THESIS

EVOLUTION OF LARGE ARROYOS

THE RIO PUERCO OF NEW MEXICO

Submitted by

John Grant Elliott

Department of Earth Resources

In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall, 1979

Colorado State University

October, 1979

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY JOHN GRANT ELLIOTT ENTITLED EVOLUTION OF LARGE ARROYOS, THE RIO PUERCO OF NEW MEXICO BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

Frank G. Ethridge

Elizabeth Ann Morris

[illegible]

Adviser

[illegible]

Head of Department

ABSTRACT OF THESIS

EVOLUTION OF LARGE ARROYOS,
THE RIO PUERCO OF NEW MEXICO

Since the inception of widespread erosion in the southwestern United States nearly a century ago, sufficient time has elapsed for many long-term adjustments in channel and arroyo form to become perceptible. Geomorphic and hydrologic changes indicate that the Rio Puerco of northwestern New Mexico is adjusting its morphology to new equilibrium conditions. The width of the formerly trench-like arroyo has been greatly increased, and the creation of a new flood plain today gives the arroyo a valley-like character along most of its lower course. Morphological variations up and downstream are due to different stages of arroyo development, and therefore, areal differences have been drawn upon to illustrate temporal progression of the evolutionary process.

Most of the arroyo today is characterized by one of two geomorphic phases. The arroyo of Type 1 reaches is broad and flat bottomed, and it is actively widened by periodic shifting of the sediment laden channel flowing within. Along Type 2 reaches the arroyo is more mature in its development, having an inner-flood plain and a relatively stable channel.

Following rejuvenation of its tributaries, the evolution of a large arroyo continues with lateral erosion of valley fill because the sediment burdened channel is prone to abrupt shifts in position and pattern. Under these conditions arroyo width continues to increase

until a geometry conducive to efficient transport of flood waters without excessive erosion of valley fill is attained. As tributaries mature, a reduction in mean annual discharge, peak annual flood and bedload transport with deposition of suspended sediment and establishment of riparian vegetation all tend to reduce the width of the channel within the arroyo and stabilize its banks.

Evolution of the arroyo continues with modification of the new inner-flood plain, as a sinuous channel is formed which proceeds to meander through alluvial deposits. Today, upper reaches of the Rio Puerco's arroyo are still being actively widened but the broad, vegetated valley phase of evolution characterizes most lower reaches of the valley. Therefore, there is an evolutionary sequence in an upstream direction.

John Grant Elliott
Department of Earth Resources
Colorado State University
Fort Collins, Colorado 80523
Fall, 1979

ACKNOWLEDGEMENTS

I wish to express my appreciation to my adviser, Dr. Stanley A. Schumm, for his guidance and support throughout the study; and to the members of my committee, Dr. Elizabeth A. Morris and Dr. Frank G. Ethridge, for their encouragement and advice.

Invaluable assistance in the field was provided by David Whitson, Lynn Skinner and Steve Parsons. David Meyer, Ted Nadler and other collegues contributed generously with discussion and insight. Richard F. Hadley provided early channel surveys and personal observations. The typing was done by Carol Kelly. Financial support for the study was administered by the National Science Foundation.

TABLE OF CONTENTS

LIST OF FIGURES

Figure		Page

CHAPTER I

INTRODUCTION

Statement of the Problem and Objectives

In the late 19th Century a period of widespread erosion and arroyo cutting began to have a marked affect on many drainage basins in the American Southwest. Formerly lush, well-watered valleys that supported crops, livestock and settlements were rapidly dissected by gullies and rejuvenated streams. Deep, steep-walled trenches of great length, or arroyos, replaced unobtrusive streams that had once flowed across broad flood plains, and discontinuous gullies coalesced into similar features as headcuts worked upstream. Water tables dropped and diversion structures were washed-out as intermittent streams became ephemeral and discharge became more concentrated and erosive. The effect on the ecology and economy in these areas was devastating and understandably much attention was given to the study of gullying and arroyo formation by early investigators (Bryan, 1928a; Leighly, 1936; Antevs, 1952).

Nearly a century later, many valleys are still characterized by large arroyos, ghost towns and noticeably sparce vegetation, but the character of some large arroyos has changed as their channels evolve to new conditions of geomorphic stability. Since the beginning of the most recent cycle of erosion nearly a century ago, the main channel of the Rio Puerco has evolved from a narrow, deep trench into a broad valley with a developing flood plain that supports vegetation. This suggests that the river, rather than being between periods of degradation and subsequent aggradation to its former level, is establishing a new set of equilibrium conditions by modifying its course and cross section in such a way that a broad range of discharges may be transmitted without severe erosion of its banks and terraces. In other words, an entirely new valley and flood plain are being formed.

Many studies have dealt with conditions leading to incision or with the immediate response of hydrology, agricultural land and water resources to arroyo formation, while only a few have addressed the long-term adjustments of the arroyo itself. It is the intention of this study to investigate large-scale arroyo evolution in semiarid regions following rejuvenation. Emphasis will be placed on the mechanisms that lead to modification of valleys and formation of new flood plains.

The objectives of this thesis are fourfold. They are:

1) to document changes in the main valley and channel of a major ephemeral drainage system since the most recent period of incision,
2) to explain contemporary and former geomorphic processes leading to arroyo enlargement,
3) to develop an evolutionary model illustrating the sequence of events, conditions and morphologies of arroyo enlargement,
4) to predict the future morphology of the Rio Puerco's valley, and those of other major drainages in similar climatic and geologic settins.

The Rio Puerco "of the East" in northwestern New Mexico has for many years been the subject of hydrologic studies and was chosen as the field location for this investigation (Fig. 1-1). Because of the large quantities of silt it introduces into the Rio Grande and the vast area its rejuvenation has adversely affected, changes in the Rio Puerco have been noted in many historical and scientific chronicles. This largest tributary of the Rio Grande, in the middle Rio Grande valley, drains approximately 15,180 square kilometers (5860 mi^2) and has been, for nearly 90 years, the site of much erosion and sediment production. Since it began to trench its valley and since the first detailed studies were initiated, sufficient time has passed to allow many discernible changes in channel and valley morphology. This transformation is documented in photos, maps and surveys spanning several decades. The arroyo today exhibits a diverse character and stage of maturation, from aggraded reaches in the sediment producing upper basin to more stable, vegetated reaches downstream. This warrants a substitution of space for time in an attempt to develop a model of arroyo evolution. Aerial photograph coverage during approximately 40 years and the previous field studies make this an excellent location for observing river metamorphosis.

The geomorphic processes that are modifying the upstream reaches of Rio Puerco are probably the same processes that were active in the lower reaches earlier this century. Study of early aerial photographs and of the sediment preserved in terrace remnants tends to confirm this hypothesis. With the identification of processes and a comparison of arroyo morphology, a model can be developed of the erosional evolution in this valley from its incision to an advanced state of "relative stability."

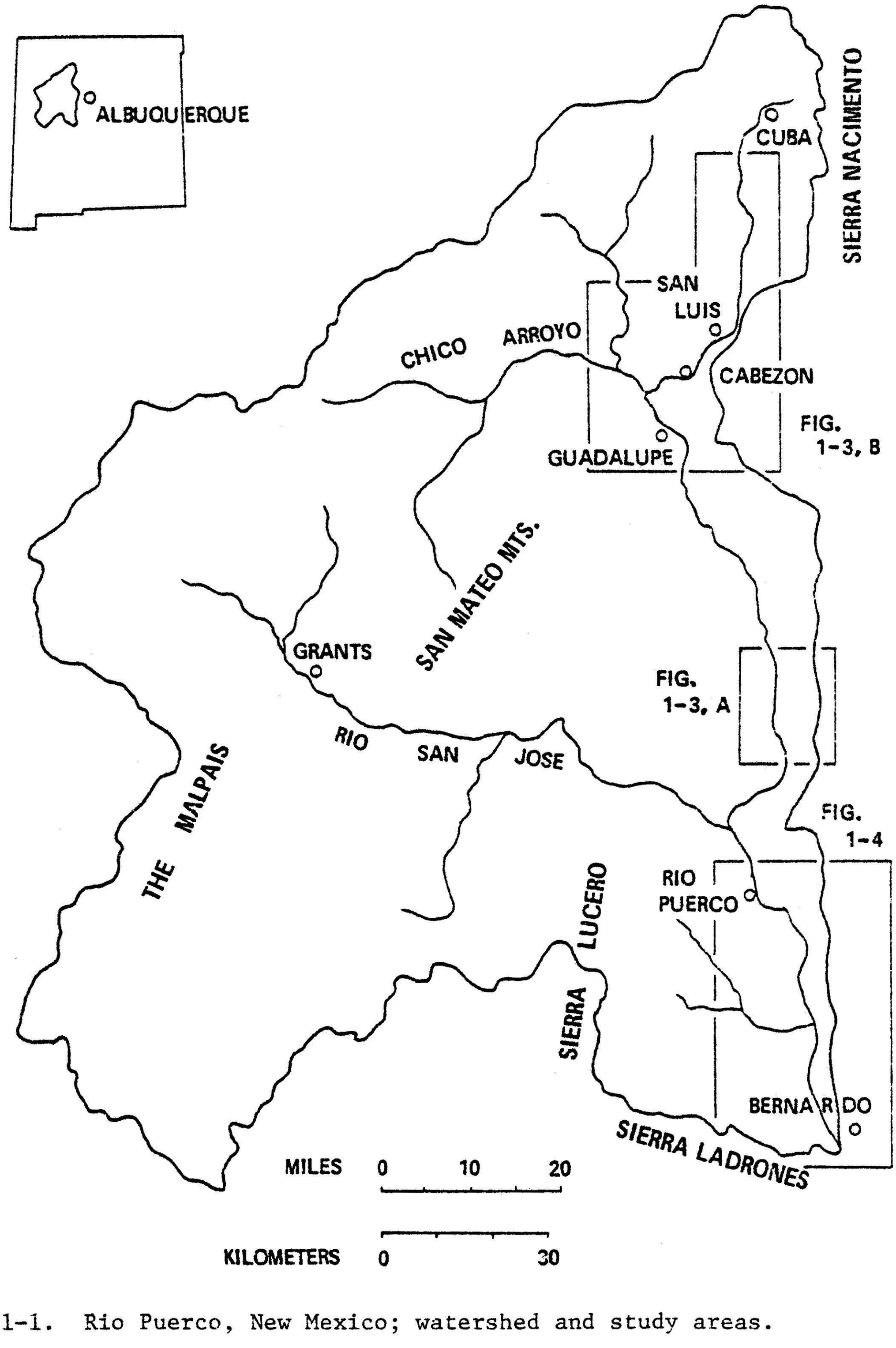


Fig. 1-1. Rio Puerco, New Mexico; watershed and study areas.

Episodic Erosion

In many valleys of the southwestern United States the valley alluvium contains several buried channels which are evidence of past incision and filling (Fig. 1-2). Bryan and Post noted these ancient, buried channels as early as 1927, and the propensity for periodic erosion and sedimentation in semiarid regions was investigated by Schumm and Hadley (1957). There is, apparently, a fundamental difference between the cyclic pattern of gully cutting and filling observed by Schumm and Hadley in small basins, and the longer-term erosional progression that has been associated with large watersheds, such as the Rio Puerco, since the 1880's. Though both types of channel incision may be initiated by the same hydrologic and geomorphic conditions, the evolution of large arroyos into broad valleys may reflect a major change in extrinsic factors, such as broad climatic fluctuations, or a change in regional baselevel.

Recent arroyo cutting in the Southwest has revealed valley alluvium of several ages, and Bryan (1941) identified three cycles of major erosion and deposition since the Pleistocene. According to Bryan, the first period of erosion was long, arroyos "larger than today" were formed and the earlier alluvium was completely removed in many valleys. The second period of erosion has been dated with greater precision due to an abundance of archaeological material. These arroyos began to form in many places after 1100 to 1200 A.D., and they were one factor in the demise of local Anasazi population centers (Bryan, 1929; Hack, 1942; Herold, 1961; Judd, 1964; Euler, et al., 1979). Throughout most of the Southwest the third and last period of

Fig. 1-2. Exposed valley alluvium with several cut-and-filled channels. Near cross section 17.

aggradation commenced by about 1400 A.D. The most recent epicycle of erosion, beginning at the close of the last century, has been well documented by historical accounts and scientific studies and it is the one with which this paper is concerned.

A Review of Causes

Since the most recent period of erosion in semiarid regions, beginning in the late nineteenth century, researchers have sought to explain why undisturbed valley slopes and well-vegetated valley floors can quite suddenly degenerate into gullied slopes and gaping arroyos. In an area where productive surface land is minimal, losses from accelerated erosion and its prevention have become the concern of farmers, ranchers, water users, engineers, and the various government agencies responsible for resource management.

Severe erosion in the valleys of the southwest first gained wide recognition after the introduction of farming and grazing by early settlers in the 1870's and 1880's, and understandably, poor land use was often blamed. Loss of natural vegetation by overgrazing and plowing allows water to runoff more rapidly and with more erosive force; compaction by trampling prevents infiltration into the soil thereby contributing to increased runoff, and wagon ruts and cattle trails allow runoff to channelize. Antevs (1952) cites unrestricted grazing on public lands in the late 1800's as the cause of gullying in southeastern Arizona.

Climatic conditions have been suggested as another factor leading to periods of episodic erosion. Extended droughts, temporally and spatially correlated with widespread erosion, are revealed from studies of tree ring growth (Judd, 1964; Antevs, 1952), pollen (Schoenwetter and Dittert, 1968) and sand dunes (Hack, 1942). Irregularity of annual rainfall patterns has been examined by several authors. Leopold (1951) believes an increase in the intensity of summer storms may contribute to faster and greater runoff which could initiate gullying. Schoenwetter and Dittert (1968) discuss the seasonality of rainfall; periods of erosion are characterized by a "summer moisture regime" where most of the annual precipitation occurs during a long summer of intense thunderstorms; periods of alluviation are characterized by a "winter moisture regime" where precipitation accumulated as snow over a long winter, runs off slowly and infiltrates more readily.

A more noticeable trigger of valley erosion is flooding. From a study of the Cimarron River in Kansas, Schumm and Lichty (1963) conclude that the channel widening that destroyed its flood plain was induced by the maximum flood of record in 1914. This was followed in the 1930's by low annual precipitation and destructive floods. A 10-year period of flood plain construction followed, which was characterized by above average annual precipitation and insignificant floods of low to moderate discharge. This permitted vegetation to become established in the wide, sandy channel and allowed banks to become more stabilized. Malde and Scott (1977) have determined that the upstream migration of a headcut in a degrading channel is a logarithmic function of runoff, but great erosion may also occur with relatively little runoff if there is a short interval between rains or if the ground is wet.

As previously mentioned, a cyclic pattern in the fluvial histories of many areas has become accepted. A situation such as the following may be imagined: as headcuts and the loci of sediment production are transmitted upstream into smaller but increasingly numerous tributaries, a flood of sediment is moved downstream. This causes aggradation in lower reaches of the previously degraded channel, where the capacity to transport this increased load has been surpassed. Over time, reaches of the main valley are oversteepened through backfilling and vertical accretion, thereby creating a very unstable valley floor. Eventually this instability exceeds some failure threshold and once again streams in the valley are degraded and stored sediment is flushed out.

