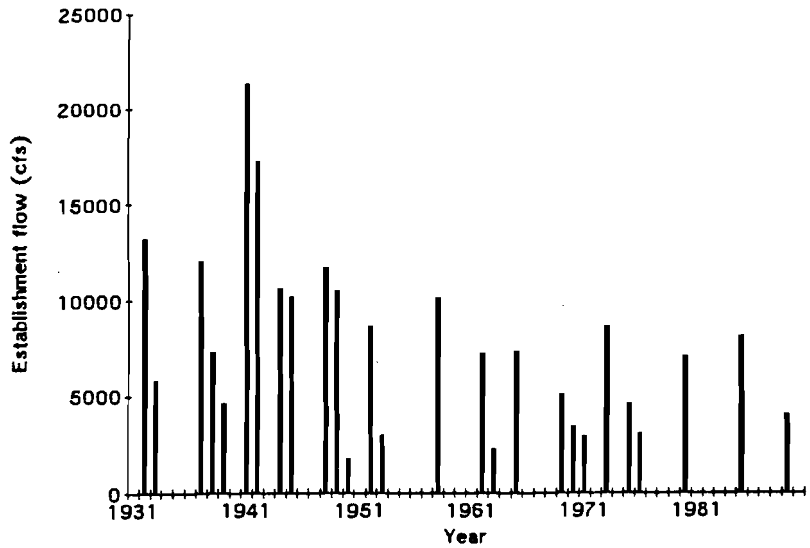


Fig. 30. Annual daily flows based on surviving peak flows for the Rio Grande at San Felipe, New Mexico, water years 1931-1990.

If the streamflow available to prepare an area for cottonwood establishment is QEST and the flow following the establishment period that limits the area available for establishment is QDST, then the width available for establishment (WEST) is

$$WEST = A*((QEST^{B}) - (QDST^{B}))$$

Setting A = 1, then the establishment index (ESTI) is

$$ESTI = (QEST^{B}) - (QDST^{B})$$

In the calculation for the Rio Grande, the value of B was taken as 0.5, the streamflow used for QEST was the maximum average 5-day flow in the period April 1 through July 15, and the value of QDST was the maximum stream flow in the rest of the water year and the period after April 1 in the following water year. Based on this index, there have been periods suitable for cottonwood establishment throughout the period of record, although there has probably been a reduction in the amount and frequency as a result of the reservoir construction (Fig. 31). From 1931 through 1952 the establishment index was 14.4 based on the streamflow data for the gage at San Felipe and 14.0 based on the gage at Embudo (upstream of the reservoirs). From 1975 through 1990, the index was 10.2 at Embudo and 5.4 at San Felipe. Streamflow modifications have reduced the establishment potential by at least 50%.

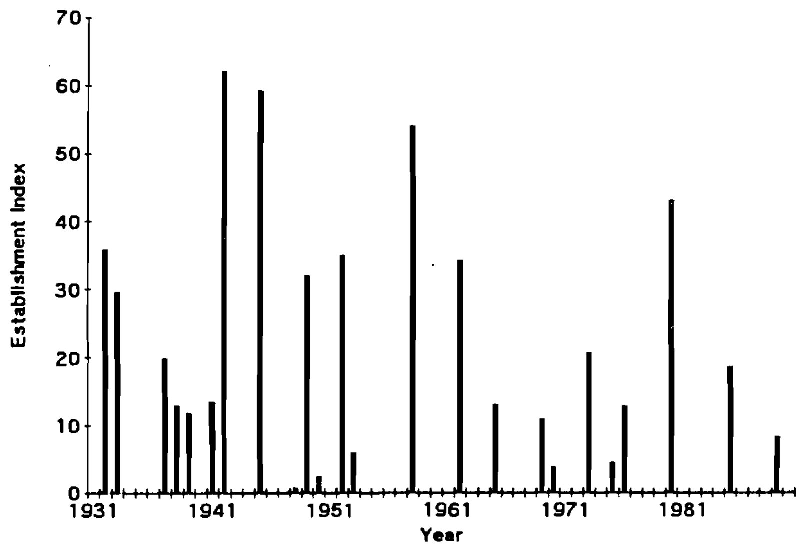


Fig. 31. Annual establishment index based on surviving area for the Rio Grande at San Felipe, New Mexico, water years 1931-1991.

The relationship between the apparent age of the trees, as determined by Howe and Knopf (1991), and the establishment index is not direct but there is a relationship. The tree age data were collected during 1988. The establishment index for the period 1975 through 1985 was 7.2; therefore we would expect a reduction of about 50% in the number of trees established during that period as compared to the 1931 through 1952 period. Based on the Howe and Knopf (1991) data, the average number of trees established was 3.2 in the 1931-1952 period and 0.9 in the 1975-1985 period, a reduction of 72%.

Cell-based Establishment Model

A cell-based model was developed as a refinement of the cottonwood establishment index. Width versus discharge relationships were developed for Albuquerque and San Marcial using USGS data at those gaging stations (Figs. 32 and 33).

These relationships were used with daily streamflows to model cottonwood establishment. River width was divided into 21 cells each 20 feet wide. For each cell, the model keeps track of the date of cottonwood establishment (if any) and the time since establishment.

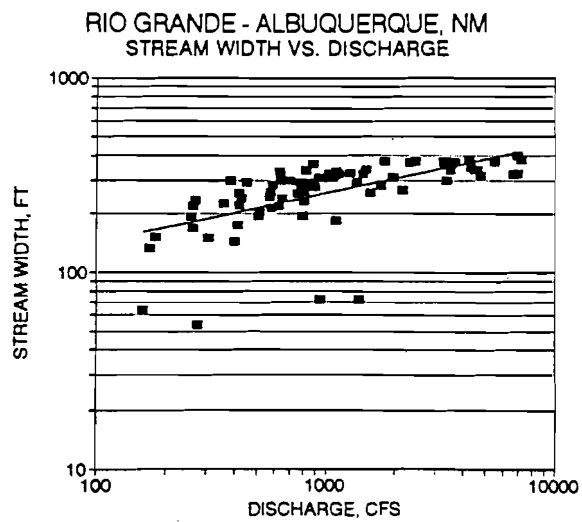


Fig. 32. Stream width as related to stream discharge near Albuquerque, New Mexico. Data for water years 1988-1990. Regression equation is width = 45.19 $Q^{0.2512}$.

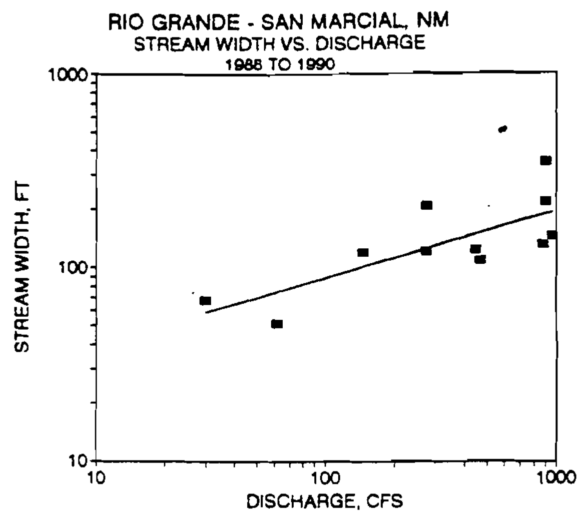


Fig. 33. Stream width as related to stream discharge, near San Marcial, New Mexico. Data for water years 1988-1990. Equation is width = 18.31 $Q^{0.34}$.

The model first checks to see if the date is between April and July (time of seed dispersal). If it is not seed dispersal time, the model calculates river width to see which cells are wetted. If a wetted cell has cottonwoods >2 years old, it is not scoured; all other wetted cells are scoured.

If the date is within the seed dispersal window, river width is calculated for the current day and the next day. If width decreases, cottonwood establishment occurs on all newly exposed cells, unless they already contain cottonwoods >2 years old. If river width does not decrease, all wetted cells are scoured unless they have cottonwoods >2 years old.

The Albuquerque model was run with 11 years of daily flows (1980-1990). At the end of the run, three cells contained cottonwoods; only one cell (21) contained cottonwoods >2 years old. Cottonwoods in cell 21 were recruited during a flow of 6,870 cfs in June 1985. Cottonwoods were recruited in cells 17 and 18 during a flow of 3,710 cfs in April 1989.

Twelve years of daily flows were analyzed for the San Marcial model. Cottonwoods were recruited in five cells. A flow of 3,100 cfs in April 1989 established cottonwoods in cell 15. A flow of 5,360 cfs in June 1985 produced cottonwoods in cell 17, and a flow of 6,000 cfs in June 1980 resulted in cottonwoods in cell 18. Cells 19 and 20 recruited cottonwoods from a flow of 6,550 in May of 1985.

Hydraulic Simulation Models

The final approach was to develop maps of the Bosque del Apache reach showing wetted area at different discharges (Figs. 34 and 35). The techniques and logic used to develop these maps are presented in Appendix A. If cottonwood establishment required only wet substrate, the maps would suffice. Unfortunately, the substrate may also need to be scoured. Velocities and shear stresses in the main channel and the side channels in the vicinity of Bosque del Apache NWR were investigated using HEC-6. The techniques used and details of the results are presented in Appendix B. Because of the dense stands of salt cedar and the existence of the jetty jacks, velocities associated with observed flows for the period 1965-1989 were almost certainly too low to cause scouring (Figs. 36 and 37). The velocity required to cause scouring is not known precisely, but certainly exceeds 1 foot per second.

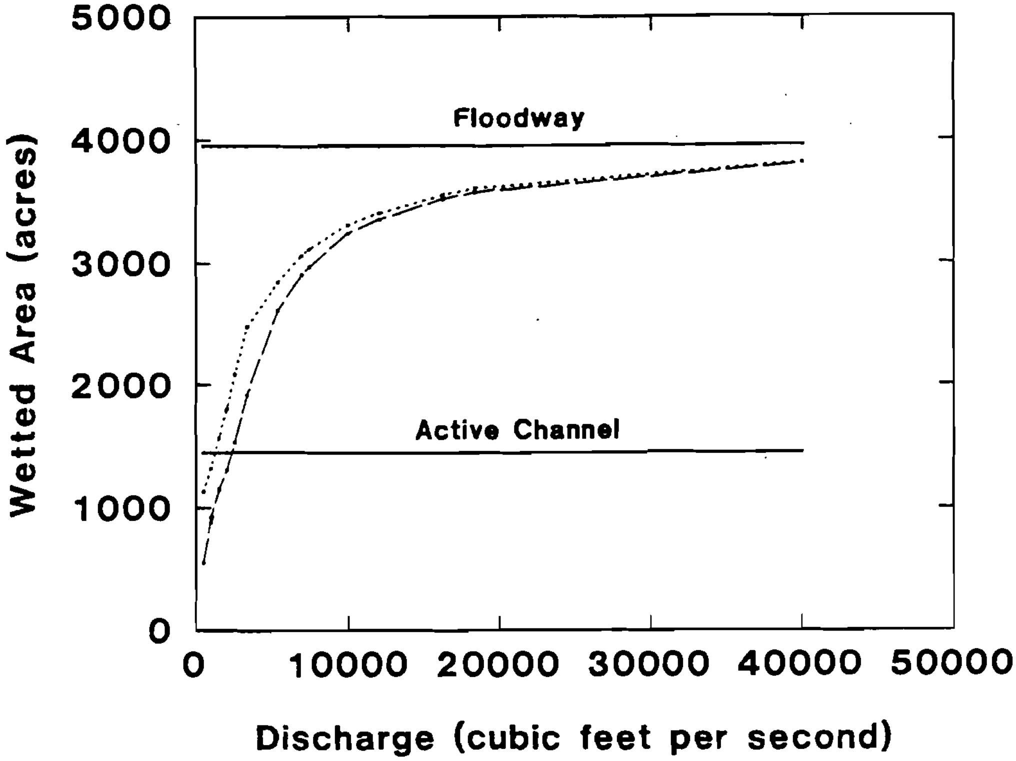


Fig. 34. Wetted area versus discharge function for the Bosque del Apache reach of the Rio Grande. The two lines represent different model assumptions as described in Appendix A.

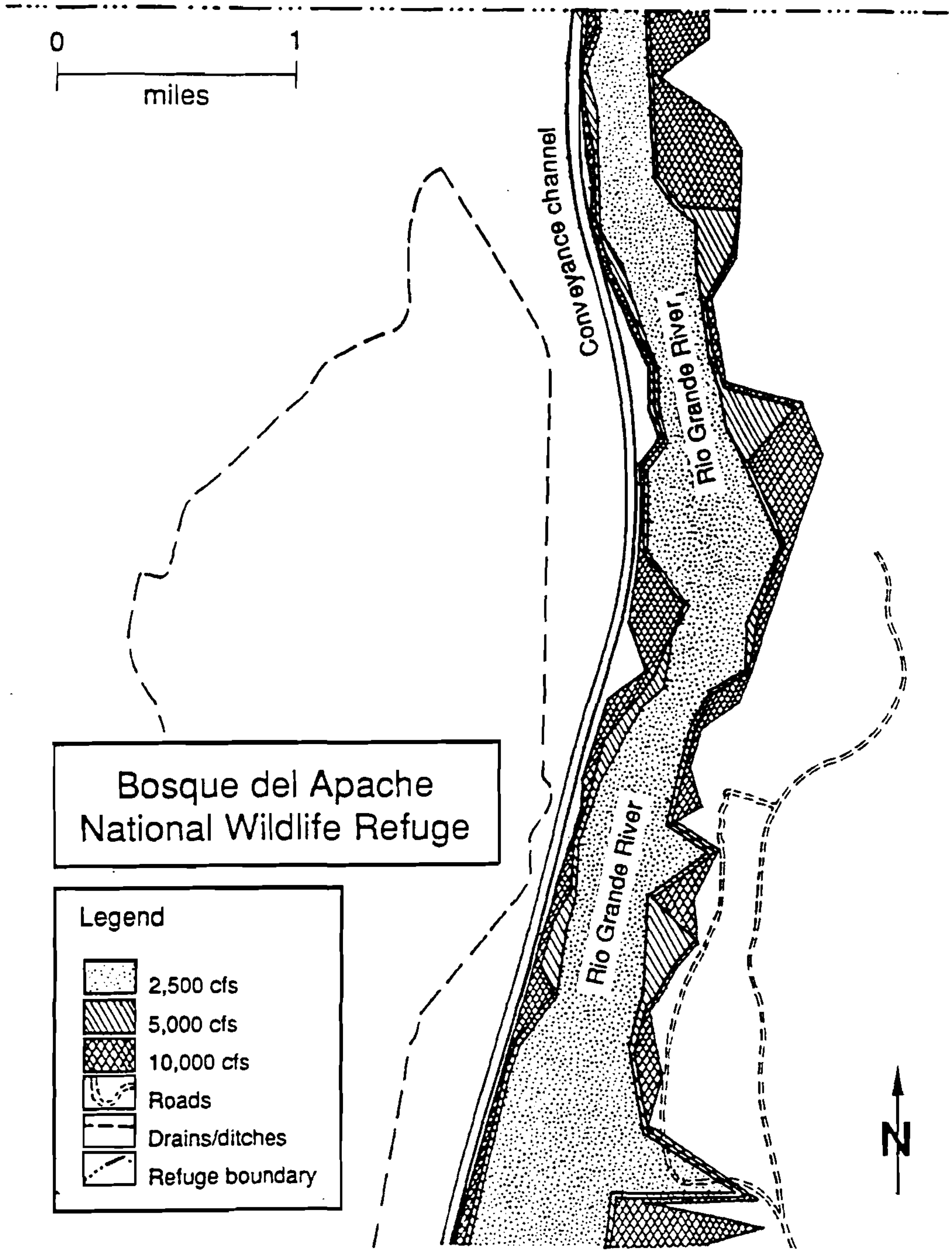


Fig. 35a. Map of the flooded area at three different discharges in a portion of the Bosque del Apache reach.