Regardless of the specific combination of climatic, geologic or man-induced factors in any particular watershed, gullies and arroyos may be initiated by: (1) increased erodability, from increasing exposure of the land to running water, decreasing the infiltration capacity of soils, weakening the soil structure, or masking the valley floor with easily erodable sediments; or by (2) increased erosiveness of flow, from increased valley slope, effective baselevel lowering, increase in channel slope, increase in hydraulic radius (depth), or reduction of surface roughness by removal of vegetation (Cooke and Reeves, 1976).

Effects of Arroyo Formation

When a small channel or river becomes entrenched, tremendous changes take place in the hydrology of the basin and in the hydraulics of the channel. After runoff has been channelized flow velocity and sediment transport are increased, and peak discharge passing through the degraded channel is greater than that conveyed by a channel on an ungullied valley floor (Leopold, Wolman and Miller, 1964). The resulting increase in the streams ability to do work is reflected in further scour of the bed, lateral erosion of the banks, or valley fill, and introduction of enormous amounts of sediment into the system (Bryan and Post, 1927). Nordin (1963 and 1964) has shown that flow velocity is proportional to the log of channel depth and that the capacity to transport sediments increases as the viscosity of water increases, when there is a high concentration of fine sediments in the flow. It appears that once incision has begun, it proceeds at a very rapid rate. Antevs (1952) reports Kanab Creek and the San Pedro River in southeastern Arizona were gullied 24 kilometers (15 mi) in 3 years, and 200 kilometers (125 mi) in 10 years, respectively. For a storm event producing 25 mm of precipitation, Malde and Scott (1977) note headcut advancement of 2 and 10 meters in two small drainage basins near Santa Fe.

In addition to dessication of productive land as headcuts work up through small tributaries, the volume of alluvium introduced to the lower channels soon exceeds the streams' ability to transport it, and aggradation occurs. This raises the bed elevation and makes the channel more susceptible to overbank flooding. Reservoirs downstream experience high rates of sedimentation and a diminished storage capacity. Needless to say, the efficiency of water control structures and the quality of water are reduced when the stream transports large quantities of sediment.

The water table of the whole valley can be reduced by an amount equal to the depth of incision in the main channel (Hack, 1942). When this happens, a noticeable change in plant association follows. Bryan (1928 b) described the valley of the Santa Cruz River before 1880, covered by groves of mesquite, sacaton grass and swampy areas of high tule. After arroyo formation lowered the stream bed, the water table decreased 15 feet, and the valley could only support dense mesquite, a phreatophyte capable of exploiting deep water. Since most cultigens cannot utilize deep ground water, once arroyos formed near their fields, farmers could no longer rely on a groundwater moisture supply for crops. Irrigation systems dependent on diversion from main streams were rendered useless, and they are now pearched high on terraces that were formerly part of the flood plain.

Method of Study

During the summer of 1977 and in January 1978, channel surveys and sediment samples were taken at 29 locations in the upper, middle and lower reaches of the Rio Puerco. Cross sections are plotted in Figures 1-3 and 1-4, and their location is given in Appendix I. Sample sites were selected that exemplified the diversity in the arroyo, and that were accessible or near former surveys. Channel cross sections, channel gradients and inner-valley cross sections were surveyed with a self-leveling level or an alidade. Widths and maximum depths were measured from the margin of established vegetation and breaks in topography. Maps and air photos spanning four decades were used to determine valley gradients and to plot the location of terraces and changes in channel pattern.

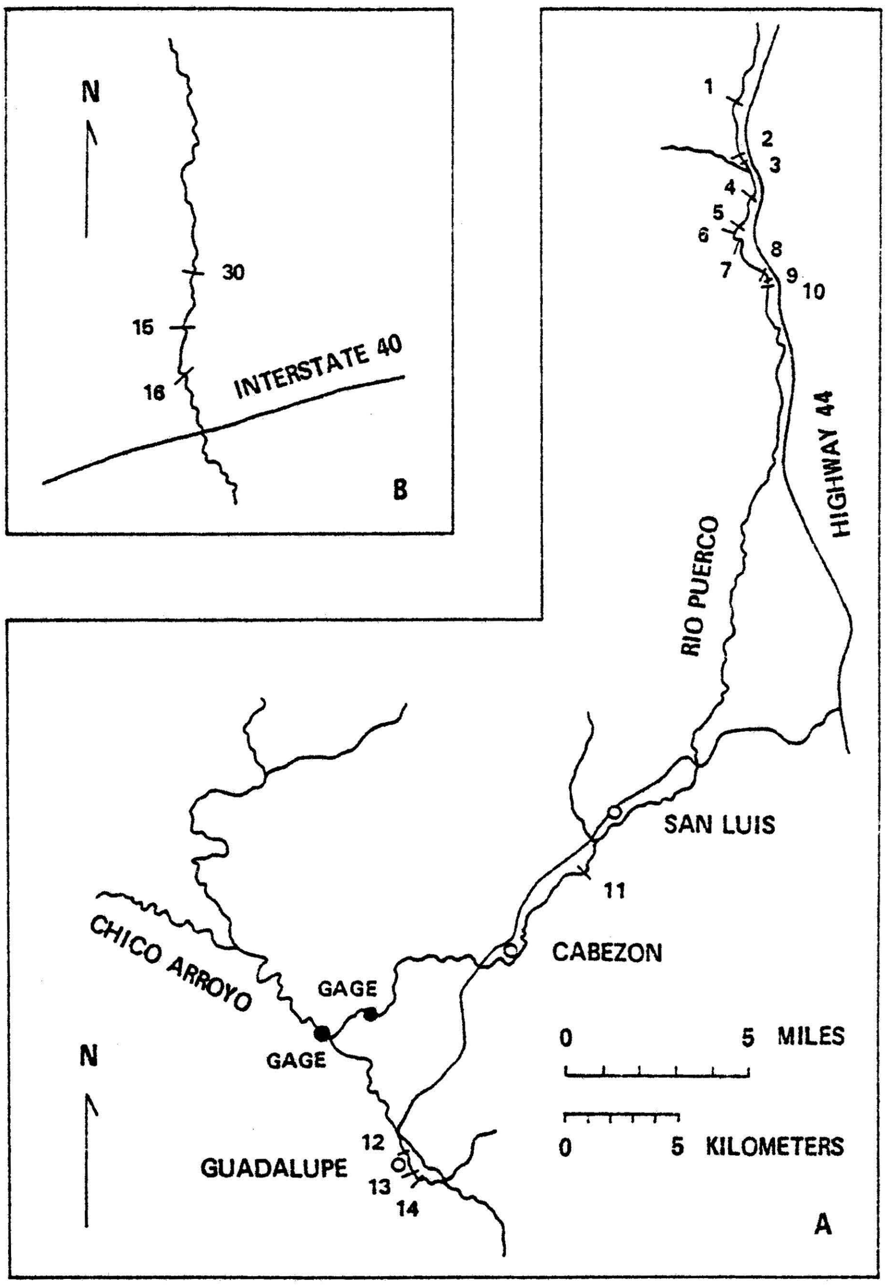


Fig. 1-3. Location of cross sections and gages along the middle and upper reaches of the Rio Puerco.

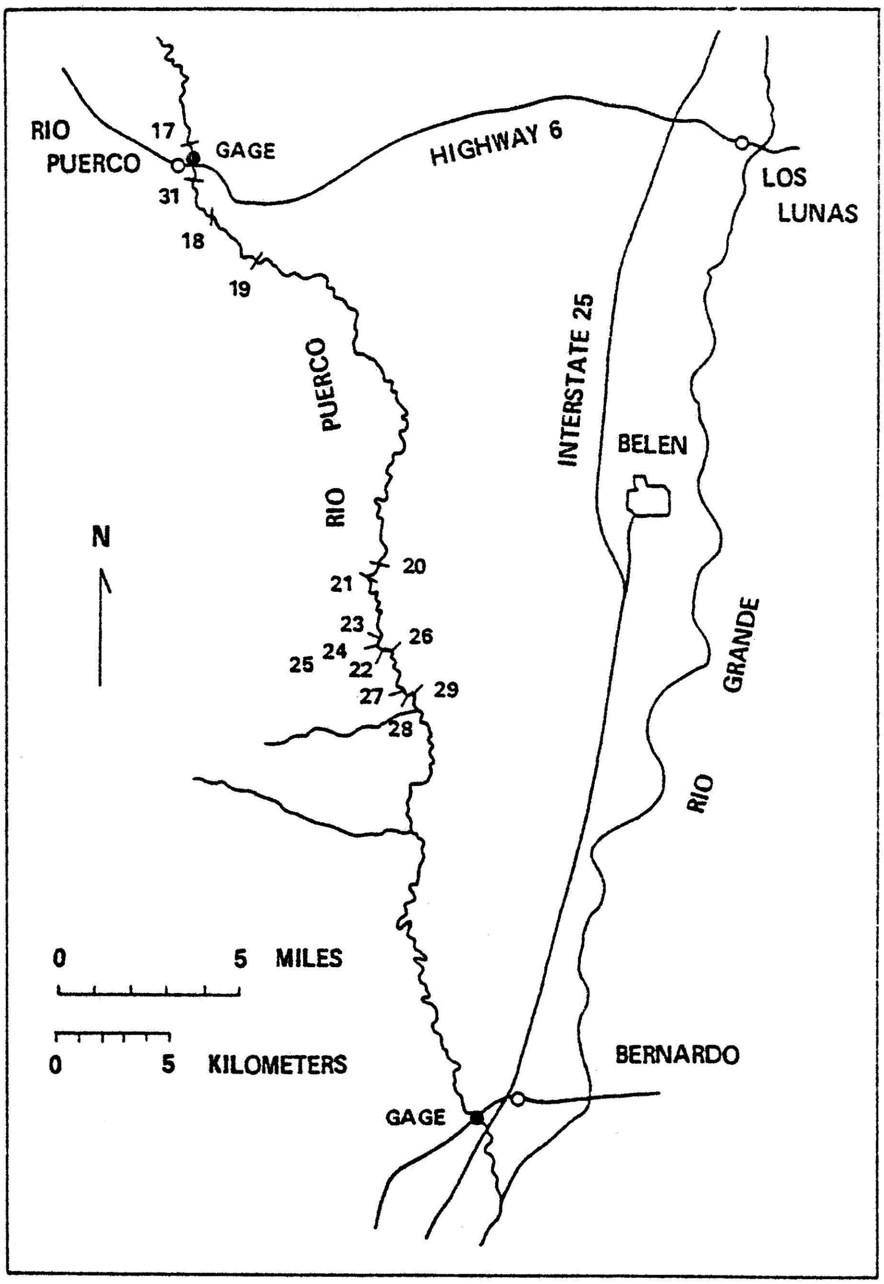


Fig. 1-4. Location of cross sections and gages along the lower reaches of the Rio Puerco.

Sediment samples were taken from the banks and bed at 27 of the cross sections. It is emphasized here that banks are defined as that part of the channel composed of material transported and deposited by the post-incision river, and this material should be distinguished from previously deposited valley alluvium through which the new arroyo has been cut (Fig. 1-5). Channel deposits were sampled to a depth of two inches at evenly spaced intervals from bank to bank. Bed samples were mixed in equal proportions, as were bank samples, to create two composite samples from each cross section; the procedure was used by Schumm (1960) in an earlier study of intermittent channels.

Grain size distributions for both bed and bank aggregate samples were obtained in the following manner. After deflocculating clays with a solution of sodium hexamethaphosphate (Calgon) (Folk, 1974), the samples were wet sieved through a 230 U.S. Mesh screen, dried, and the difference in weights before and after sieving were noted in order to determine the amount of sediment with a grain size of 4.0 ϕ or less. The remaining sediment was dry sieved through 1/2 ϕ interval screens in a Ro-Tap machine for 15 minutes, and the weight of sediment on each sieve was recorded. The weight of the pan fraction, smaller than 230 mesh, was added to the weight of the same size sediments determined from wet sieving in order to calculate the percentage of silt and clay in both the bed and bank samples.

A standard computer program, SEDPET, was used to compute the graphic mean grain size for both bank (M_{zb}) and bed (M_{zc}) aggregates (Folk, 1974):

$$M_z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} \qquad \text{(Eq. 1-1)}$$

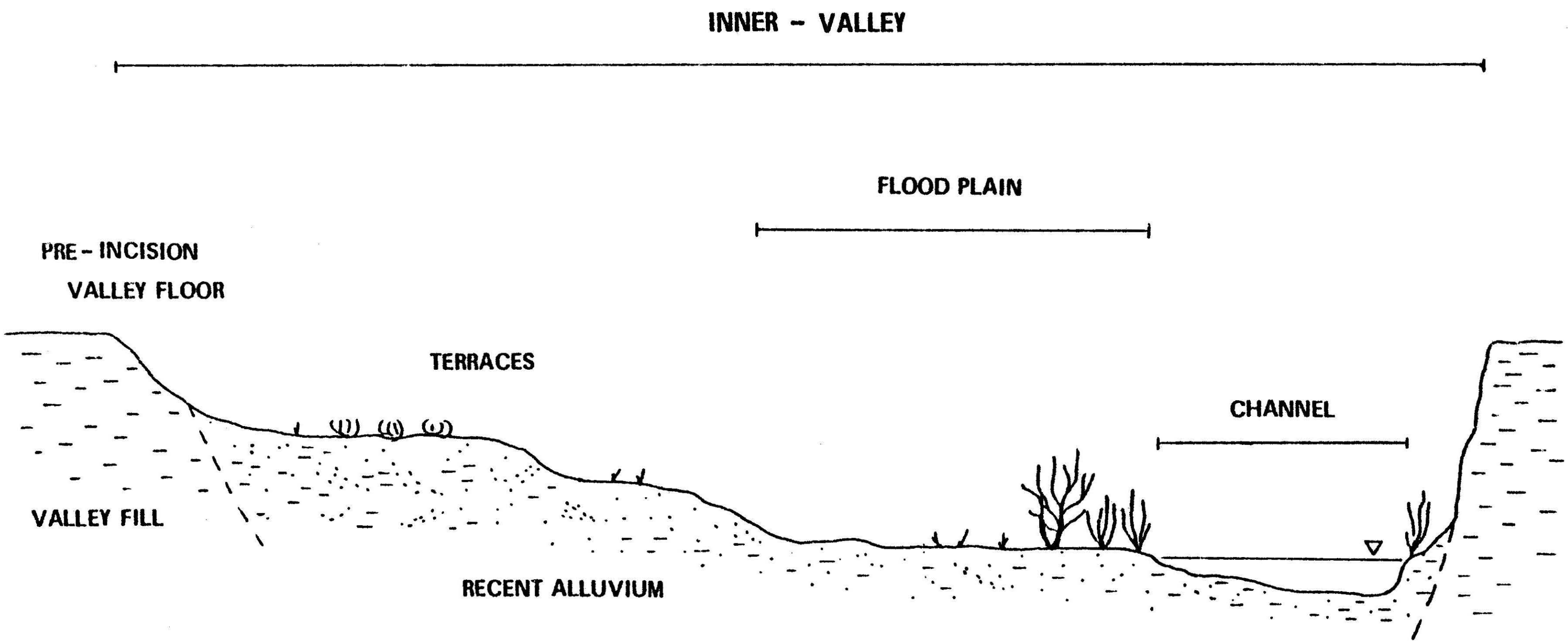


Fig. 1-5. Schematic arroyo cross section and terminology.

and the weighted mean percent silt and clay (M) was determined for each cross section (Schumm, 1960):

$$M = \frac{(S_c)(W) + (S_b)(2D)}{W + 2D} \qquad \text{(Eq. 1-2)}$$

where: S_c = percentage silt and clay in the bed

S_b = percentage silt and clay in the banks

W = channel width

D = channel depth

Discriminant function analysis was employed in an attempt to identify those sampled variables that would best discriminate reaches of the arroyo considered to be youthful from those considered to be in a more mature phase of evolution. Because the sample size was small relative to the number of variables, discriminant function analysis was performed three times, each with a different set of three to five variables. One or two variables in each set that were determined to be good discriminators of channel type or those that have in the past been most often measured were then grouped together in a final analysis.

CHAPTER II

THE RIO PUERCO

Geology and Hydrology

In central New Mexico, an area as great as that drained by the Rio Puerco embraces a diverse geography (Fig. 1-1). The headwaters arise near Cuba in the Precambrian crystalline rocks of the Sierra Nacimiento, which form the northeastern boundary of the drainage and exceed 9,000 feet in elevation. In the western part of this watershed are the San Mateo Mountains, a broad mesa and plateau area capped with basaltic lava of Cenezoic age. Vulcanism in this region is so recent that inhabitants of the Acoma Pueblo are believed to have witnessed an eruption near Grants (Bryan and Post, 1927). The upper reaches of the two largest tributaries of the Rio Puerco, Arroyo Chico and Rio San José, drain this region, and like the headwaters in the Sierra Nacimiento, they contribute relatively large amounts of runoff but little silt.

South of the Sierra Nacimiento and extending nearly to the mouth of the Rio Puerco is a gravel capped escarpment which divides the Rio Puerco and Rio Grande watersheds. This gravel overlies the Santa Fe formation of upper Tertiary age and it represents a long period of Pleistocene alluviation which buried both the Rio Puerco and Rio Grande valleys, in places to a thickness of more than 1000 feet (Bryan and Post, 1927). The southern boundary of the Puerco drainage basin includes the Precambrian granitic Sierra Ladrones, the Tertiary basalts of the Malpais and the Permian sandstones of Sierra Lucero.

The greatest portion of the valley is underlain by Tertiary and upper Cretaceous sandstone and shale; sediments that are generally flat lying but easily erodible when exposed. In the upper part of the basin members of the Mesaverde Group and the Mancos Shale are exposed, whereas the river in its lower reaches flows through the Santa Fe formation and Quaternary flood plain deposits.

The climate of most of the Rio Puerco watershed is semiarid. At Bernardo, near the mouth, the mean annual rainfall is about 6 inches (Patton, 1973), and vegetation is very sparse. However, in the mountainous regions and the high plateau areas the climate is cooler and more humid with precipitation double that of the lower reaches, and in winter, snow is common above 6500 feet (Bryan and Post, 1927). Soils in this environment are better developed, supporting piñon, juniper and range grasses (Nordin, 1963) and, though runoff may be relatively high, erosion is low.

Most of the annual precipitation falling on the Rio Puerco drainage basin occurs during July and August in the form of high intensity thundershowers. Individual storms, that produce over an inch of rain, may occur several times per season. In parts of the watershed, where vegetation is scarce, there is little to impede runoff, and gullies, if present, channelize flow, further contributing to accelerated runoff and flash flooding. Malde and Scott (1977) report a 25 mm (1 inch) storm near Santa Fe which resulted in a discharge of about 140 cubic meters per second (5,000 cfs) that crested about 20 minutes after the rain began. After an hour discharge had subsided to one tenth the maximum flow.

As noted above, there have been several periods of valley fill erosion and deposition since the Pleistocene. The thickness of recent alluvium in the Rio Puerco watershed is variable from place to place. Bryan and Post (1927) note depths of fill ranging from 16 to 26 meters (51 to 87 ft.) near Cuba to over 91 meters (300 ft.) on the Laguna Reservation northwest of Albuquerque. Nordin (1963) cites a core log obtained from an area near Bernardo that reveals alternating layers of fine sand and clay to a depth of about 21 meters (70 ft.). Where the channel does encounter bedrock it is probable that the river is not flowing over the area of deepest fill. Along the valley, the alluvium is consistantly composed of alternating fine sands, silt and small amounts of gravel. The fill is believed by Wagner (1963) to be largely derived from the Santa Fe formation.

The primary sources of alluvium in the Rio Puerco valley are the shales and sandstones of the upper Cretaceous and lower Tertiary formations. When these rocks are exposed on the flanks of mesas or hill slopes erosion is rapid. The sediment is carried downslope, and most of it is deposited on alluvial fans and on the valley floor. An ephemeral stream generally carries a high concentration of silt, but the formation of an arroyo and subsequent rejuvenation of tributaries greatly increases sediment production and sediment load, as material stored as valley alluvium or in fans is again available for transport.

Once an arroyo has been established in a valley and gullies have begun to work up through tributary streams, alluvium may be mobilized by several processes. Fracture planes and desiccation cracks along the arroyo margin are widened into large fissures and pipes by surface runoff, and large masses of alluvium become detached from the side of the trench. If the channel is impinging on the bank below such a detached block, it may be undercut sufficiently to collapse into the arroyo (Fig. 2-1). When sandy clay becomes saturated from prolonged contact with floodwater and the water level falls, pore pressure increases thereby weakening the material at the base of the riser. This often results in large scale slumping after the recession of high flows (Leopold, Wolman and Miller, 1964). Bryan and Post (1927) comment on the gross quantities of sediment introduced into the Rio Puerco by such processes. Below the mouth of the Rio San Jose they document the collapse of a mass of alluvium "15 feet (4.6 m) wide, 43 feet (13.1 m) high, and 250 feet (76.2 m) long," which contained 161,000 cubic feet (4,600 m^3) of alluvium.

Before the middle 1880's, the channel of the Rio Puerco and the channels of its tributaries were small and inconspicuous. Bryan and Post (1927) estimated the volume of the main channel and its tributaries to have been 22,500 acre feet (2.78×10^7 m^3) before incision and 417,400 acre feet (5.15×10^8 m^3) afterward, therefore net erosion was 394,900 acre feet (4.87×10^8 m^3) in 42 years, or an average of 9400 acre feet (1.16×10^7 m^3) per year. Accelerated erosion also has had an effect on water quality. Wagner (1963) notes a suspended sediment concentration of over 100,000 parts per million (ppm) in the Rio Puerco of which 50 percent was clay sized particles. The capacity for transport of sand is tremendously increased with a high concentration of fine sediments. Nordin (1963) documented a

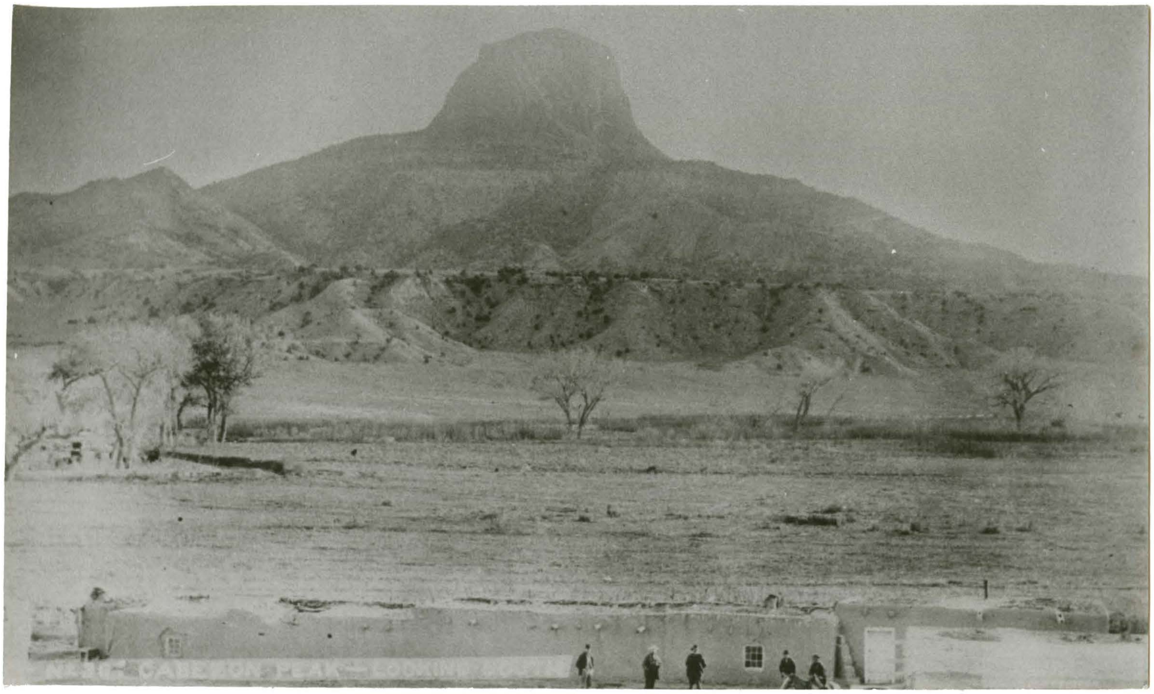
Fig. 2-1. Mass wasting of the arroyo wall. Cross section 14 at Guadalupe.

30 cubic meter per second (1080 cfs) flow having a sediment concentration of 327,000 ppm with 40 percent of the sediment sand size. In addition he states that the Rio Puerco, because of its high percentage of suspended sediment (40-45%), may transport as much as ten times more sand than the Rio Grande, given the same discharge and provided that such a quantity of sand is available.

Incision and Arroyo Formation

Prior to 1885 the valley of the Rio Puerco supported a fairly continuous plant cover. At that time, the arroyo was discontinuous; in places it was very conspicuous with walls up to 20 feet high, whereas elsewhere the banks were obscure. During floods, most of the valley floor was inundated and the channel was free to shift its course. Natural hay fields, irrigated by floodwaters, could be found in the valley and they were, as late as 1895, a source of fodder for liveries in Albuquerque. Several small communities existed along the upper and middle reaches of the Rio Puerco; their livelihood based on crops of wheat, corn and beans and upon livestock (Bryan, 1928 a).

Sometime between 1885 and 1890 the channel of the Rio Puerco began to incise. Shallow reaches deepened and formerly discontinuous gullies rapidly coalesced into one long trench with disasterous effects on agriculture and grazing (Fig. 2-2). Through conversations with former inhabitants and other sources, Bryan (1928 a) was able to date the abandonment of several communities and hence the approximate time of trenching at various locations along the river. From his interpretation the deep channel of the Puerco was generally formed from the mouth



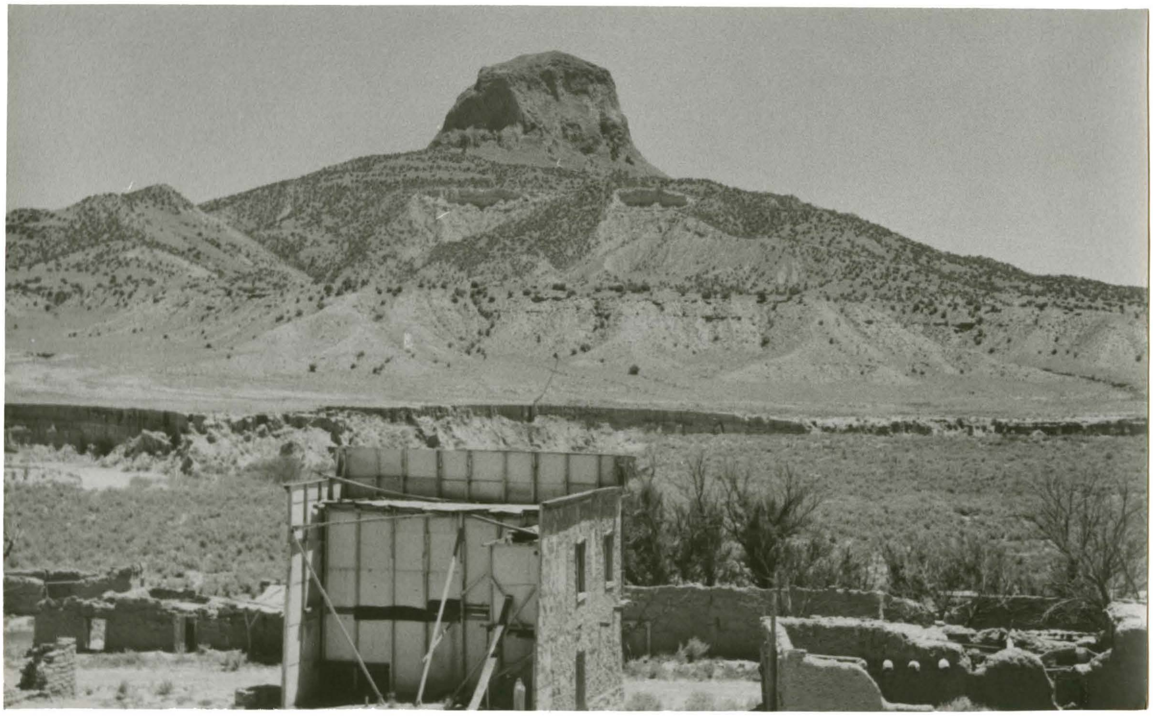


Fig. 2-2. Incision of the Rio Puerco at Cabezon. Top E.A. Bass, 1885; bottom, H.E. Malde, U.S.G.S., 1977.

headward, with most of the incision occuring in the late 1880's. At the time of his writing the entire length of the river had been trenched. The valley floor had been abandoned as the flood plain, and rejuvenation of tributaries and widening of the main channel was in progress. Bryan and Post (1927) state the movement of a headcut in a tributary may proceed as quickly as 50 to 100 feet per year. Centainly the ecology and hydrology of the valley were rapidly changed once incision began.

Factors that could have initiated incision in the Rio Puerco valley have been proposed by several authors. From a careful reconstruction of historic events, Bryan (1928 a) concludes the increased erosiveness of runoff resulting from depletion of natural vegetation by overgrazing is responsible for arroyo cutting. Large scale settlement of the Rio Puerco valley began in the 1870's following the conquest of the Navajos. After 1880 the area was "fully stocked with cattle," and destructive erosion followed promptly. In New Mexico there was a considerable fluctuation in precipitation between 1850 and 1870 and, for the next three decades, rainfall was generally below average, except locally during the wet years of 1881, 1884 and 1897. Antevs (1952) believes natural vegetation could have endured the dry spell, thereby maintaining the integrity of the valley floor, had grazing not been introduced at this critical time.

Flooding could have been responsible for enlarging the channel at several locations in the watershed. Bryan (1928 a) has documented two instances near Cabezon where diversion of flood flows by man-made structures resulted in local scouring of the channel.