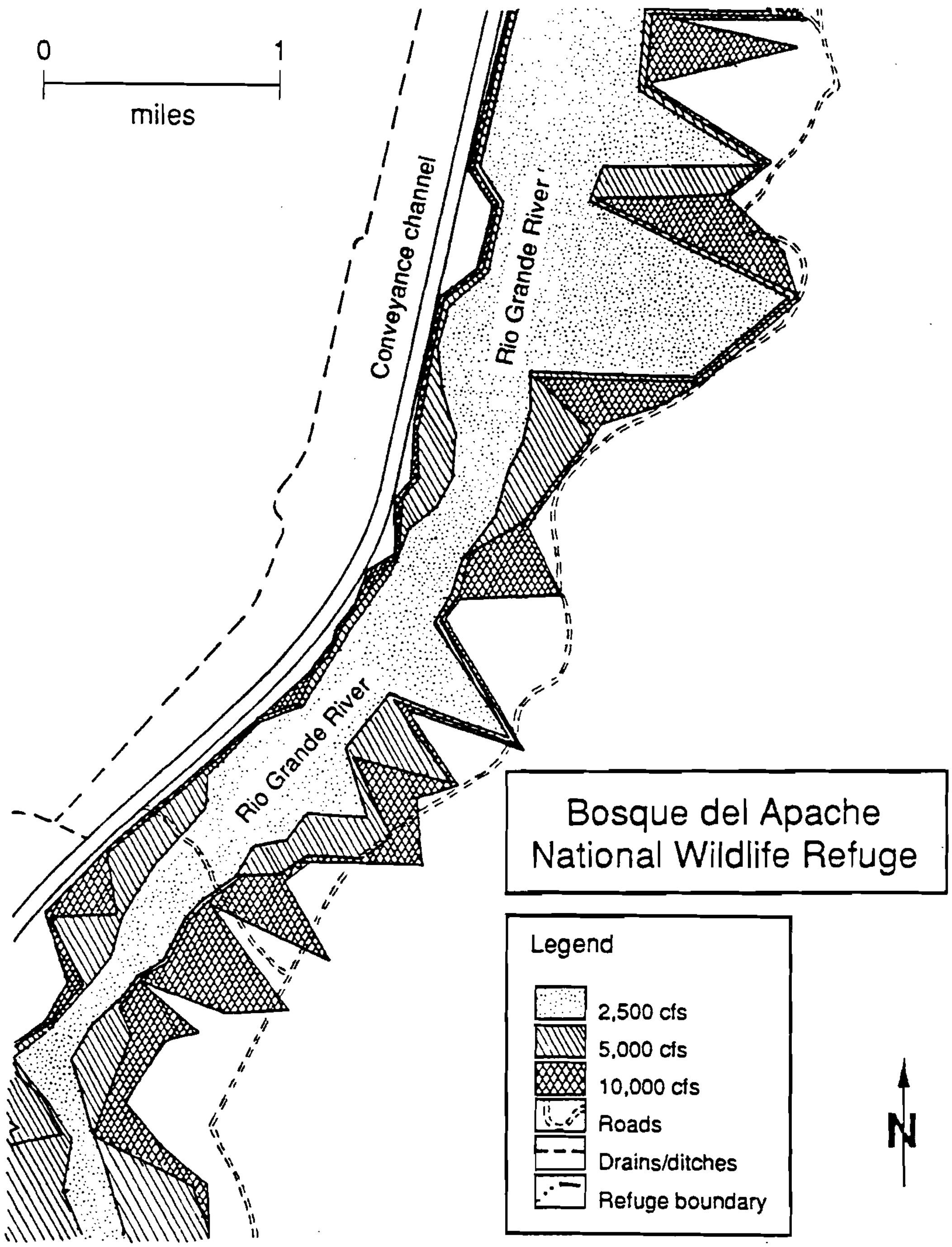


Fig. 35b. Map of the flooded area at three different discharges in a portion of the Bosque del Apache reach.

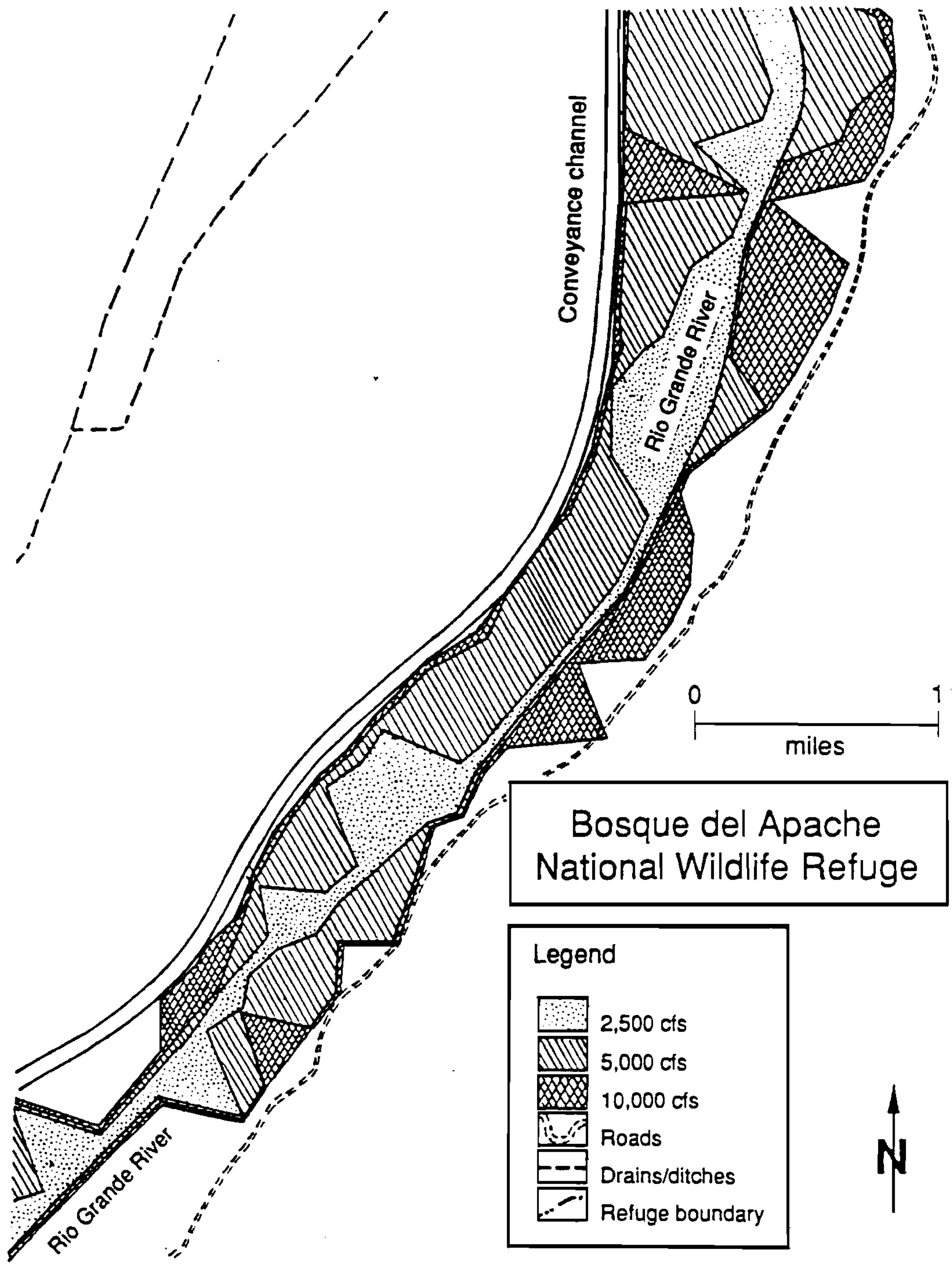


Fig. 35c. Map of the flooded area at three different discharges in a portion of the Bosque del Apache reach.

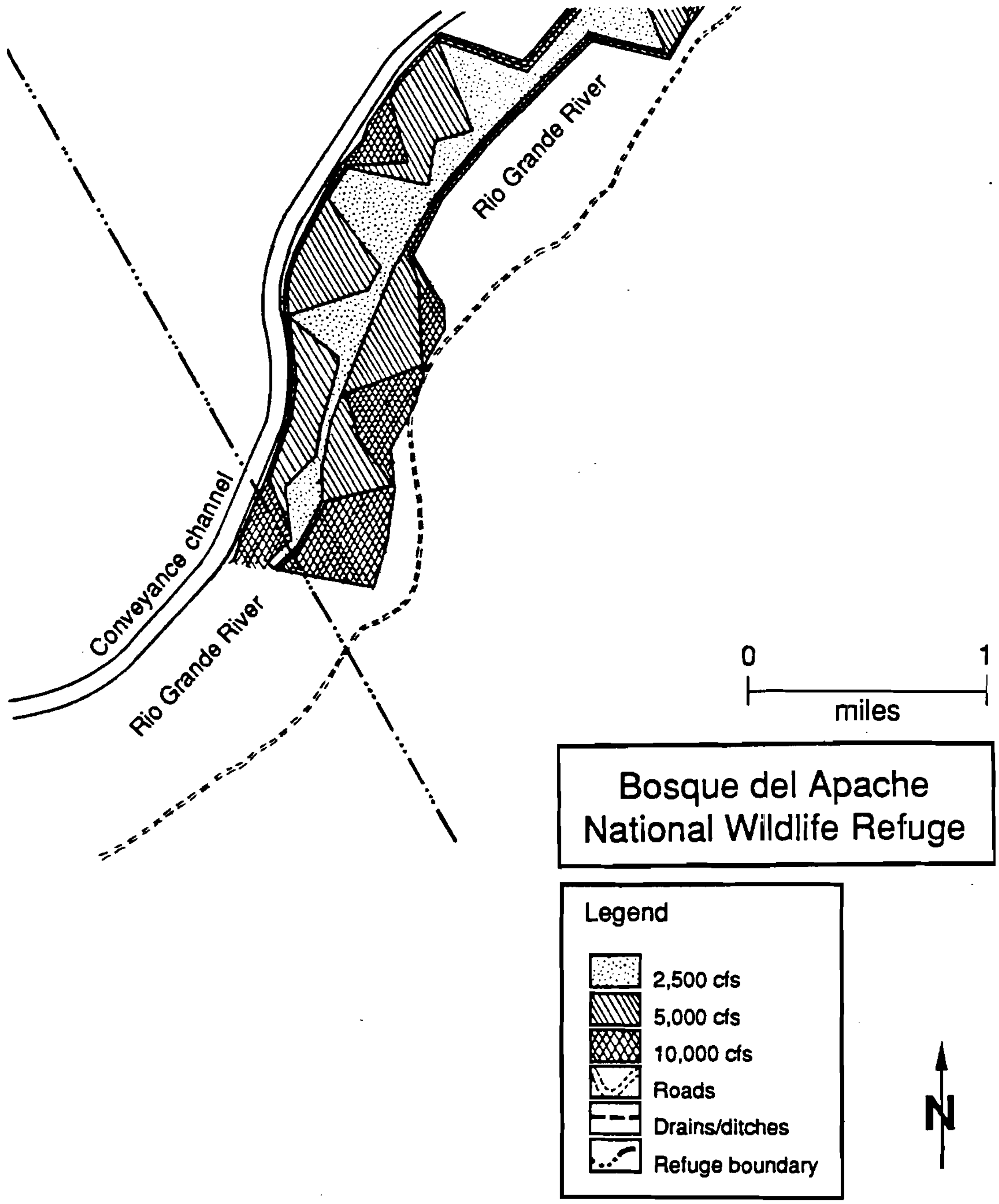


Fig. 35d. Map of the flooded area at three different discharges in a portion of the Bosque del Apache reach.

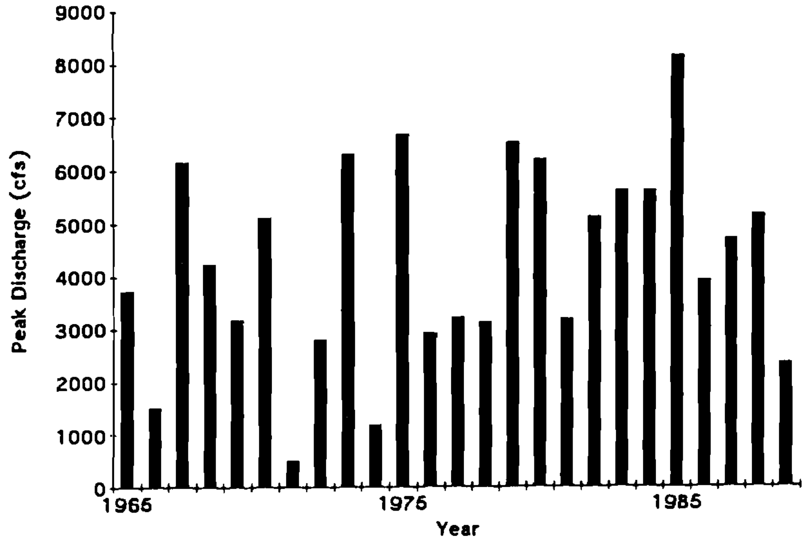


Fig. 36. Instantaneous peak flows at San Marcial, New Mexico, water years 1965-1989.

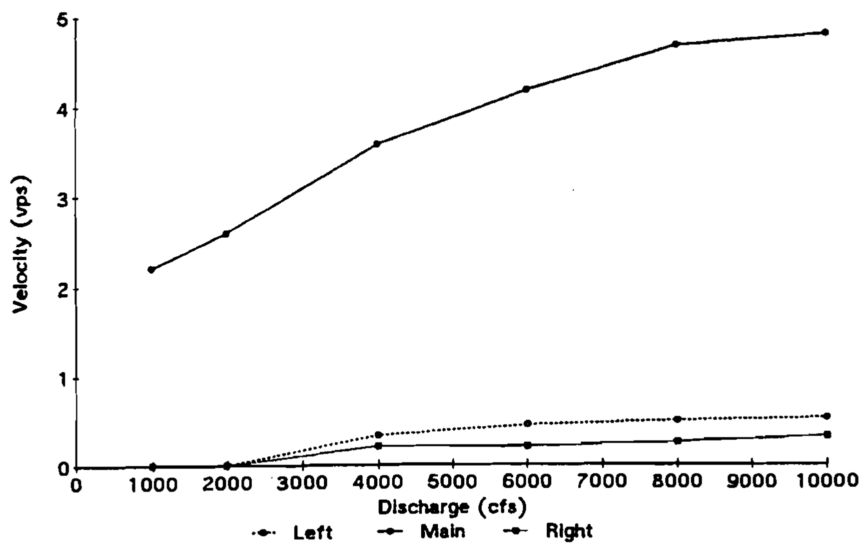


Fig. 37. Velocity versus discharge function for a section of the Bosque del Apache reach.

Summary and Conclusions

The first task of this study was to demonstrate that an increase in spring peak flows will lead to an increase in the establishment of cottonwoods in the MRG. This is the guiding assumption of many people working on cottonwood in the MRG valley. Unfortunately, the guiding assumption could not conclusively be shown to be true. The relationship may be much more complex than first assumed. The conclusion is that the simple release of more water from reservoirs will not improve the cottonwood forests because a simple relation between flow and cottonwood establishment (or recruitment) does not exist.

The water resources system has been modified by the construction of reservoirs, levees, and jetty jacks. The construction of channel stabilization works has resulted in a channel located in its present position and the natural process of lateral movement of the channel, which allows replacement of old forest with new forest, will not occur in the future unless a very destructive flood occurs.

The establishment index investigations show that cottonwood should be established under the present flow conditions in some years. Cottonwood seedlings do sprout on bars within the maintained channel. Unfortunately these seedlings are removed either by mowing or by the next large flood and do not grow into a mature forest. In a natural state the Rio Grande would wander about its floodplain and create regions where cottonwood would become established and not be removed by the flows in the next spring. During the last 50 years engineering works have not allowed the river to create good locations for cottonwood establishment and then move away from those locations. In other words, the Rio Grande is pinned into one location by levees and the jetty jacks and no longer wanders about the floodplain. The result is low to nonexistent levels of cottonwood development into mature stands. The present cottonwood forests are probably a result of the same engineering works that have stabilized the river. A review of historic information suggests that the pre-development river had fewer, but much more open, stands of cottonwood. The present line of relatively dense cottonwoods is likely a result of the river being stabilized in its present position. The cottonwoods are interspaced with the jetty jacks in some locations and form a line up to the inside edge of the jacks; inside of that line maintenance activities or high flows remove the cottonwoods.

Howe and Knopf (1991) found trees established in the 1940's. This period was before construction of jetty jacks and major reservoirs. It was also a period of lower peak flows, which may have occurred because of changes in climate. Attempts to clearly relate the Howe and Knopf (1991) data to either the establishment index or to peak flows were not very successful. It is possible that the major establishment of cottonwoods in the 1940's was partly a result of reduced peak flows that followed a period of significantly higher floods in the previous 20 years, and partly a result of channel stabilization activities discussed above.

In the lower reach (below La Joya), invasion of salt cedar has prevented establishment of cottonwoods in the stabilized areas. The existence of salt cedar in the valley means that in some areas the cottonwood gallery forests will probably not be established because of competition from salt cedar. This is probably true for the lower valley but not for the reach above La Joya. This may be a result of increases in salinity downstream and/or changes in the climate as one goes south. Water quality may change the competitive advantage of salt cedar over cottonwood and should be investigated further.