Changes in the channel pattern or bed elevation of a major stream can have a pronounced effect on its tributaries. A lowering of the bed, such as that following a meander avulsion, has the effect of lowering baselevel for tributaries entering nearby. Nordin (1964) determined that a recent headcut in the Rio Puerco was initiated by local scour and the formation of a plunge pool in the Rio Grande. Incision of the Rio Puerco channel also could have been triggered by an artificial cutoff of the Rio Grande near San Acacia. The river was rerouted and shortened by 1-1/2 or 2 miles to avoid bridging it in two places when the railroad was being built in 1880 (Happ, 1948).

No one factor appears to be dominant in triggering the destructive erosion of the late 1880's. For the purposes of this study, it is best to conclude that the interaction of a number of variables, both natural and man induced, is responsible for exceeding the erosional threshold of this valley.

The Arroyo of the Rio Puerco

Today, in the valley of the Rio Puerco, the arroyo is very conspicuous and its presence continues to affect the distribution of vegetation in the vicinity. Habitation along the river consists mainly of scattered ranches, but in only a few places on the old valley floor is there substantial grazing land. Much of the pre-incision valley near the arroyo is severely gullied (Fig. 2-3), and large blocks of alluvium periodically calve from walls of the trench.

When traveling along the Rio Puerco, one may observe the arroyo in different phases of enlargement. In the upper reaches, and where major sediment carrying tributaries enter, the arroyo is broad and

Fig. 2-3. Gullying along the arroyo margin. Near cross section 15.

its margins precipitous. The channel flowing within the arroyo is wide and shallow, and its banks are easily erodible and poorly defined. Here the Rio Puerco carries much sediment and the river is often characterized by transverse bars and a braided channel that is prone to frequent shifting (Fig. 2-4). Vegetation is generally scarce or youthful, being eradicated periodically by floods. Anastomosing channels and dissected transverse bars characterize these sediment choked areas during periods of low flow.

Channel shifting and relocation of the site of impingement of flow against the arroyo wall is common during high discharges. The result is that most of the arroyo margin in a given reach is being actively eroded, or has been so recently, and large piles of fresh debris at the base of the riser await entrainment by the next large discharge event. For the sake of brevity, reaches of the arroyo that exhibit such a morphology and which are being rapidly enlarged by lateral erosion will be referred to as "Type 1" reaches. Type 1 arroyo cross sections are illustrated in Figure 2-5.

Downstream a broad, terrace-flanked arroyo having a breadth often in excess of 400 meters replaces the Type 1 arroyo, and it is referred to as a Type 2 arroyo. The well defined channel flowing through this inner-valley meanders with occasional shifts or avulsions, and in most places is flanked by dense stands of salt cedar (Fig. 2-6). Vegetation on the adjacent flood plain and lower terraces is less dense, but it is in striking contrast to the barren appearance of the highest terrace, the pre-incision valley floor. Lateral erosion into recently formed cut-and-filled terraces exposes sandy channel deposits whereas an exposure of the valley fill reveals a much greater

Fig. 2-4. Broad, sediment-laden channel of the upper Rio Puerco. Near cross section 14.

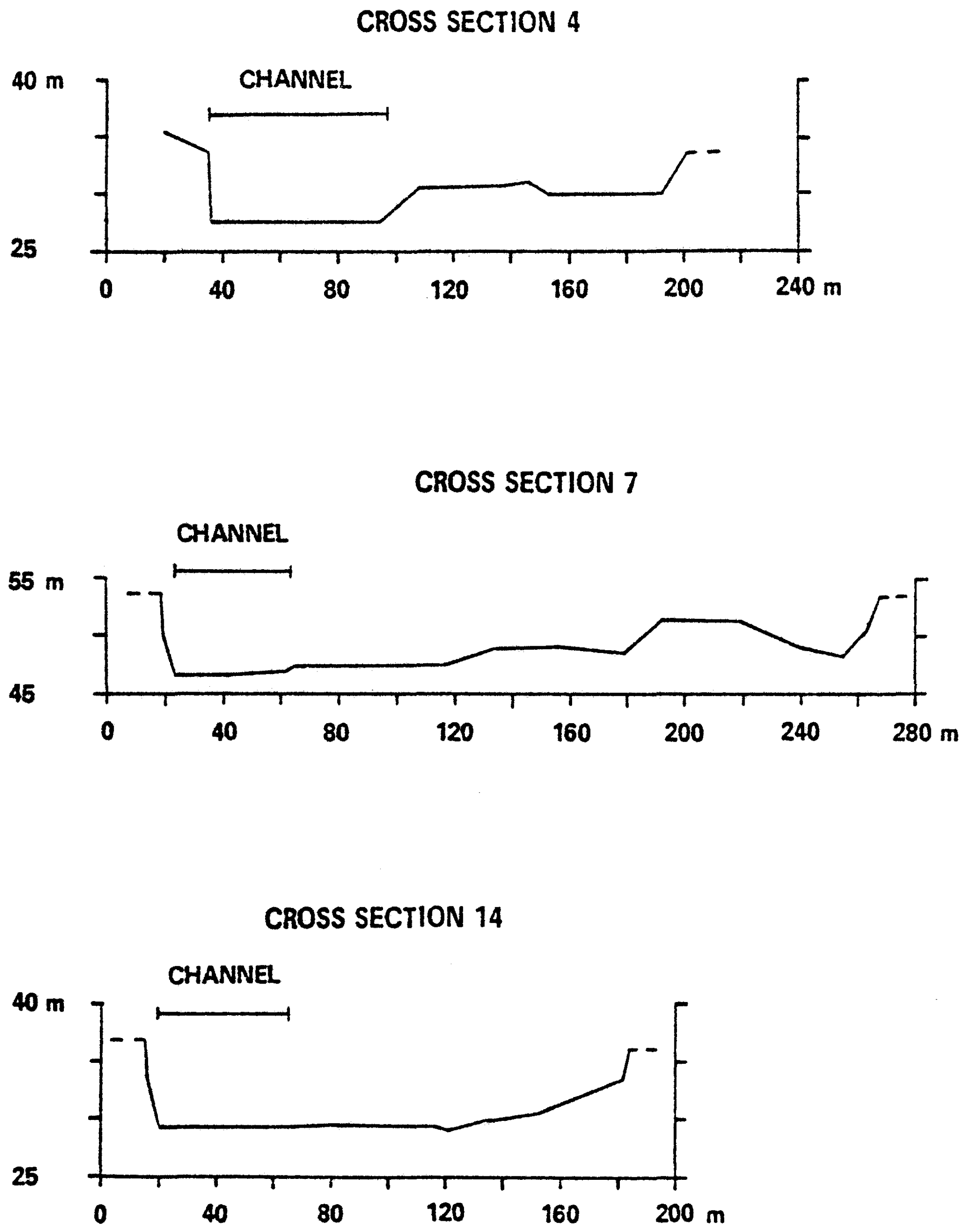


Fig. 2-5. Arroyo cross sections 4, 7 and 14, Type 1 reaches.

Fig. 2-6. Confined channel and vegetated inner-valley of the lower Rio Puerco. Near cross section 29.

amount of silty material. Cut-and-filled channels are discernable from the contrast in sediment type and sedimentary structure. Lateral erosion of the arroyo walls and valley fill is less active than in Type 1 reaches, and when it has been minimal for several decades the arroyo walls have been subject to hillslope erosion and have declined, obscuring terraces and resulting in a smoother, concave inner-valley cross section. Such "Type 2" reaches are illustrated in Figures 2-7 and 2-8.

Data Analysis

Intuitively, morphological differences between Type 1 and Type 2 arroyo phases are readily distinguishable. From the standpoint of scientific investigation, however, it is necessary to categorize the river segments quantitatively. Utilizing Bio-Med program BMD07M, multiple discriminant function analysis was performed to identify the variables best suited for discriminating reaches of the arroyo in a phase of net sediment accumulation and lateral erosion from those reaches that have formed more stable channels in recently deposited alluvium (see page 16). Variables sampled were those used frequently in other fluvial studies: width-depth ratio (W/D), channel slope (S), sinuosity (P), valley slope (S_v), weighted mean percent silt and clay in the channel perimeter (M) and mean radius of bend curvature (r_m). In addition, Brice's (1964) form ratio (L/H) and Folk's (1974) graphic mean grain size (M_z) for both bed and bank aggregate samples were calculated. Sampling techniques are described in the opening chapter, and the values for these variables are presented in Appendix II.

Due to the small sample size, the coefficient of variation was high for some variables. None the less, with combinations of a few

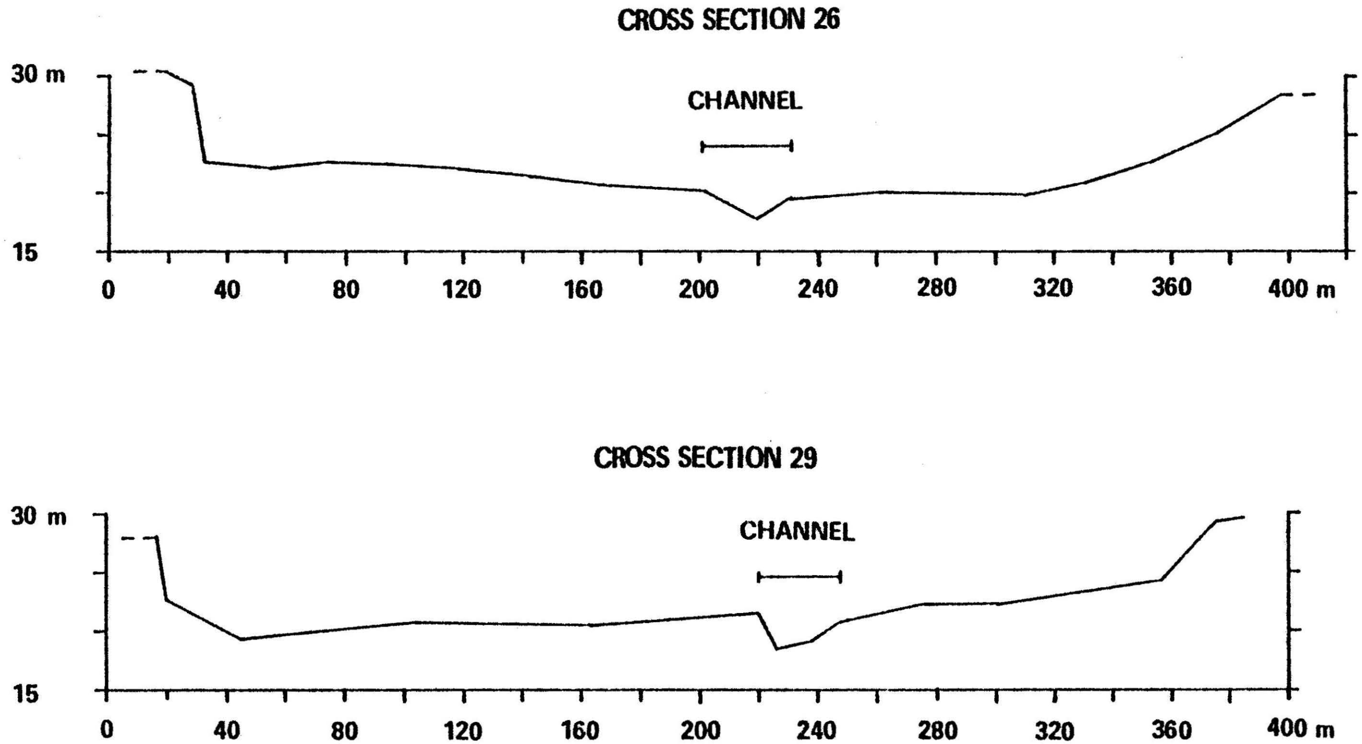


Fig. 2-7. Arroyo cross sections 26 and 29, Type 2 reaches.

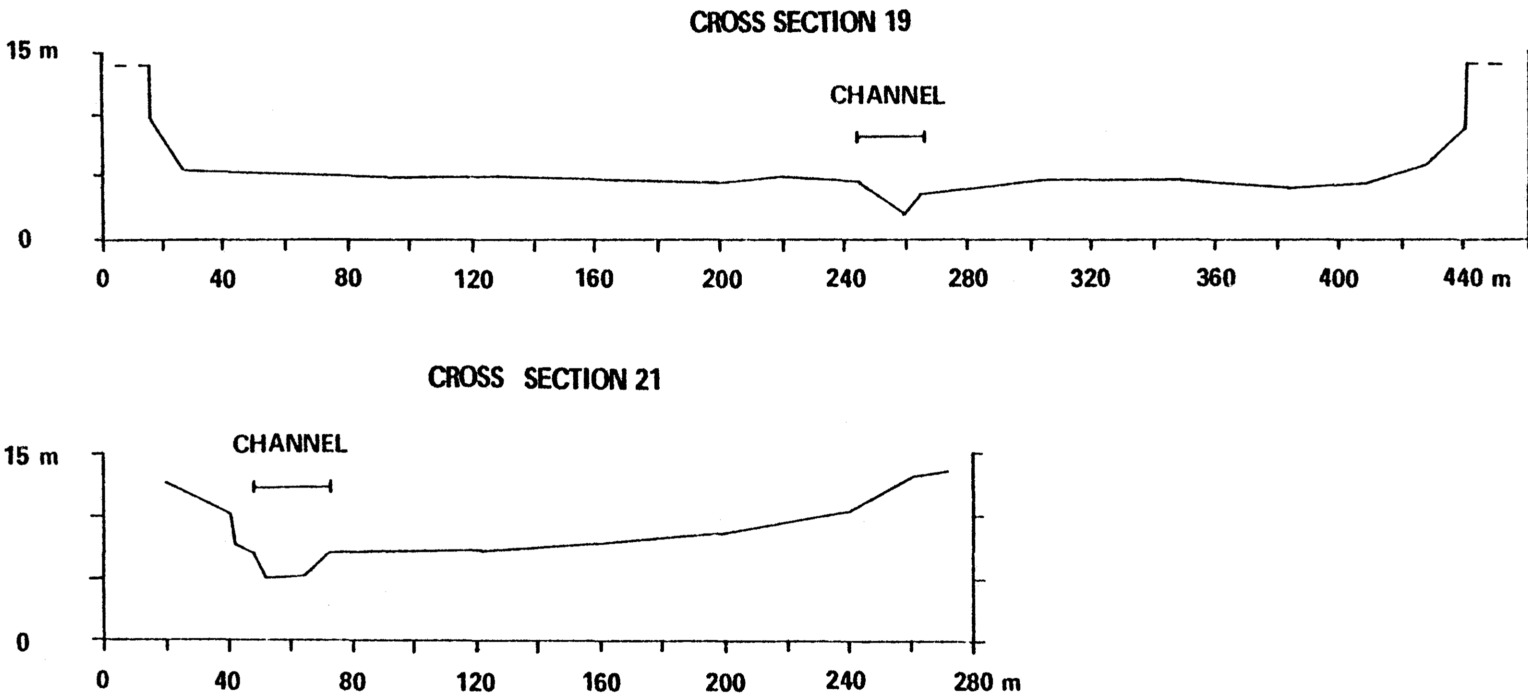


Fig. 2-8. Arroyo cross sections 19 and 21, Type 2 reaches.

variables, samples could be identified as members of Type 1 or Type 2 river segments. Some of the more suitable discriminating variables were those commonly used in previous studies; W/D, S, M and r_m. The results of discriminant function analysis are presented in Appendix III.