The work using HEC-6 presented in the section on river morphology and Appendix B suggests it may be possible to cause scour in some areas by imaginative combination of sediment and water management and this scour would allow cottonwood to be established. The work on links between sediment transport and salt cedar establishment cannot be considered to be complete at this time.

The major conclusion from the work reported here is that no simple increase in flows will result in dramatic regeneration of the cottonwood gallery forests. At this time we cannot fully specify the link between the gallery cottonwood forest and water management; we definitely know it is not a simple process of increasing the flows.

Large-scale scouring of vegetative cover may occur only after very large magnitude floods. Reservoir operations are intended to reduce or eliminate the possibility of a large scale flood. In this study, the possibility of releasing a large flow from Cochiti dam for cottonwood recruitment was explored. The HEC-6 model of the Rio Grande study reach showed that the banks of the river were flooded with flows of 5,000 cfs or greater. Although the overbanks may be covered with water, the shear stress and velocities were not high enough to scour away the vegetation. Flows above 5,000 cfs in the Rio Grande are considered flood flows. The San Marcial floodway gaging station has recorded peak flows of over 5,000 cfs for 6 out of the last 10 years. In 1985, a peak flow of over 8,000 cfs occurred in the floodway. As previously stated in the section on the Rio Grande's planform, very little change in planform has occurred since 1962, pre-Cochiti Dam. The last large flood occurred in the 1940's and a peak flow of 25,000 cfs was recorded at the Albuquerque USGS gaging station. To release a flow of this magnitude from the dam would be impractical as a method for recruiting cottonwood forests due to conflicts with other water uses for irrigation and the water transfer compact with Texas. In addition, the levees and jetty jacks have greatly stabilized the Rio Grande so that large flows should not overtop the levees. This conclusion is in agreement with the following statement made by Hink and Ohmart (1984):

> "The Rio Grande still floods the area between the levees periodically (about every 5-7 years), but since Cochiti Dam was completed the rate of water release is kept below what would threaten the integrity of the levees and flooding is thus unlikely to be of sufficient

magnitude to remove established woody vegetation. The last flooding episodes that apparently cleared a significant acreage of bosque occurred in 1941-42 (Corps of Engineers, Albuquerque). When channelization was completed there was a fundamental change in river dynamics which led to far-reaching changes in patterns of vegetation succession. With the elimination of channel migration, the river no longer exposed new areas of alluvium outside the established, cleared river channel. Now colonization of sandbars by cottonwood and other seedlings takes place primarily and perhaps exclusively within the sandy river channel."

This report concurs with the observation that conditions needed by cottonwood are not likely to occur in the present maintained channel.

Recommendations

There are two recommendations resulting from these studies. These are:

1. Do not base activities for the maintenance and establishment of cottonwood on the concept that an increase of peak flows will necessarily result in better cottonwood forests.

2. Regeneration of the existing cottonwood forest will require active clearing and replacement in the regions with jack jettys. Water should be managed to enhance the likelihood the planted trees will not be destroyed by being out-competed by salt cedar or Russian olive.

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Appendix A. Wetted Area as Related to Discharge in the Bosque Del Apache Reach

A drastically altered river channel and hydrologic regime are believed to limit natural cottonwood regeneration along the Rio Grande. Regeneration of native species from deliberate high flow releases at critical times is one possible management technique that deserves investigation. To examine this approach, predicted or measured changes in channel configuration, cross sectional geometry, and wetted perimeter (associated with different discharges) were used to determine those areas that have the necessary hydrologic conditions suitable for cottonwood establishment. This information will assist managers in determining the potential use of deliberate high flow releases to insure regeneration and continued survival of cottonwood and other selected riparian species.

Flow Routing Methods

The USACE, Albuquerque District utilized HEC-2, a water surface profile model, to assess the integrity of flood control levees throughout the Albuquerque reach (Bernalillo to Belen) and along the low-flow conveyance channel (San Acacia to Elephant Butte Reservoir). The input data file was constructed from a series of channel cross sections that were digitized (by the Bureau of Reclamation) from 1984-1985 aerial photography. These cross sections were located approximately every 500 feet along the river, and HEC-2 was used to determine the levee-overtopping flow at each of the digitized cross sections. We applied the same model (developed for the San Acacia to Elephant Butte reach) to that segment of the Rio Grande that flows through Bosque del Apache NWR (the Bosque del Apache reach) to determine the net change in wetted area associated with different discharges. This approach was used to identify those areas within the refuge that are wetted by a particular flow and that may have the potential (i.e., the necessary hydrologic conditions) for cottonwood establishment.

Prior to applying the Albuquerque District's model to the Bosque del Apache reach, a few modifications were necessary. Our initial intent was to take advantage of the existing model and to use it as the Albuquerque District had originally designed, and in the manner in which they continue to implement the model today. The Albuquerque District initially used this model as part of a levee integrity study, to estimate the levee-overtopping flow at various points along the reach, and the input file was designed accordingly. (As an aside, the Albuquerque District found the levee-overtopping flow in the reach along the low-flow conveyance channel to be approximately 40,000 cfs.)

Throughout the Albuquerque District's original HEC-2 data file, the modeled discharge was changed (e.g., 38,000 to 41,000 to 40,000 cfs) at different locations along the study reach to account for diversions and/or irrigation return flows. Because we had limited knowledge of the system and how it behaves across the range of flows we were modeling (500 to 40,000 cfs), and because our analysis was restricted to the Bosque del Apache reach, we did not account for diversions or return flows. Similarly, because the Albuquerque District was interested in the long-term integrity of the levees (i.e., projected 100 years into the future), they estimated the amount of sediment aggradation that would be expected to occur over the next 100 years, and tried to account for this in the model. Consequently, the original Albuquerque District model included a minimum sediment elevation for each cross section, below which the entire cross section was assumed to be filled with sediment. In our analysis, we conducted separate runs with and without the minimum sediment elevations included at each cross section. As expected, the addition of the minimum sediment elevation raised the water surface elevation associated with each modeled flow. However, as illustrated in Fig. 34, the relationship between wetted area and discharge changed only slightly (i.e., the shape of the curve remained the same). It did, however, shift up or down depending on whether or not the minimum sediment elevations were included.

Figure 34 depicts the change in wetted area (in acres) as a function of discharge. Note that within this range of flows, wetted area is bounded by the active channel and existing levees. Within the active channel, the potential for successful cottonwood establishment and survival is relatively small because these areas are often too wet, or too dynamic, and subject to repeated scour or deposition. With increasing discharge (i.e., outside the active channel) wetted area increases rapidly up to a discharge of about 10,000 cfs, beyond which even large increases in discharge produce only slight increases in wetted area. Any significant increase in wetted area would require flows that are beyond the feasible range of deliberate flow releases from upstream reservoirs. Discharges of this magnitude are often beyond the control of river managers and would threaten or jeopardize the integrity of the existing system of levees, drains, and canals.

From Fig. 34 it appears that the areas wetted by flows ranging from 2,000 or 3,000 cfs to 10,000 cfs might be suitable (i.e., possesses the necessary hydrologic conditions) for cottonwood establishment and recruitment; however, cottonwoods do not appear to be establishing on these surfaces at the present time. Assuming that these flows have been occurring during the seed dispersal and germination window, there should be some evidence of successful cottonwood establishment.

One possible explanation for the absence of cottonwoods is that germination and establishment are indeed occurring, but that newly established seedlings rarely, if ever, survive to the sapling stage because they are repeatedly scoured or mowed. Consequently, recruitment to larger size classes does not appear to be taking place. Recent field observations throughout the Bosque del Apache reach indicate that establishment is occurring. However, there is little evidence of recruitment to larger size classes. Another possible explanation, and one offered by Howe and Knopf (1991), is that flow regulation, construction of levees, jetty-fields, reservoirs, and channelization have confined the river to a relatively narrow channel, thereby reducing the potential for high scouring flows, sediment deposition, channel movement, and river meandering, all of which are critical to cottonwood establishment and survival. Consequently, the banks have become vegetated by other species (e.g., salt cedar, Russian olive, willow and herbaceous vegetation) that are better adapted to these conditions.

Aside from the few modifications listed above, the majority of the Albuquerque District's original input file was unchanged, and was used to model flows of 500 to 40,000 cfs through the Bosque del Apache reach. In retrospect there are a few additional modifications that we might have made (e.g., changing Manning's "n" values to better represent channel and overbank roughness) to improve the accuracy and reliability of the model. However, we attempted to retain and use the Albuquerque District's input file as they designed it, with as few modifications as possible.