Notable differences in channel geometry and pattern exist between Type 1 and Type 2 river segments. Type 1 members were generally broader, shallower and steeper than Type 2 reaches, and they also had a larger bend radius of curvature and a lower percentage of silt and clay material in the channel perimeter (Table 2-1). These pecularities are intimately related to the nature of sediment transported through and stored in a reach.

Absolute channel dimensions are largely controlled by mean annual discharge (Leopold and Maddock, 1953) or by bankfull discharge (Leopold and Wolman, 1957), but sediment load is the determining factor in channel shape and pattern. River morphology and sinuosity are more dependent on the type of sediment load than on the total quantity of material transported, and for this reason the distinction between bed-material load and suspended load is critical. Schumm (1960) has related the percentage of silt and clay in sediments forming the perimeter of the channel, (M), to the ratio of width and depth, (F), by the equation:

$$F = 225\ M^{-1.08} \qquad \text{(Eq. 2-1)}$$

The lower mean W/D ratio of Type 2 river segments is, therefore, a reflection of the higher percentage of fine sediment passing through and deposited in the reach. Mean radius of channel curvature (r_m), measured along the centerline of the bend nearest the cross section,

Table 2-1. Rio Puerco channel characteristics.

Variable	Type 1 Mean	Type 1 Stan. Dev.	Type 1 Coef. Var.	Type 1 n	Type 2 Mean	Type 2 Stan. Dev.	Type 2 Coef. Var.	Type 2 n
W/D	78.3	49.8	.64	13	12.2	2.2	.18	15
S (m/m)	.0032	.0011	.34	13	.0014	.0006	.46	15
M (%)	23.7	13.3	.56	11	44.9	11.8	.26	15
r_m (m)	97.7	29.0	.30	11	69.6	24.8	.36	15
P	1.6	.34	.21	13	1.5	.34	.23	15
S_v (m/m)	.0032	.0008	.26	13	.0019	.0006	.32	15
M_{zc} (mm)	.22	.09	.43	11	.11	.02	.22	15

also was lower in Type 2 reaches. Presumably this is due to the strong correlation between channel width and radius of curvature in many natural river channels (Hickin, 1974).

In another paper, Schumm (1963) illustrated the dependence of sinuosity (P) upon M:

$$P = 0.94\ M^{0.25} \qquad \text{(Eq. 2-2)}$$

Therefore, channels with a higher M should have a greater sinuosity. But the average sinuosity of sampled reaches along the Rio Puerco is about the same for both Type 1 and Type 2 reaches. Apparently the steeper valley slopes of todays Type 1 river segments offset the relatively high Type 1 sinuosity, thereby maintaining a channel slope sufficient for transportation of the given load.

Cross sections illustrating Type 1 and Type 2 channel geometry are presented in Figures 2-9 through 2-14, and may be compared with the arroyo cross sections in Figures 2-5, 2-7 and 2-8.

Linear regression of the width/depth ratio (F) and the mean percent silt and clay (M) of sixty-nine stable channels studied by Schumm (1960) resulted in the equation:

$$F = 225\ M^{-1.08} \qquad \text{(Eq. 2-1)}$$

When data from unstable reaches was included on the same graph, aggrading channels fell above the regression line while degrading channels plotted below it. In addition, the relative distance from the regression line could be used as a rough indicator of a channel's stability.

Rio Puerco cross sections all plotted above Schumm's regression line, and it is conceivable that this distribution of points could be

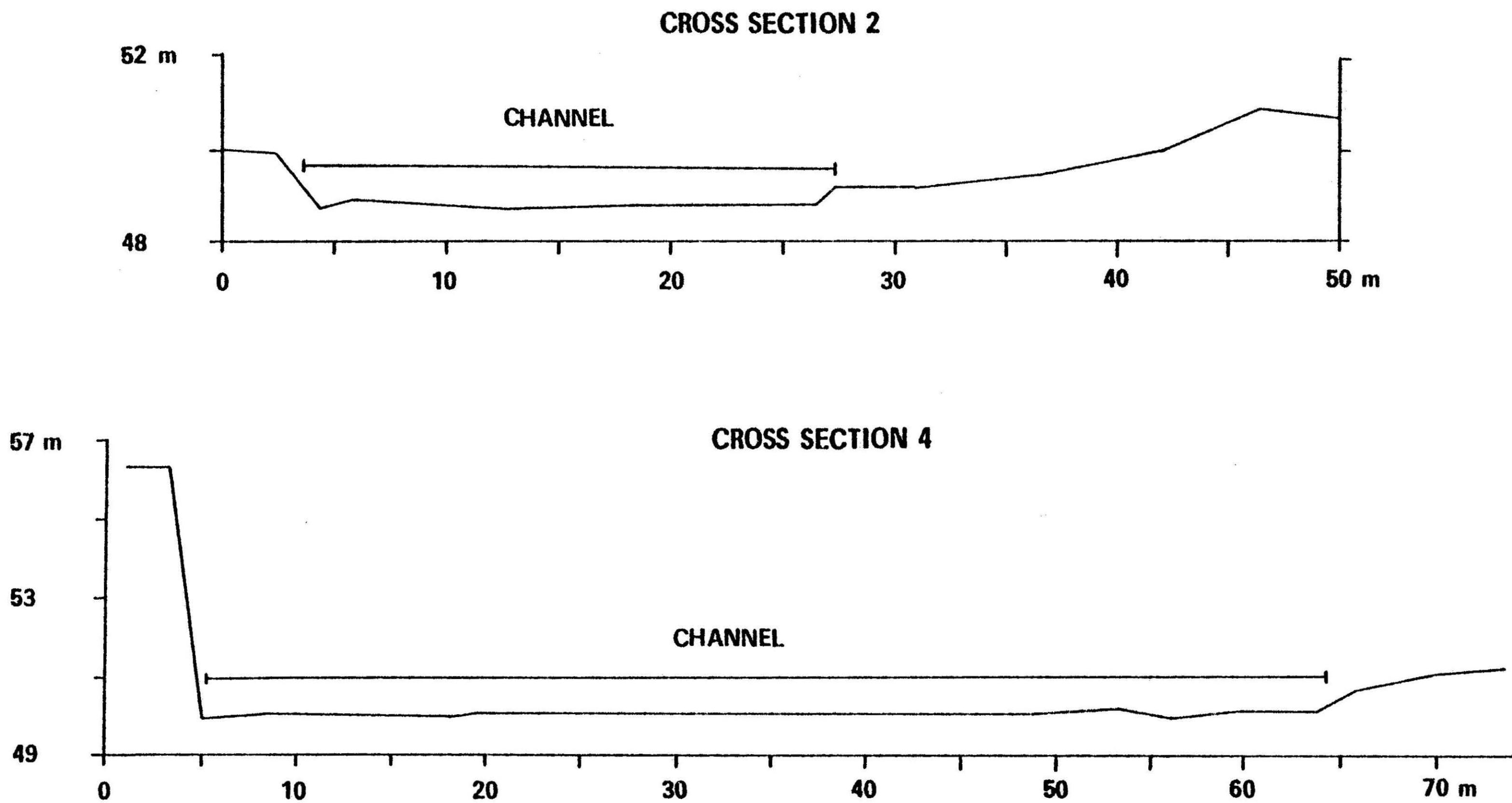


Fig. 2-9. Channel cross sections, 2 and 4, Type 1 reaches.

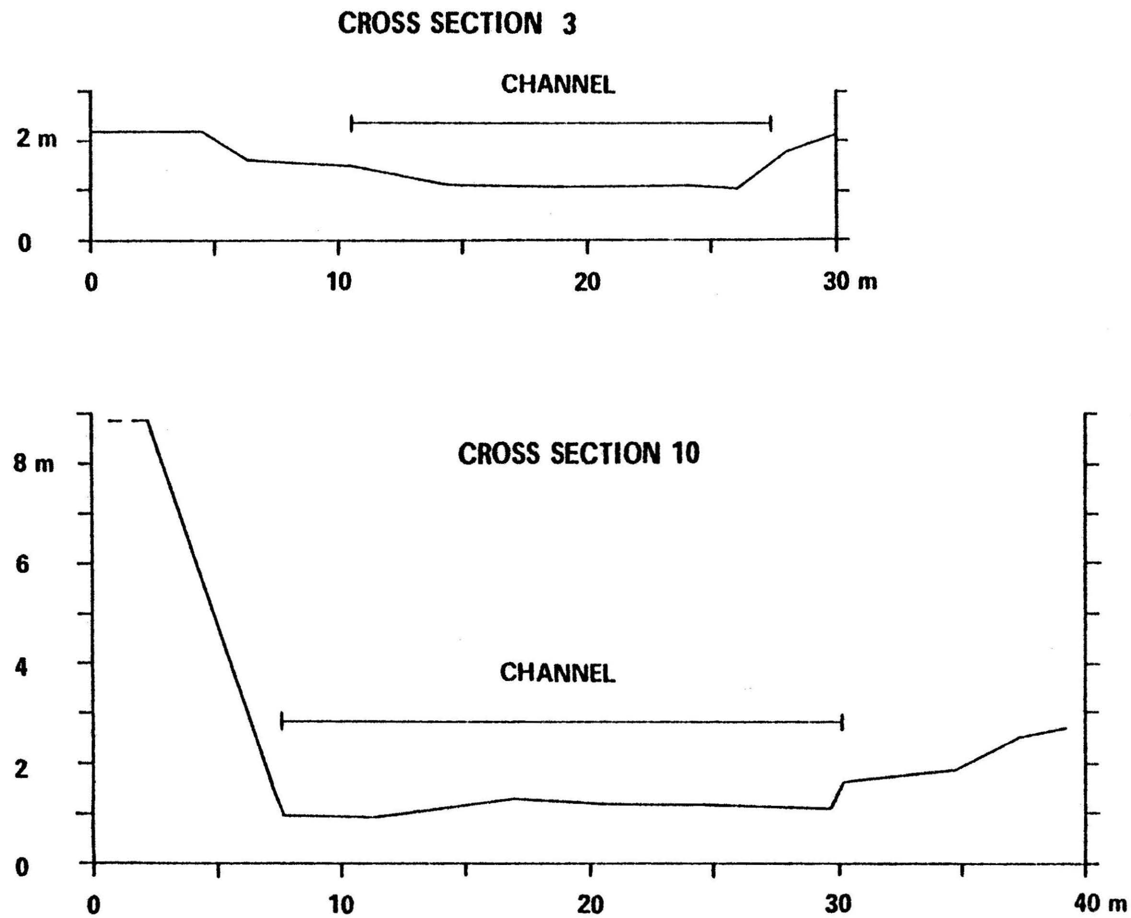


Fig. 2-10. Channel cross sections 3 and 10, Type 1 reaches.

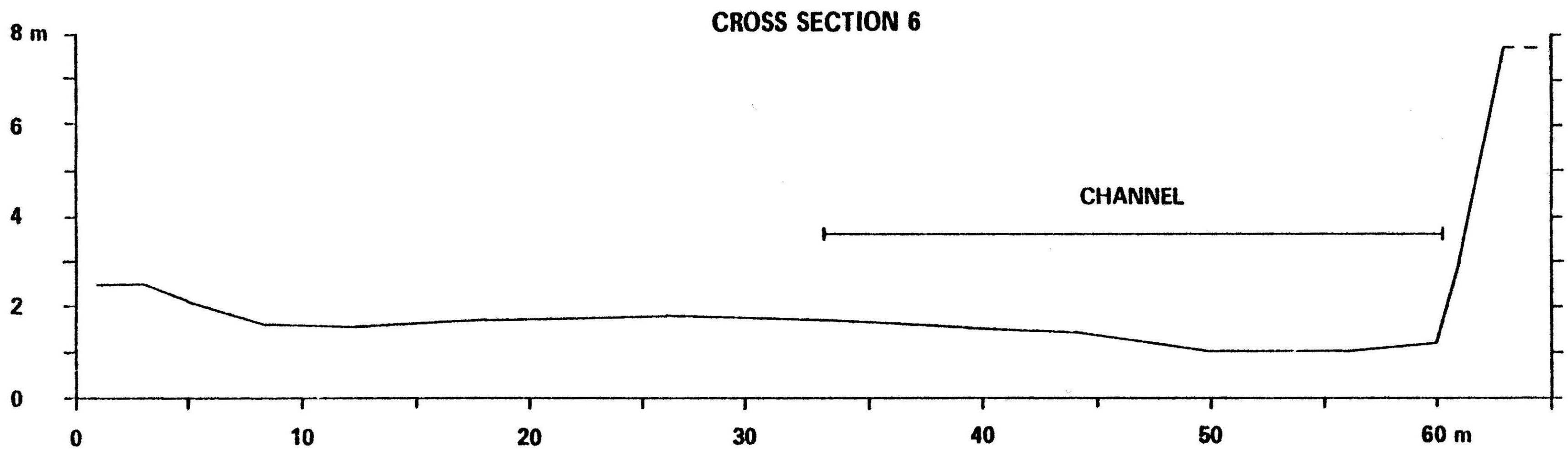


Fig. 2-11. Channel cross section 6, Type 1 reach.

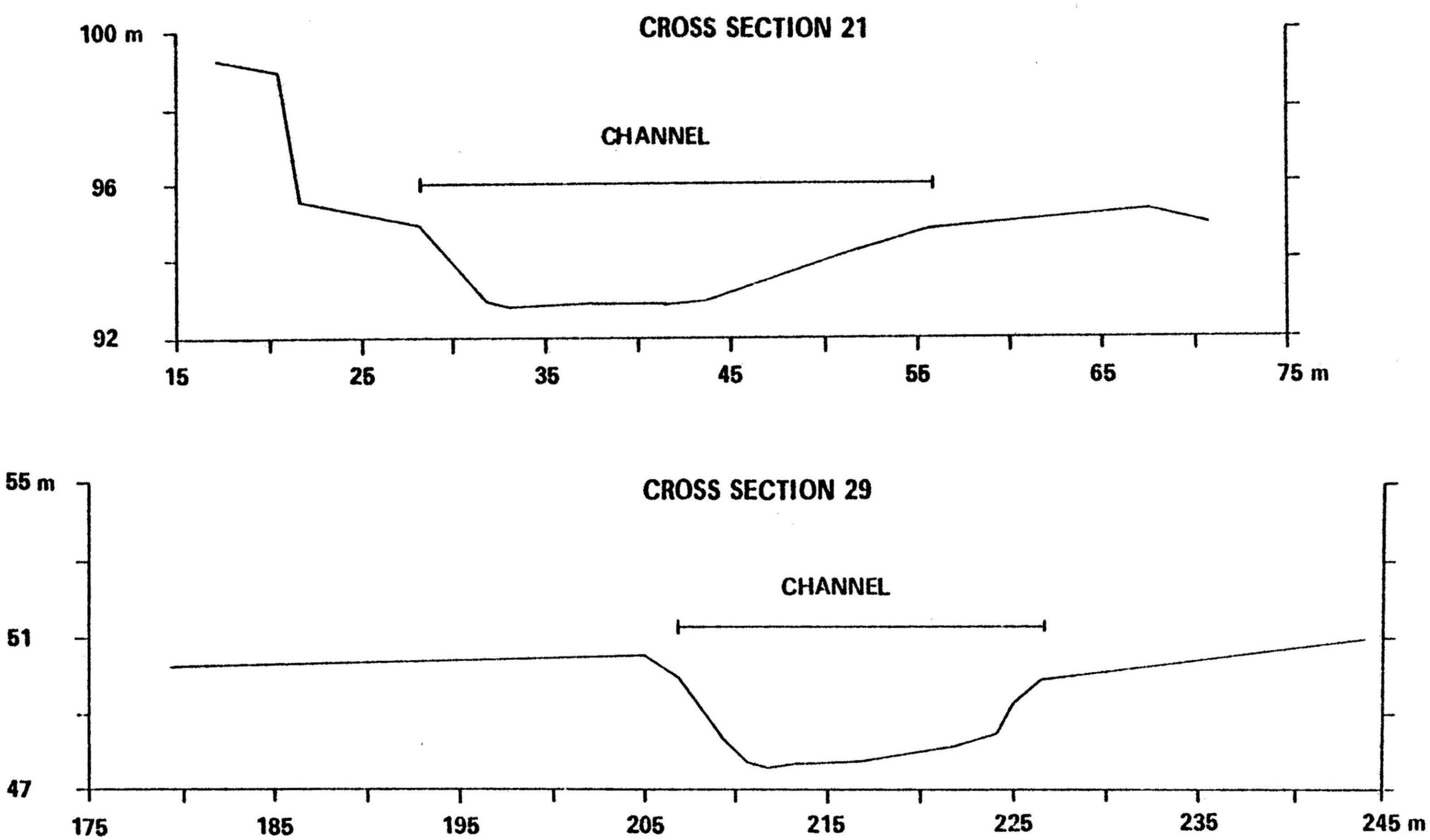


Fig. 2-12. Channel cross sections 21 and 29, Type 2 reaches.

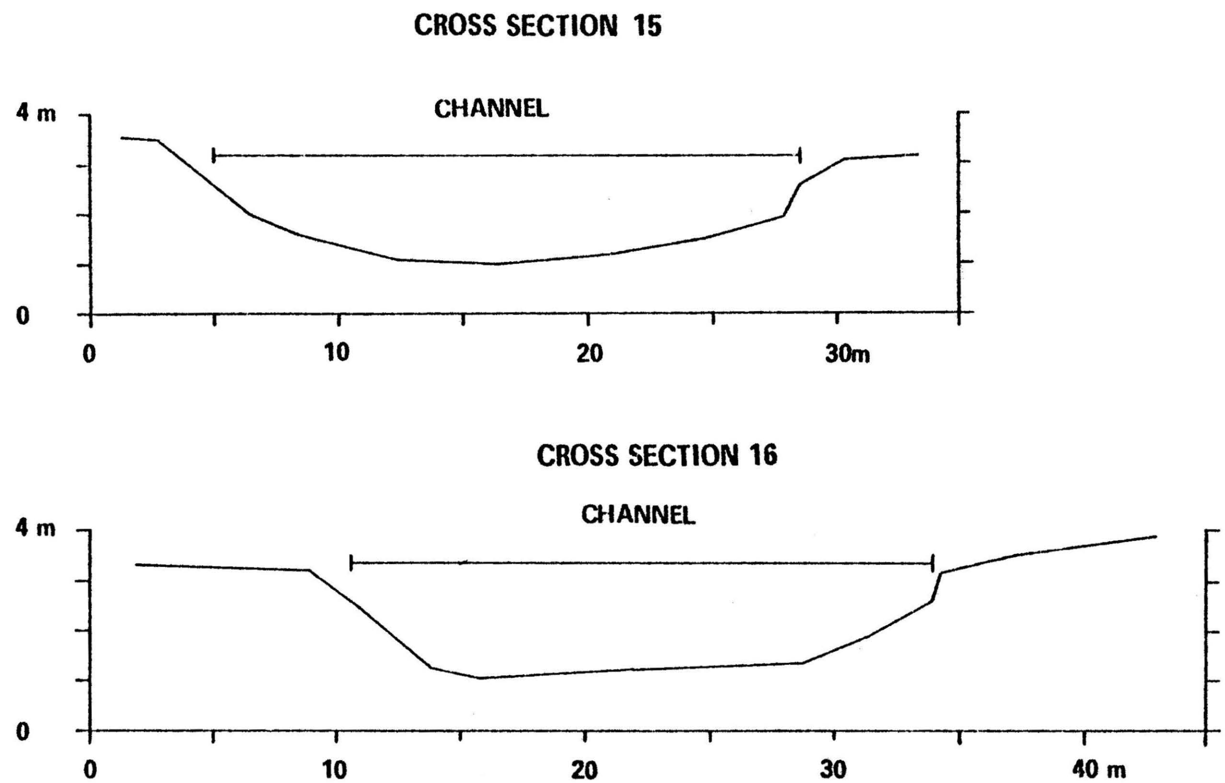


Fig. 2-13. Channel cross sections 15 and 16, Type 2 reaches.

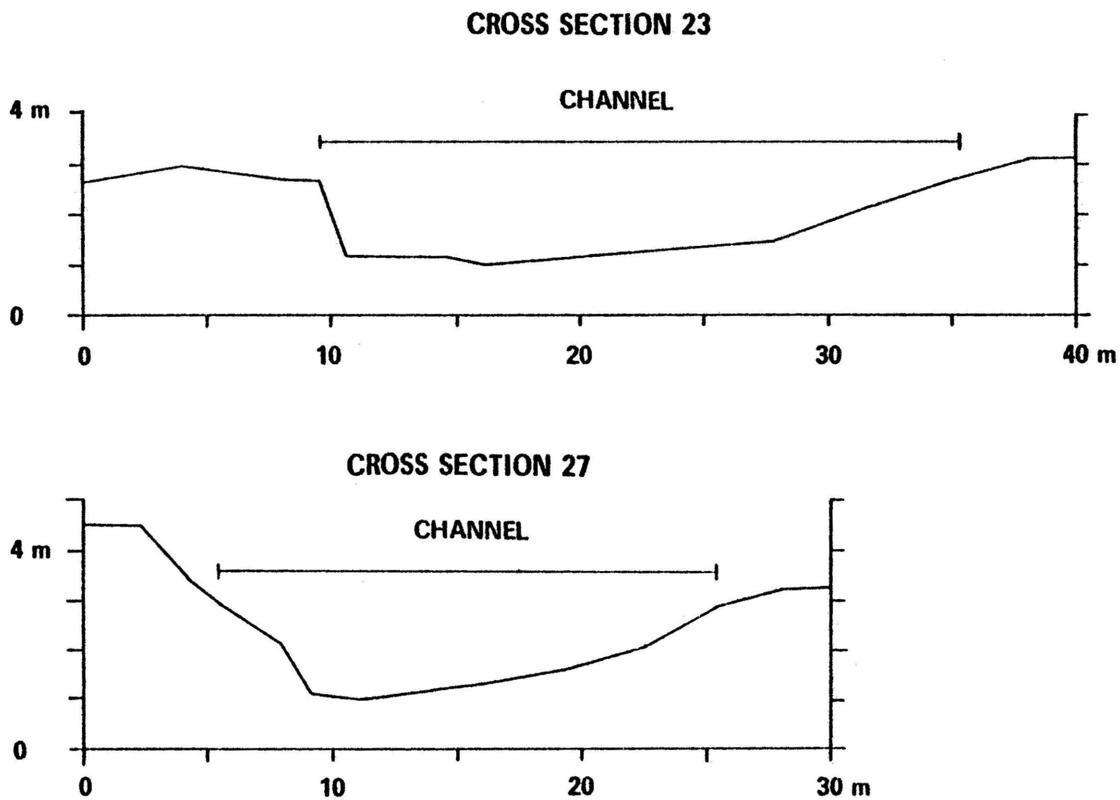


Fig. 2-14. Channel cross sections 23 and 27, Type 2 reaches.

explained by natural scatter. However, it is more probable that most sampled reaches in the New Mexico study area are unstable because they are experiencing some degree of aggradation (Fig. 2-15).

The assemblage of Type 1 reaches involves considerable scatter and most points fall some distance above the regression line. Schumm (1960) notes that a greater scatter of points is representative of sandy channels, or those with M less than about 25 percent. These streams, he states, are generally unstable in flood conditions and changes in bed elevation of a foot or more are common after such an event. Where a channel is very wide and shallow, a small change in depth will cause a large change in the W/D ratio, thereby increasing the dispersion of points. Along arroyo reaches that are eroding laterally, cross sectional area and the composition of bed load are likely to vary considerably due to profuse riser collapse and the mobilization of valley alluvium of diverse make-up. Some scatter of points representing Type 1 cross sections may be due to the nature of sediment sampling. A larger number of samples taken from a traverse where width is great would tend to reduce the influence of a locally clayey or gravelly deposit in the calculation of M.

Regression of Type 2 data resulted in a better clustering of points, reflective of more uniform channel geometry and bed and bank composition. All cross sections plot above Schumm's regression line however. Though in the field these reaches appear more stable than Type 1 reaches upstream, their position on the aggradation side of the line is plausible in light of Patton's (1973) findings. Along lower reaches, the river is still constructing and reworking the new inner flood plain by processes of overbank deposition and point bar building,

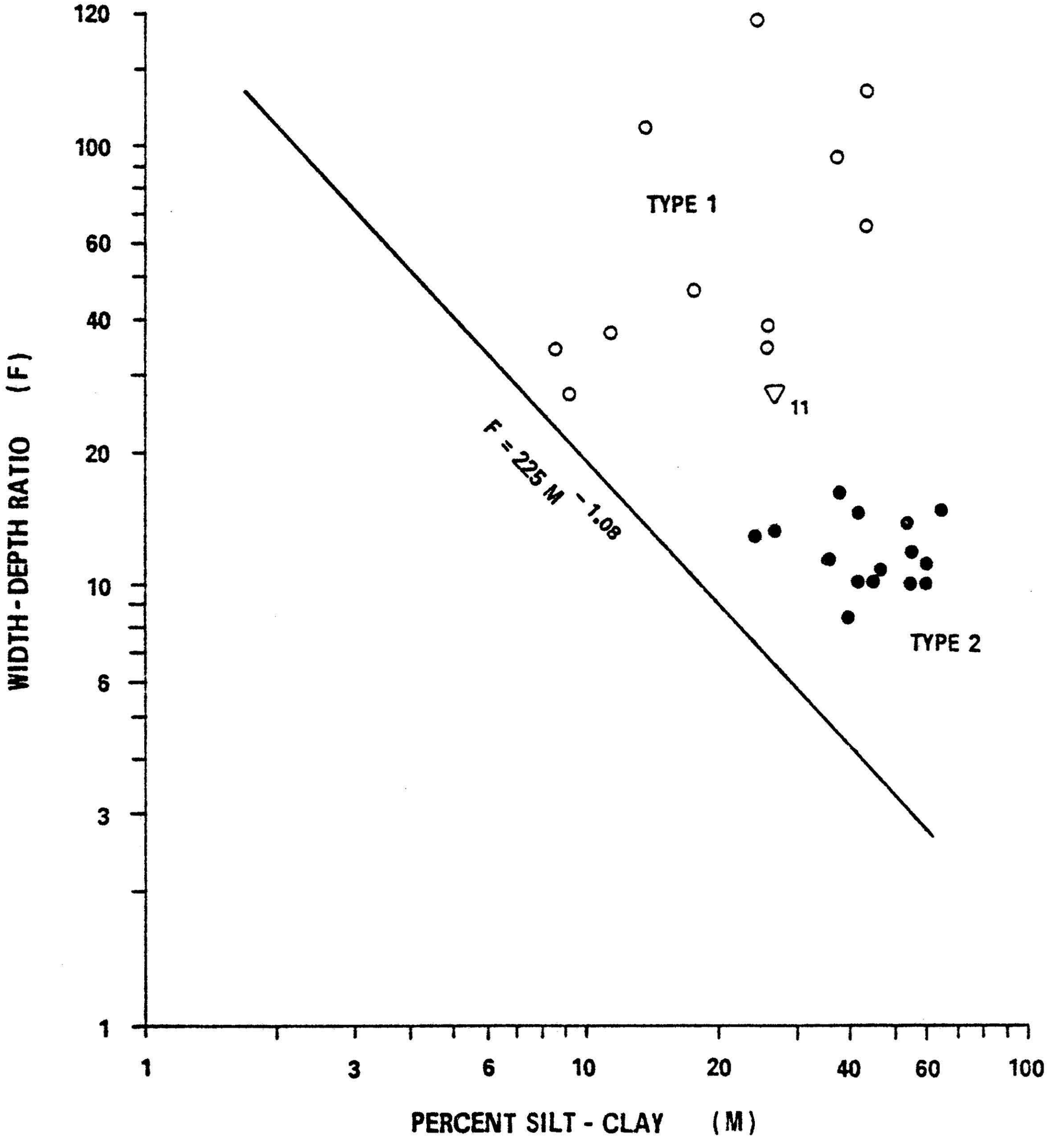


Fig. 2-15. Comparison of Rio Puerco data with Schumm's (1960) regression of width-depth ratio and percentage of silt and clay in channel perimeter.

hence aggradation occurs albeit less noticeably. Lateral accretion in a Type 2 channel lowers the W/D ratio bringing the points nearer to Schumm's regression line.

One sample, number 11 in Figure 2-15, deserves individual consideration. The arroyo and channel along this reach have physical characteristics of both Type 1 and Type 2 phases of evolution. Lateral erosion of valley fill is still active at some locations in this reach thereby mobilizing sediment for transportation. The channel is relatively steep (.0023), but unlike the broad, shallow cross section of a typical Type 1 reach, the river here has a better defined channel with a W/D ratio of 27.7 (Fig. 2-16). Its bed is 1.5 to 2.5 meters below the adjacent terraces which have become well vegetated since 1961 when the channel occupied the left side of the arroyo at a higher elevation.

On the aerial photographs of 1935 and 1954 this segment of the river had the appearance of a Type 1 reach, broad, sandy and without much vegetation adjacent to the channel. When the contemporary values of W/D and M are regressed and plotted, the result is that sample 11 still lies with the Type 1 group, but on the periphery of the cluster and near the Type 2 group. Therefore it appears that the river near section 11 is undergoing a transition from a Type 1 character to a more stable Type 2 condition.

In summary, two phases of arroyo evolution have been observed in the Rio Puerco. The Type 1 phase, in the upper reaches, is characterized by a broad, shallow channel, coarse sediment load and lateral enlargement of the arroyo. The Type 2 phase, in the lower

Fig. 2-16. Cross section 11, the channel in a transitional phase. January, 1978.

reaches, is characterized by a narrow, well defined channel, a broad, vegetated inner-valley, and reworking of flood plain deposits. Regression of W/D and M implies channel aggradation in both circumstances; vertical aggradation in Type 1 reaches and lateral point bar building in Type 2 reaches.

CHAPTER III

ARROYO EVOLUTION AND INNER-FLOOD PLAIN DEVELOPMENT

One objective of this study is to examine the mechanisms and the sequence of morphologic development of a large arroyo. The Rio Puerco became incised sometime in the late 19th century. At the beginning of this most recent epicycle of erosion the arroyo was deep and narrow (Bryan, 1928 a). The first aerial photographs of the Rio Puerco were made almost half a century after rejuvenation of the drainage basin began. By then, most tributaries had been rejuvenated (Bryan, 1928 a) and in the 1935 photos the river appeared choked with sediment for nearly its entire course. Within the trench there was a noticeable paucity of vegetation and in places a braided channel occupied the entire width of the arroyo. Much arroyo enlargement had occurred along the lower and middle reaches. Many river bends had increased in length and amplitude, while in some reaches channel shifting and avulsion formed broad, arcuate terraces.