HEC-2 was initially developed for use in streams or rivers with fixed or rigid boundaries and constant channel geometry. Consequently its application to moveable bed streams or sand bed channels, like the Rio Grande in southern New Mexico, is questionable. However, HEC-2 can be expected to produce relatively accurate and reliable water surface elevations associated with large magnitude, low-frequency floods, and consequently its application to a levee integrity study for example is less suspect. In our analysis, however, we realize that the assumption of fixed channel geometry does not hold, and that the model is less accurate and reliable for flows of relatively small discharge (e.g., 500 to 10,000 cfs). We further realize the error associated with using hydraulic cross sections that were digitized from aerial photography. Notwithstanding, we elected to use the Albuquerque District's HEC-2 model for the following reasons: (1) it is currently used and accepted by the Albuquerque District to model water surface profiles throughout the study reach; (2) it is the best available representation or approximation of the 1989/1990 conditions (which is the year of the most recent aerial photography), and it accounts for recent aggradation in the lower reach during the wet years and high water levels in Elephant Butte Reservoir from 1986-1990; and (3) the

TOPWID (top width) variable output from HEC-2 provides an easy means of capturing changes in wetted perimeter and area associated with different discharges. Our initial intent was to model the system with HEC-2 and accept the limitations and problems associated with it and the assumption of fixed channel geometry. The next step in flow routing and modeling was to apply HEC-6, which takes into consideration scour and deposition associated with sand bed channels and moveable beds (Appendix B).

Using the post-Cochiti Dam (1975-1991) and pre-Abiquiu Dam (1899-1962) periods of record, data from the USGS gage at San Marcial (Rio Grande floodway) was used to estimate and select the modeled discharges. Table A-1 describes the discharges that were modeled and their magnitude. In addition to the values listed in Table A-1, discharges of 500, 1,000, 1,500, 2,000, 2,500, and 10,000 cfs were also modeled.

HEC-2 provides an option which allows either: (1) the lowest portions of the channel to be inundated first regardless of their position with respect to the active channel; or (2) filling the active channel first and wetting remaining parts of the channel or floodplain (even if they are lower than the active channel) only when the banks of the active channel are overtopped. With respect to the Bosque del Apache reach, neither of these options accurately captures the means by which a given area might be inundated. Consequently, flows were modeled both with both options, as well as with and without the minimum sediment elevations at each cross section. The most reasonable scenario, however, was to model the system without the minimum sediment elevations included, and to have the flow fill the active channel first and then proceed to wet outlying areas by overtopping the banks. Results of this combination are presented in Fig. 35, which depicts the zones of inundation associated with discharges of 2,500, 5,000, and 10,000 cfs.

Table A-1. *HEC-2 modeled discharges for the Rio Grande floodway through Bosque del Apache National Wildlife Refuge. Data are from the USGS gage at San Marcial (USGS ID# 035400).*

Discharge	Description
3,300	post-Cochiti May/June median maximum
5,300	post-Cochiti May/June average maximum
6,900	pre-Abiquiu May/June median maximum
7,400	post-Cochiti 10-year recurrence interval flow
12,000	pre-Abiquiu June average maximum
16,200	pre-Abiquiu May average maximum
18,300	pre-Abiquiu 10-year recurrence interval flow
40,000	approximate levee-overtopping flow

For each modeled flow, HEC-2 provides the location on the left and right bank, and the width of the water surface at each cross section. By transferring the location of these points to a map and then connecting them we were able to produce a plan-view map of the Bosque del Apache reach depicting the zones of inundation associated with different discharges. Figure 35 displays the wetted area or zones of inundation associated with discharges of 2,500, 5,000, and 10,000 cfs. Note that similar to Fig. 35, which illustrates change in wetted area with increasing discharge, there is a considerable increase in wetted area with increasing discharge to about 10,000 cfs, beyond which any further increase in wetted area or increase in the zone of inundation is limited by the levees on the west bank and by natural geomorphic features on the east bank.

The jagged appearance of the zones of inundation is a product of connecting the left and right bank high water marks between adjacent cross sections roughly 500 feet apart. In reality, the high water marks would most likely intergrade across adjacent cross sections, and consequently the resultant zone of inundation for a given flow would appear less broken. Although crude, Fig. 35 provides a rough estimate of those areas within the Bosque del Apache that are inundated by flows of a given magnitude.

Note that much of the area within the active channel and floodway appears to be inundated by flows of at least 5,000 cfs. As Table A-1 suggests, a flow of approximately 5,000 cfs corresponds to the average May/June maximum during the post-Cochiti period of record. Obviously the limitations of using HEC-2 to model anything but low frequency, high magnitude events, and its inability to account for scour and deposition, may cause the model to overestimate the area of inundation associated with any particular flow. However, flows of 5,000-10,000 cfs will most likely wet the entire active channel, and most, and in some places all, of the floodway. It would appear then that much of the area within the floodplain is suitable, at least in terms of meeting the necessary hydrologic criteria, for cottonwood germination, establishment, and early growth. However, this should not be interpreted to mean that given the proper flow conditions, cottonwoods will necessarily establish and flourish. As has been pointed out earlier, the lack of suitable sites (i.e., barren, freshly deposited substrate) may prevent initial germination and establishment of the seedlings even when proper moisture conditions exist. Furthermore, subsequent high flows later in the year may scour recently established seedlings, thus precluding their survival and growth.

In summary, Figs. 34 and 35 suggest that current, or at least recent, water management within the valley is probably sufficient (in terms of the timing and magnitude of flows) to support germination and initial establishment of cottonwoods within the Rio Grande floodway at Bosque del Apache NWR. This is further supported by the presence of newly established seedlings on several sandbars throughout the Bosque del Apache reach, as we observed during the summer of 1992. The lack of older seedlings and/or young saplings, however, suggests that many, if not all, of these seedlings fail to survive through the next growing season.

Loss of these newly established seedlings may be caused by desiccation, but most likely they are scoured away by subsequent high flows associated with late summer thunderstorms or the next year's spring runoff. As described earlier in this report, the highly confined nature of the floodway and the inability of the river to meander, coupled with pilot channeling and other maintenance activities, leaves many newly established seedlings unprotected from the scouring intensity of subsequent high flows. Consequently, the cycle of cottonwood germination and initial establishment followed by scour and removal will most likely continue under the current channel maintenance and water management regime.

Appendix B. Application of HEC-6 Sediment Transport Model

The HEC-6 (U.S. Army Corps of Engineers 1991) sediment transport model was used to develop information on the availability of flows needed to produce conditions suitable for cottonwood establishment. Major results are presented in the section on "Cottonwood Establishment Investigations". Specifics on the application of the HEC-6 model to the San Marcial reach are presented in this appendix.

Model Setup

The HEC-6 model was utilized to simulate discharges in the Rio Grande with a movable bed. Cross section data, digitized from 1984-85 aerial photos, were developed by the Bureau of Reclamation at about 500-foot intervals. The model's upstream cross section (1512) is at the north border of the Bosque Del Apache NWR. The most downstream cross section in the model (1702) is at the San Marcial gaging station. There are a total of 150 cross sections in the model. Some of the cross sectional data were slightly modified so that the thalweg slopes continuously downstream.

Sediment

On July 28, 1992, samples of Rio Grande and Rio Puerco bed material were collected. The mouth of the Rio Puerco is located approximately 60 miles upstream from the San Marcial gaging station. The Rio Puerco yields great quantities of sediment (concentrations in excess of 400,000 ppm by weight have been recorded), mainly consisting of fines such as clay and silt. The Rio Puerco was sampled near Bernardo, and the Rio Grande was sampled at Bernardo (upstream of the mouth of the Rio Puerco), San Antonio, 4.5 miles downstream from the refuge north border, and San Marcial. Grain size distribution was determined for each sample and are presented in Ritter (1993). Median particle sizes were: Bernardo and San Antonio - 0.25 mm; 4.5 miles from the northern border of the refuge (cross section 1558) - 0.15 mm; San Marcial - 0.2 mm; Rio Puerco - 0.055 mm.

The analysis for San Marcial corresponds to the size gradation curve developed using the USGS bed material data for 1987 to 1990. The calculated median diameter for the San Marcial gage is 0.17 mm. This is also consistent with work done by Nordin and Culbertson (1961), who reported median diameters of 0.14 mm at San Marcial and 0.20 mm at San Antonio.

The total sediment load was further broken down into fractions of load which were clay (.002 to .004 mm), silts (.004 to .0625 mm), very fine sand (.0625 to .125 mm), fine sand (.125 to .250 mm), medium sand (.250 to .50 mm), and coarse sand (.5 to 1.0 mm). Analysis of the USGS suspended sediment load data for clay, silt, and very fine sand confirmed the study by Nordin and Beverage (1964), which indicated that there is random scatter in discharge-transport relations for fines. Nordin and Beverage (1964) concluded that some of the random scatter can be explained in terms of the time dependency of the concentration of the finer sand classes and of material finer than 0.062 mm. They determined that the time dependency is due, in part, to temporary storage within the active channel. Analysis of the USGS sediment data confirmed that fine material does not vary as a function of discharge. Therefore, relationships of discharge with fine sand and median sand were determined in relation to the total sediment load then the remainder was divided up among the fines. Table B-1 shows the breakdown of the sediment size used in the model based on USGS sediment transport data for the San Marcial gage.

The bed material percent finer curves that were developed from the bed samples were input into the model. The reach was divided into thirds, with the San Antonio sample applying to the upper third, the cross section 1558 samples to the middle third, and the San Marcial sample to the lower third. The Toffaletti sediment transport formula was applied to this model because it

Table B-1. *Discharge-sediment load relationship.*

Discharge, cfs	30	1220	3000	5000	10000
Total load, t/day	241	4465	9070	13563	23413
	Percent of total load				
Clay	0.360	0.256	0.182	0.154	0.114
Silt 1	0.160	0.134	0.133	0.120	0.089
Silt 3	0.150	0.085	0.084	0.077	0.074
Very fine sand	0.090	0.075	0.074	0.069	0.066
Fine sand	0.190	0.382	0.453	0.500	0.571
Medium sand	0.040	0.063	0.071	0.076	0.083
Coarse sand	0.010	0.006	0.004	0.004	0.003

works well for sand bed rivers such as the Rio Grande. The depth of the movable bed was set at 20 feet. This value was derived from depth to gravel in well logs of the region.

Roughness Coefficient

Manning's roughness coefficients, "n-values", were utilized in the model to determine friction losses associated with bed form. The n-values for the Rio Grande in this particular reach were calculated based on a bed form analysis. As previously stated, the Rio Grande median diameter near the Bosque del Apache NWR was determined to be 0.17 mm. Using this value, the stream power was determined for the boundary of each flow regime.
Table B-2 shows Manning's roughness coefficients for each bed form and stream power. Overbank roughness coefficients of either .011, .01, or 0.085 were used depending on the vegetation. Vegetation along the Rio Grande overbank is quite dense and mainly consists of cottonwoods, salt cedar, willow, seep-willow or baccharis, and various grasses.

Table B-2. *Manning's "n" values as a function of bedform and stream power.*

Bedform	Stream power range ft-lb/s/ft^2	Manning's n
Flat	.001 - .006	.012
Ripple	.006 - .080	.035
Dune	.080 - .380	.020
Antidune	.380 - 2.00	.015

The study reach was divided into four reaches based on the channel geometry: cross sections 1512 to 1578, 1579 to 1640, 1641 to 1673, and 1674 to 1702. For example, the average width of the section from 1512 to 1578 at 500 cfs is 800 feet whereas the width for the section from 1579 to 1640 at 500 cfs is 138 feet. Different discharges were run in the HEC-6 model to calculate an average wetted perimeter for sections of the river. Stream power was calculated by multiplying specific weight times discharge and slope (.0012), then dividing by the wetted perimeter.

Analysis

The model was run for three conditions: a fixed bed with the 1980 monthly hydrograph, a movable bed with the 1980 monthly hydrograph, and a movable bed with flows up to 10,000 cfs. Twenty representative cross sections, approximately one per half mile of the study reach, were analyzed for each run. The results of the water surface elevation, velocity for channel and overbanks, change in bed elevation, and Manning's n-values for each cross section were extracted from the runs and input into a data file. This data file was used as an input file for a program that developed to divide each cross section into small cells and calculate the shear stress for each cell. The shear stress and velocity of the overbanks were of particular interest. The shear stress of the overbank was of importance to the determination of scour of the vegetation of the overbanks to provide an ideal site for cottonwood germination.

Shear Stress

Results for two of the 20 cross sections (1617 and 1558) are discussed in this section. Results from other cross sections were similar. Cross section 1558 is approximately 4.5 miles downstream from the Bosque Del Apache NWR northern border. Cross section 1617 is approximately 2 miles north of the refuge southern border.

Table B-3 shows the results for the fixed bed run at cross section 1617. The movable bed model results for this cross section are shown in Table B-4. Discharge, water surface elevation (WSE), bed change, velocity, and Manning's n- value for the left bank, main channel, and right bank are presented. The bed change is zero for the fixed bed. The movable bed changes due to sediment scour and deposition. With the 1980 hydrograph, banks were overtopped only when the flow was above 5,000 cfs (May and June). Velocities on the left and right banks were relatively low.

Fixed bed and movable bed shear stress for cross section 1617 with the 1980 discharges is shown in Table B-5. Shear stress (lbs/ft^2) is a function of depth and slope. The fixed bed main channel shear stress varied from 0.0483 to 0.1633. The movable bed shear stress in the main channel ranged from 0.0536 to 0.1494. Shear stresses on the overbanks were relatively low, the highest being 0.0462 as compared to the main channel with a shear stress of 0.1633. Lower shear stress on the banks is to be expected because the depth of the water is lower than in the main channel. Shear stress of this magnitude on the overbanks may be too low to scour any vegetation.

Table B-3. *Rio Grande-fixed bed model, cross section 1617. Monthly hydrograph for water year 1980.*

Discharge (cfs)	WSE (ft)	Left bank Vel. (fps)	Left bank Manning's n-value	Main channel Vel. (fps)	Main channel Manning's n-value	Right bank Vel. (fps)	Right bank Manning's n-value	Bed change (ft)
299	4491.52	0	0.11	1.35	0.035	0	0.11	0
1,604	4495.04	0	0.11	2.50	0.032	0	0.11	0
1,795	4495.37	0	0.11	2.62	0.032	0	0.11	0
1,015	4493.66	0	0.11	2.17	0.034	0	0.11	0
1,168	4493.99	0	0.11	2.29	0.033	0	0.11	0
864.5	4493.3	0	0.11	2.03	0.034	0	0.11	0
1,517	4494.88	0	0.11	2.44	0.033	0	0.11	0
5,323	4497.91	0.43	0.11	4.15	0.026	0.23	0.11	0
5,058	4497.82	0.41	0.11	4.01	0.026	0.30	0.11	0
1,230	4494.15	0	0.11	2.33	0.033	0	0.11	0
481.1	4492.21	0	0.11	1.61	0.034	0	0.11	0
647.7	4492.73	0	0.11	1.81	0.034	0	0.11	0

Table B-4. *Rio Grande-movable bed model, cross section 1617. Monthly hydrograph for water year 1980.*

Discharge (cfs)	WSE (ft)	Left bank Vel. (fps)	Left bank Manning's n-value	Main channel Vel. (fps)	Main channel Manning's n-value	Right bank Vel. (fps)	Right bank Manning's n-value	Bed change (ft)
299	4491.39	0	0.11	1.41	0.035	0	0.11	-0.03
1,604	4494.64	0	0.11	2.62	0.032	0	0.11	-0.15
1,795	4495	0	0.11	2.76	0.032	0	0.11	-0.08
1,015	4493.34	0	0.11	2.27	0.034	0	0.11	-0.12
1,168	4493.68	0	0.11	2.39	0.033	0	0.11	-0.12
864.5	4493.06	0	0.11	2.13	0.034	0	0.11	-0.05
1,517	4494.76	0	0.11	2.53	0.033	0	0.11	0.08
5,323	4497.9	0.43	0.11	3.97	0.026	0.19	0.11	-0.12
5,058	4497.8	0.41	0.11	3.80	0.026	0.19	0.11	-0.16
1,230	4493.91	0	0.11	2.53	0.033	0	0.11	0.18
481.1	4492.22	0	0.11	1.77	0.034	0	0.11	0.28
647.7	4492.7	0	0.11	1.98	0.034	0	0.11	0.28

Table B-5. *Shear stress, cross section 1617. Monthly hydrograph for water year 1980.*