As observed in the earliest aerial photographs, most of the river was characterized by Type 1 conditions; it was broad, sandy and braided in appearance. When the next aerial photographs were taken in the mid-1950's much of the river exhibited the same conditions, but in some lower reaches the channel was much narrower than in the 1935 photos and vegetation appeared to have become established along banks and on developing point bars. In two decades, a Type 2 mode had begun to supplant Type 1 conditions in the lower reaches, an indication that river metamorphosis was proceeding rapidly (Fig. 3-1).

The propensity for arroyos to broaden after the initial entrenchment has been addressed by several investigators. Following initiation, the maximum depth of a youthful arroyo is quickly achieved, but thereafter little additional deepening occurs despite the presence of easily erodible material (Leopold and Miller, 1956). Removal of valley fill continues at a rapid rate via lateral erosion of arroyo walls rather than by continued downcutting. Cooke and Reeves (1976) and Leighly (1936) have emphasized the general tendency for creation, within an arroyo, of a new channel and flood plain that is capable of accommodating flood events of widely differing magnitudes and frequencies. To carry the discharge, so increased by incision and channelization, an arroyo will adjust by straightening and widening its course. Initial sinuosity is reduced mainly by the attrition of incised meander lobes rather than by the avulsion of entire bends, and width is increased until the arroyo can carry flood discharges "without suffering serious attack on its walls" (Leighly, 1936).

It should be stressed at this time that arroyo widening, owing to shifting of the channel within the arroyo, should not be confused with widening of the channel itself, which occurs when sediment load or discharge are increased. When first entrenched, a channel may flow from scarp to scarp but with continued channel shifting and lateral erosion of valley fill, the breadth of the arroyo will come to greatly exceed the width associated with flow in the channel.

Bryan and Post (1927) suggested that as the main channel and tributaries continue to erode and shift laterally, the arroyo of the

Fig. 3-1. River metamorphosis in the lower Rio Puerco; section 31, T4N, R1E. Top, S.C.S. photo, 1935; bottom, A.M.S. photo, 1954.

Rio Puerco would one day evolve into a broad, valley form similar in appearance to the pre-incision valley but adjusted to a lower base-level. In a more recent study of the Rio Puerco, Patton (1973) has found evidence that tends to corroborate this hypothesis of valley reformation. Along lower reaches of the river, lateral erosion of valley fill has been succeeded by point bar formation and overbank deposition leading to the creation of a flood plain within the broadened arroyo.

Drainage Basin Evolution

Interpreting the evolutionary sequence of any fluvial system is a complicated undertaking. In order to understand the metamorphosis of river channels and major tributaries, one must have some comprehension of erosional processes in the headwater portions of the watershed, for it is here that most runoff and sediment load are derived.

In an experimental watershed at Colorado State University, Parker (1977) was able to observe the response of a stream channel to the development of its drainage basin. Most sediment is produced from only a small percentage of the basin, usually from erosion in channels rather than on slopes (Gregory and Walling, 1973). In the early stages of basin development following rejuvenation, most sediment was produced near the mouth of the basin and was quickly removed. When headcuts and the locus of sediment production advanced up tributaries, the number of streams being eroded increased at a geometric rate and so too did sediment production (Schumm, 1977). The path distance and travel time along channels increased and the efficiency of the basin to evacuate runoff and sediment was reduced. Deposition, braiding and channel widening resulted when the stream was unable to cope with high rates of headwater sediment production.

Runoff, and hence the production of sediment, are proportional to the basin area above the nickpoints (Burkham, 1966). As nickpoints advanced headward and discharge decreased from a progressively smaller catchment above them, the production of sediment also declined. The accompanying decrease in load allowed the main channel to narrow and erode into the alluvial fill, forming a second, lower set of terraces. Thus, the morphology of the stream changed from broad and shallow when excess sediment was stored in the channel, to narrow, deep and more sinuous as the headwater portions of the basin evolved. The cross sections in Figure 3-2 illustrate changes in channel morphology and the formation of terraces following the rejuvenation of a watershed.

Model of Arroyo Metamorphosis

The complex response of Parker's (1977) rejuvenated drainage basin has a parallel in the Rio Puerco watershed, and is useful in describing processes involved in the enlargement of major arroyos. Long-term changes in many large-scale, ephemeral channels can be illustrated by the following model (Figs. 3-3 and 3-4).

Prior to rejuvenation, streams flow through and periodically inundate their flood plains (A). Incision follows, triggered by any combination of natural or cultural factors, and the entire discharge is confined to a narrow and deep trench (B). Highly erosive flows attack the walls of the trench and widening of the arroyo begins (C).

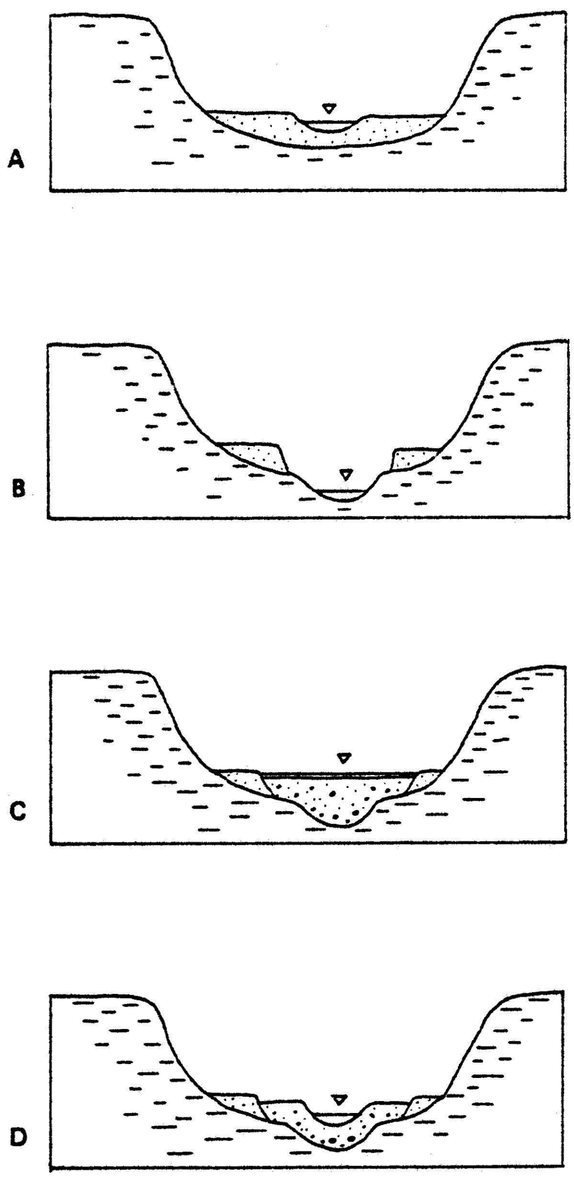


Fig. 3-2. Complex response of an experimental drainage basin (after Schumm and Parker, 1973).

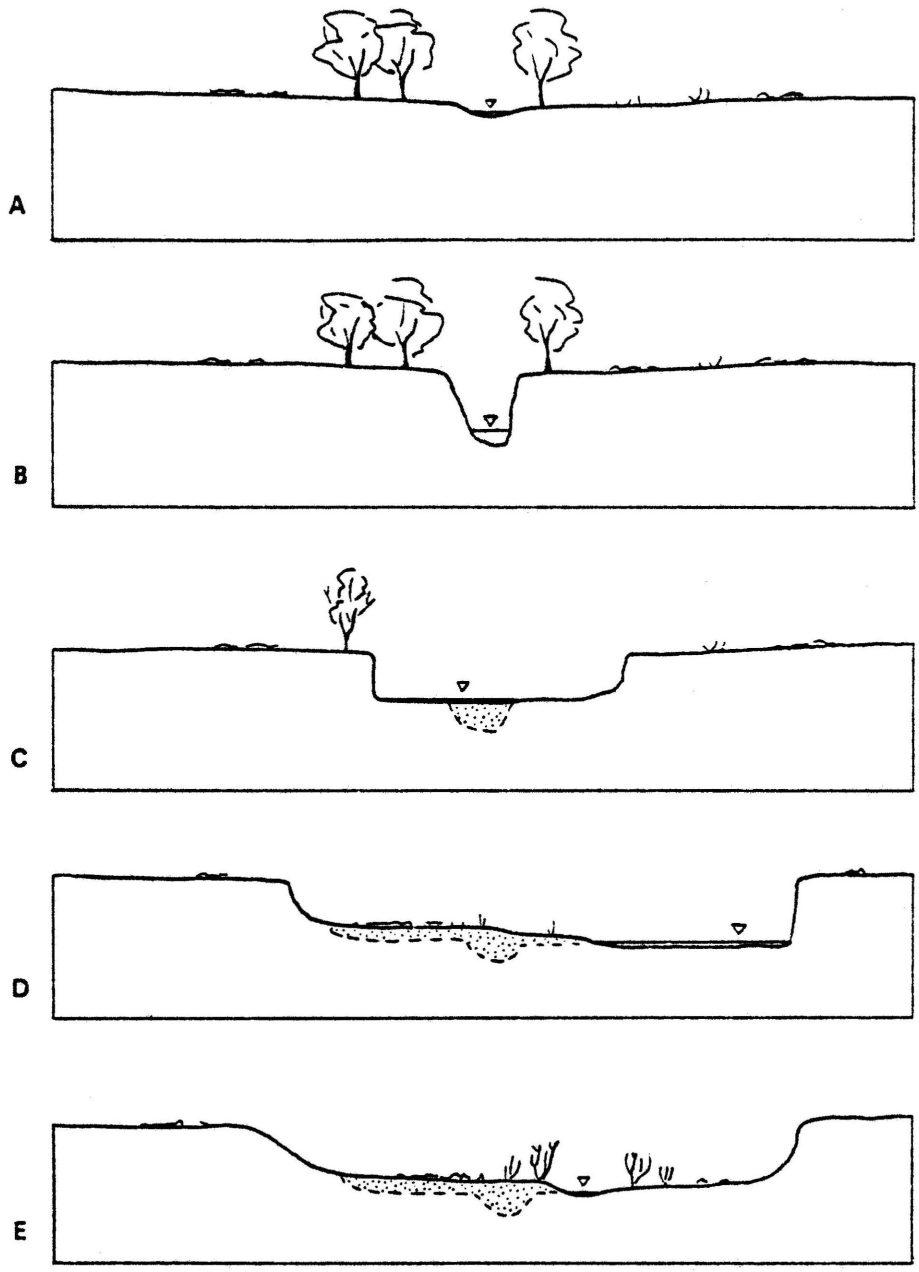


Fig. 3-3. Hypothetical sequence of arroyo cross sections.

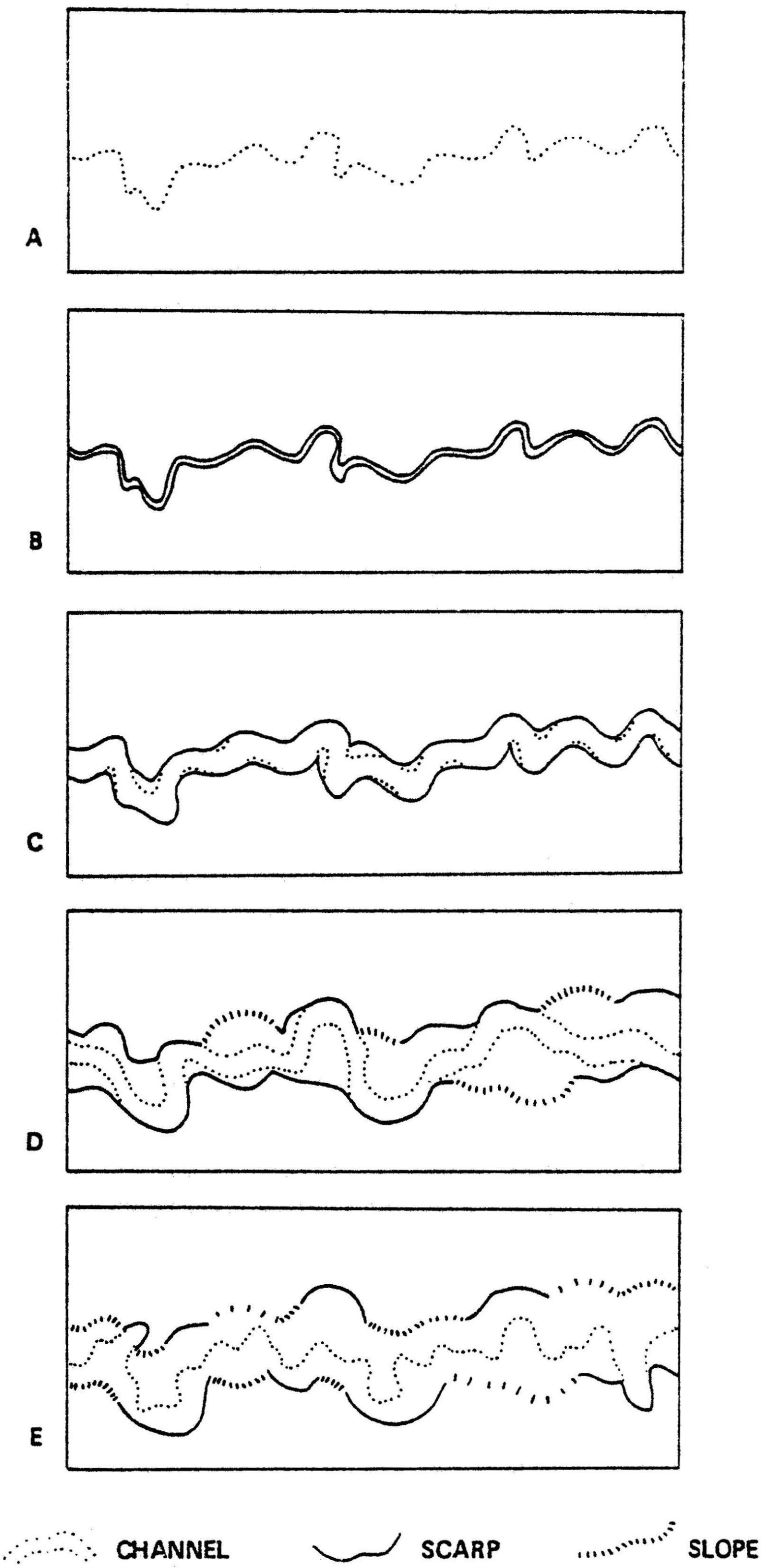


Fig. 3-4. Hypothetical sequence of arroyo plan geometry.

Large quantities of sediment, derived from the rejuvenation of tributaries upstream and from the collapse of arroyo walls, overburden the main channel causing the stream to braid and shift laterally, further widening the arroyo (D).