Discharge (cfs)	Fixed bed: Left bank	Fixed bed: Main channel	Fixed bed: Right bank	Movable bed: Left bank	Movable bed: Main channel	Movable bed: Right bank
299	0	0.0483	0	0	0.0536	0
1,604	0	0.1051	0	0	0.1175	0
1,795	0	0.1112	0	0	0.1251	0
1,015	0	0.0926	0	0	0.1031	0
1,168	0	0.0989	0	0	0.1092	0
864.5	0	0.0844	0	0	0.0941	0
1,517	0	0.1023	0	0	0.1108	0
5,323	0.0462	0.1633	0.0088	0.0462	0.1494	0.0060
5,058	0.0425	0.1578	0.0150	0.0419	0.1410	0.0060
1,230	0	0.1007	0	0	0.1208	0
481.1	0	0.0615	0	0	0.0764	0
647.7	0	0.0723	0	0	0.0894	0

The movable bed model was run with increasing flow from 1,000 to 10,000 cfs (Table B-6). The overbank was inundated by flows greater than or equal to 4,000 cfs. Velocities on the banks were low compared to the main channel. At 10,000 cfs the main channel had a velocity of 4.78 fps whereas the left bank velocity was 0.52 fps and the right bank velocity was 0.31 fps. Shear stresses corresponding to these flows can be seen in Table B-7. The left bank shear stress ranged from 0.0287 to 0.0543, and the right bank shear stress ranged from 0.0074 to 0.0164. In comparison, the main channel shear stress ranged from 0.0976 to 0.1476.

Tables B-8 and B-9 present the results for the fixed bed and the movable bed models run with the 1980 hydrograph at cross section 1558. As with cross section 1617, the banks were flooded only when flows exceeded 5,000 cfs. Velocities in the main channel for this cross section are lower than for cross section 1617 because the area is larger at this location. However, the shear stresses on the right bank were slightly higher (Table B-10). The movable bed maximum shear stress was 0.0441 on the left bank and 0.07 on the right bank.

At cross section 1558, the water surface elevation, velocity, and bed change were evaluated for increasing flows. The results are presented on Table B-11. The left bank did not flood until the flow was above 4,000 cfs. The right bank flooded when the flow was greater than 3,000 cfs. The shear stress on the right bank varied from 0.0296 to 0.0548 (Table B-12). The left bank shear stress ranged from 0.0123 to 0.0235.

Table B-6. *Rio Grande-movable bed model, cross section 1617. Composite discharge by increasing flow.*

Discharge (cfs)	WSE (ft)	Left bank Vel. (fps)	Left bank Manning's n-value	Main channel Vel. (fps)	Main channel Manning's n-value	Right bank Vel. (fps)	Right bank Manning's n-value	Bed change (ft)
1,000	4493.38	0	0.11	2.21	0.034	0	0.11	-0.15
2,000	4495.82	0	0.11	2.59	0.032	0	0.11	-0.21
4,000	4497.22	0.33	0.11	3.58	0.028	0.21	0.11	-0.22
6,000	4497.93	0.44	0.11	4.17	0.025	0.2	0.11	-0.62
8,000	4498.19	0.49	0.11	4.66	0.021	0.25	0.11	-1.56
10,000	4498.53	0.52	0.11	4.78	0.02	0.31	0.11	-2.32

Table B-7. *Shear stress, cross section 1617. Composite discharge by increasing flow.*

Discharge (cfs)	Movable bed Left bank	Movable bed Main channel	Movable bed Right bank
1,000	0	0.0976	0
2,000	0	0.1033	0
4,000	0.0287	0.1468	0.0074
6,000	0.0462	0.1476	0.0066
8,000	0.0526	0.1315	0.0103
10,000	0.0543	0.1151	0.0164

Table B-8. *Rio Grande-fixed bed model, cross section 1558. Monthly hydrograph for water year 1980.*

Discharge (cfs)	WSE (ft)	Left bank Vel. (fps)	Left bank Manning's n-value	Main channel Vel. (fps)	Main channel Manning's n-value	Right bank Vel. (fps)	Right bank Manning's n-value	Bed change (ft)
299	4511.9	0	0.11	1.00	0.018	0	0.11	0
1,604	4513.36	0	0.11	1.30	0.034	0	0.11	0
1,795	4513.46	0	0.11	1.38	0.034	0	0.11	0
1,015	4512.96	0	0.11	1.07	0.035	0	0.11	0
1,168	4513.07	0	0.11	1.14	0.035	0	0.11	0
864.5	4512.74	0	0.11	1.07	0.032	0	0.11	0
1,517	4513.3	0	0.11	1.26	0.034	0	0.11	0
5,323	4514.74	0.18	0.11	2.30	0.027	0.34	0.11	0
5,058	4514.68	0	0.11	2.24	0.028	0.34	0.11	0
1,230	4513.12	0	0.11	1.16	0.035	0	0.11	0
481.1	4512.19	0	0.11	1.05	0.022	0	0.11	0
647.7	4512.48	0	0.11	1.03	0.026	0	0.11	0

Table B-9. *Rio Grande movable bed model, cross section 1558. Monthly hydrograph for water year 1980.*

Discharge (cfs)	WSE (ft)	Left bank Vel. (fps)	Left bank Manning's n-value	Main channel Vel. (fps)	Main channel Manning's n-value	Right bank Vel. (fps)	Right bank Manning's n-value	Bed change (ft)
299	4511.98	0	0.11	1.15	0.018	0	0.11	0.20
1,604	4513.47	0	0.11	1.46	0.034	0	0.11	0.32
1,795	4513.65	0	0.11	1.49	0.034	0	0.11	0.42
1,015	4513.1	0	0.11	1.30	0.035	0	0.11	0.45
1,168	4513.28	0	0.11	1.31	0.035	0	0.11	0.51
864.5	4513.03	0	0.11	1.31	0.032	0	0.11	0.54
1,517	4513.63	0	0.11	1.51	0.034	0	0.11	0.64
5,323	4514.83	0.25	0.11	2.54	0.027	0.45	0.11	0.60
5,058	4514.8	0.23	0.11	2.58	0.028	0.45	0.11	0.69
1,230	4513.38	0	0.11	1.43	0.035	0	0.11	0.61
481.1	4512.48	0	0.11	1.46	0.022	0	0.11	0.54
647.7	4512.78	0	0.11	1.38	0.026	0	0.11	0.57

Table B-10. *Shear stress, cross section 1558. Monthly hydrograph for water year 1980.*

Discharge (cfs)	Fixed bed			Movable bed		
	Left bank	Main channel	Right bank	Left bank	Main channel	Right bank
299	0	0.0105	0	0	0.0140	0
1,604	0	0.0436	0	0	0.0564	0
1,795	0	0.0476	0	0	0.0571	0
1,015	0	0.0338	0	0	0.0529	0
1,168	0	0.0369	0	0	0.0513	0
864.5	0	0.0289	0	0	0.0457	0
1,517	0	0.0419	0	0	0.0629	0
5,323	0.0122	0.0755	0.0326	0.0440	0.0972	0.0700
5,058	0	0.0747	0.0329	0.0441	0.1047	0.0707
1,230	0	0.0377	0	0	0.0617	0
481.1	0	0.0160	0	0	0.0346	0
647.7	0	0.0198	0	0	0.0382	0

Table B-11. *Rio Grande-movable bed model, cross section 1558. Composite discharge by increasing flow.*

Discharge (cfs)	WSE (ft)	Left bank Vel. (fps)	Left bank Manning's n-value	Main channel Vel. (fps)	Main channel Manning's n-value	Right bank Vel. (fps)	Right bank Manning's n-value	Bed change (ft)
1,000	4512.93	0	0.11	1.09	0.035	0	0.11	0.03
2,000	4513.63	0	0.11	1.51	0.033	0	0.11	0.11
4,000	4514.37	0	0.11	2.10	0.030	0.31	0.11	0.16
6,000	4514.83	0.21	0.11	2.76	0.026	0.39	0.11	0.31
8,000	4515.14	0.18	0.11	3.58	0.023	0.44	0.11	0.57
10,000	4515.44	0.25	0.11	2.60	0.020	0.39	0.11	0.91

Table B-12. *Shear stress, cross section 1558. Composite discharge by increasing flow.*

Discharge (cfs)	Movable bed Left bank	Movable bed Main channel	Movable bed Right bank
1,000	0	0.0353	0
2,000	0	0.0548	0
4,000	0	0.0779	0.0296
6,000	0.0172	0.1009	0.0438
8,000	0.0123	0.1261	0.0548
10,000	0.0235	0.0511	0.0431