As the arroyo is broadened, inner-flood plain construction begins with deposition of sediment within and adjacent to the channel. Eventually sediment production diminishes and the magnitude of flood events decreases resulting in a change of channel character from braided to narrow and sinuous. Flood plain construction within the arroyo continues through overbank deposition, the building of point bars and with the establishment of vegetation on these sediments (E). The evolution of the arroyo, now valley-like in proportions, proceeds as scarps are reduced in angle by hillslope processes and as vegetation on the inner-flood plain becomes permanent and diversified.

Arroyo Enlargement and Sediment Mobilization

Upon initial incision, a stream is no longer able to overtop its banks during flood events. Because discharge is then totally confined within a young, deep arroyo, flow velocity, erosiveness and transport ability increase dramatically, as illustrated by the following relation:

$$V \propto \log D, \qquad \text{(Nordin, 1963)} \qquad \text{(Eq. 3-1)}$$

where: V = velocity

D = depth.

The main process in arroyo enlargement is widening by lateral erosion of valley alluvium. Arroyo walls, undercut and weakened by high flows, collapse into the stream and the debris is subsequently removed by the next flood.

As sediment production in tributaries accelerates and as lateral erosion of the main arroyo continues, the amount of sediment introduced to the stream exceeds the stream's capacity to carry it through a reach. Channel modifications ensue that tend to increase the ability of the same discharge to move a larger quantity of bedload (Leopold, et al., 1964). Adjustments in slope and sinuosity will occur if the river is suddenly burdened with a greater bedload. From Equation 2-2, a decrease in the relative amount of suspended sediment will be accompanied by a decrease in sinuosity. Sinuosity may be defined as the ratio of valley gradient to channel gradient, and by definition, a decrease in sinuosity is accompanied by an increase in channel slope. By adopting a straighter course, and thereby increasing its slope, the river has increased its power and capacity to transport bedload. Bagnold (1966) defined stream power, (ω), as the rate of energy expenditure per unit length of stream and may be expressed by the equation:

$$\omega = \tau V \qquad \text{(Eq. 3-2)}$$

where τ = tractive force

V = velocity

and by

$$\tau = \gamma RS \qquad \text{(Eq. 3-3)}$$

where γ = specific weight of water

R = hydraulic radius

S = channel gradient.

Channel roughness, which influences velocity and therefore stream power, is controlled by grain size and bedform (Leopold and Wolman, 1957). To adjust to an increased bedload, or to sediments with a larger mean grain size, bedforms may become less pronounced when velocities approach the upper flow regime (Simons and Richardson, 1966). This serves to increase velocity by decreasing channel roughness (n), and therefore flow resistance. The relationship is illustrated in the Manning equation:

$$V = \left(\frac{1.49}{n}\right)R^{2/3}S^{1/2} \qquad \text{(Eq. 3-4)}$$

Changes in channel geometry also accompany an increase in bedload. Width of flow increases and depth decreases (Schumm, 1977), adjustments that result in a high velocity zone nearer to the bed making flow more conducive to bedload transport (Lane, 1937). In streams carrying mixed sediments, braiding and additional lateral erosion may commence after selective deposition of the coarsest fraction in central or longitudinal bars (Leopold, et al., 1964). Where banks have a low resistance to erosion, these bars may become semi-permanent features (Brice, 1964). Transverse bars, or sand waves, are more common in bedload streams that move well-sorted, sandy sediments. Braiding in these rivers begins by bar dissection when discharge diminishes and the remaining flow loses the capacity to sustain active sediment transport over the entire bar surface (Smith, 1971). Fahnestock (1963) summarizes several studies by stating that braided conditions are "favored by the presence of erodible banks and fluctuations in discharge." Regardless of the mode of formation, braiding is not irrefutable evidence of long-term aggradation; it may, on the other hand, represent an equilibrium pattern in the transport of available discharge and load. But deposition, and therefore movement of sediment, is essential to the formation of a braided pattern (Leopold, Wolman and Miller, 1964), which accompanies widening of the arroyo.

Field observation lends credence to the presumption that arroyos of large drainage basins are widened under the influence of braided, coarse sediment loads. Type 1 reaches are few in which extensive lateral erosion of at least one side of the arroyo is not active at high flow. Fresh scarps and slumped debris continue for hundreds of meters along the convex side of most bends. Much of the load deposited in these reaches is sandy or gravelly and poorly consolidated. Banks and point bars are inhabited only by very young salt cedar and grasses, indicative of, and contributing to the ease with which the channel may reposition itself at high flow (Fig. 2-1). The unstable disposition of these channel segments promotes the enlargement of an arroyo and is a major factor in the evolution of a new valley.

Discharge in ephemeral and intermittent streams has an inherently high degree of variability, particularly so near highland areas. Rapidly fluctuating stages contribute to the instability of the transport regime and to erosion of banks, and therefore tend to maintain a braided channel form (Leopold, Wolman and Miller, 1964). Stevens, et al. (1975), found that rivers with a high ratio of maximum annual discharge to mean annual discharge tend to have a lower sinuosity and a higher width-depth ratio than do rivers with lower peak to mean annual discharge ratios. Such a high ratio is certainly characteristic of most fluvial systems in semiarid regions and especially those whose major tributaries have become incised.

At a low stage, many channels have a thalweg or major anabranch that follows a gently meandering course through what would be classified as a braided reach at higher discharges (Smith, 1971). Fan-like deposits within the channel may impose barriers across active anabranches which divert flow and contribute to shifting of bars and channel alignment at such low discharges (Leopold, Wolman and Miller, 1964). During flood events, or when the active bed is completely inundated, the greatest degree of channel shifting and realignment occurs (Chien, 1961). Low water channels are obliterated and discharge courses through the arroyo in a more direct fashion, unrestrained by banks or vegetation. Stream power increases as the cube of velocity (Bagnold, 1966) and large amounts of bed material are mobilized.

Hickin (1974), and others, have determined that there exists a consistant relationship between width and mean radius of curvature in stable channels, a relationship that is noticeable even in the low discharge channels of braided reaches. It is not beyond reason that a river will attempt to maintain this relationship during flood events, adopting for the duration of the flood a radius of channel curvature compatible with the width of flow, and one that is mirrored in the geometry of the concave arroyo scarp against which it errodes. In as much as the low discharge channel in a Type 1 reach may have a small radius of curvature thereby intercepting the arroyo wall for only a short span, large discharges with a much greater radius of channel curvature and wavelength will erode a more extensive segment of valley alluvium on the outside of a bend. Therefore, it is discharge events of flood proportions that most influence the form of the enlarging arroyo. The presence of broad, arcuate scarps and terraces in association with Type 1 reaches is a function of the breadth and geometry of the flood water channel active at the time arroyo walls were being undermined.

High sediment loads are characteristic of runoff in ephemeral drainage systems. Because much sediment in a Type 1 channel is derived locally, the diverse composition of valley alluvium is reflected in a mixed sediment load. Bed samples in upstream reaches of the Rio Puerco exhibited a high degree of compositional variability and were poorly sorted. Most could be described as gravelly sand with a high percentage of silt and clay material. Leopold, et al. (1964) and Nordin (1963) have demonstrated that streams carrying a high concentration of fines have a greater capacity for transporting sands than do clear water streams as a result of increased viscosity and density of the water. In the presence of a large suspended load, ephemeral streams may periodically move tremendous amounts of sand; between intervals of high discharge and transport, the load is temporarily stored in these braided reaches.

Though a stream with a high percentage of fines may transport large quantities of sand, the limits of a channel's capacity inevitably will be surpassed as sediment production increases in the headwaters, or diminished as discharge is reduced. In addition to the normal decrease in stage as the peak of the hydrograph passes, a good deal of runoff is lost by infiltration into the sandy bed. Such losses may be especially great where the rate of increase in drainage area per unit of channel length is small (Schumm, 1961). Both situations are accompanied by a reduction in discharge and, from Schumm's (1977) relationship, result in a lessening of depth:

$$Q^{-} \propto W^{-},\ D^{-},\ \lambda^{-},\ S^{+}, \qquad \text{(Eq. 3-5)}$$

where: Q = water discharge

W = width

D = depth

λ = meander wavelength

S = channel slope.

Decreased depth also reduces velocity (Eq. 3-4) and stream power (Eq. 3-2), and consequently results in deposition of sediment.

An important distinction is made between aggradation in small and large ephemeral drainages. Aggradation in discontinuous gullies and small arroyos will often result in complete filling of the depression as the cycle of erosion transpires (Schumm and Hadley, 1957). But in large arroyos, such as that of the Rio Puerco, the magnitude of runoff events is great enough to offset any tendency for the channel to aggrade to its former level. In this respect, channels flowing through large arroyos behave more like alluvial rivers than ephemeral streams (Patton, 1973).

Deposition in a Type 1 reach is characterized by vertical aggradation or backfilling of the channel. Though channel gradient may decrease with backfilling, Schumm (1961) observed that gradients were steepened on the lower end of an aggrading reach and that it was on these steeper slopes that trenching of temporarily stored alluvium would first take place. Channel segments downstream eventually become burdened with a new surge of sediment produced by retrenching in a locally oversteepened part of the bed upstream. In this manner, a wave of sediment, and associated braiding and lateral erosion, could be displaced downstream, maintaining Type 1 conditions and continuing the process of arroyo widening.

In summary, upper reaches of the Rio Puerco's main channel are broad and shallow today (Fig. 2-4). The river in many places is braided at low flow and prone to frequent shifts when larger events occur. It is likely that these reaches, and those downstream that were previously characterized by Type 1 conditions, adopted a braided pattern for two reasons; impingement of floodwater against arroyo walls mobilized large volumes of valley alluvium, and recent rejuvenation of tributaries sent a pulse of sediment into a reach unable to transport it. Braiding, and associated Type 1 conditions, may be expected to continue to exist in a reach as long as excessive quantities of sediment are introduced from upstream, and until lateral erosion of the valley fill has enlarged the arroyo to such a scale that flood waters would be carried through it without impinging on either side of the arroyo. In time, as sediment transport decreases and the position of the channel becomes more defined, bank stabilization and the construction of a true flood plain may proceed. Such a transformation is illustrated today in the lower, Type 2 reaches of the Rio Puerco.

Arroyo Maturity

Along most of its length, the arroyo through which the lower Rio Puerco flows is broad and valley-like (Figs. 2-7 and 2-8). Adjacent to the channel, vegetation is noticeably more profuse than it is in the upper reaches (Fig. 2-6). Most enlargement of the arroyo occurred earlier this century when the channel was characterized by Type 1 conditions. Since then the channel has undergone a change of morphology; it is narrower and it is less prone to abrupt shifts during high discharge events (Fig. 3-1). Changes in channel position generally proceed in a relatively continuous fashion as meander bends migrate down-valley. Bend radius of curvature, like channel width, has decreased, although the sinuosity of these reaches has undergone little change.

Although the channel occasionally flows against the base of the arroyo wall, lateral erosion into valley fill is relatively infrequent and hence only small quantities of alluvium are introduced to the stream in these reaches. Sediment transported through Type 2 reaches, reflected by the value of M, consists of high concentrations of silt and clay in suspension and fine sands (Table 2-1). At the present, the coarsest sediment is produced and stored upstream in the Type 1 reaches. Because there is a high percentage of fine material in the Type 2 channel, banks and point bars are more resistant to erosion, and the W/D ratio is small (Figs. 2-12 through 2-14).

In more mature reaches of the arroyo, where an inner-flood plain has formed, the fluvial processes are common to all "stable" alluvial rivers. In a meandering channel, local shear and energy loss are concentrated in the zone of greatest curvature (Langbein and Leopold, 1966), although it is generally accepted that the loci of maximum bank erosion and point bar deposition occur just downstream of the axis of symmetry in a bend (Hickin, 1974). Therefore, in an equilibrium situation where the amount of point bar deposition equals the amount of bank erosion, meanders are inclined to shift downstream, changing position but maintaining a constant pattern and cross section. When the channel flows through uniform material there is little tendency for bends to change shape or cut off as they migrate downvalley (Friedkin, 1945). A "stable" river segment, then, is one whose form is uniform but whose position is not.

The Rio Puerco, and all natural channels, flow through material that is not homogeneous. Consequently, rates of bank erosion and channel shifting are not uniform for all stream reaches, hence the pattern of the river changes as meanders migrate. Local variations in alluvial composition and bank erodibility result in deformed meanders and cut-offs as bends migrate downvalley. The course of the stream is irregular at several locations in the lower Rio Puerco exhibiting abrupt changes in channel orientation and bends of exaggerated amplitude (Fig. 3-6). Hickin (1974) observed a general tendency for the radius of curvature of "free meander" loops to increase as the principle axis of erosion became reoriented within the bend. Brice (1974) points out that incision into alluvium and the presence of dense vegetation along stream banks inhibit the shift of meander limbs and cut-offs thereby permitting the amplitude of a bend to increase and the radius of curvature to decrease. The form ratio (the ratio of distance between loop inflection points measured across

Fig. 3-5. Deformed, incised meander below highway 6. A.M.S. photo, November, 1953.

the neck, L, to the height of the bend, H has minimum values when the channel is incised in alluvium or confined by vegetation, ranging from 0.5 to 1.6.

Many of the deformed bends in the lower Rio Puerco occur adjacent to the margins of the arroyo. Apparently the inflection points of the bend in question have become "fixed" by the great thickness of valley fill, preventing the migration of meander limbs. The principle axis of erosion, rather than eroding valley fill at numerous points along the bend, has remained relatively stationary and has assaulted the valley fill at only one point, thus elongating the meander loop and reducing its radius of curvature. The channel pattern of a high amplitude bend may be such that the force of flood waters is focused against the concave bank at the apex of the meander, thus perpetuating the unorthodox growth of an incised meander. Further investigation concerning the mechanisms of deformed meander growth is warranted.

Reduced radius of channel curvature is accompanied by a loss of energy and a decrease in transport ability (Leopold and Wolman, 1960; Langbein and Leopold, 1966). Therefore, some natural limit to the growth of meander amplitude must exist (Friedkin, 1945; Brice 1974). In a study of fluid mechanics in closed conduits and in flume meanders, Bagnold (1966) illustrated the relationship of flow resistance to bend geometry; the minimum resistance due to curvature occuring where the ratio of mean radius of curvature to channel width (r_m/W) is about two. The radii of curvature of preserved meander scrolls in Hickin's field area exhibited very low variation (with a mean r_m/W of 2.19 and a standard deviation of 0.16) and moved him to state that a "sensibly constant ratio of radius of curvature to width influences the pattern of meander growth" in natural river channels. Once a deformed pattern has become established, the incised meanders of the lower Rio Puerco continue to grow in amplitude until such a time that the channel slope and r_m/W are reduced to values that no longer permit efficient flow and sediment transport through the bend. Backwater effects upstream eventually permit a chute cut-off to capture a dominant percentage of flow, and channel pattern and gradient are modified so that hydraulic variables become more suited to the efficient transport of sediment and discharge. The channel geometry of several high amplitude meanders before and after avulsion is depicted in Table 3-1. Figure 3-7 illustrates the growth and avulsion of the deformed meander of Figure 3-6.

There exists a fundamental difference between Type 1 and Type 2 reaches concerning the manner in which the channel alters its position and pattern. Both channels have a tendency to meander and shift laterally. Because the bed and bank materials of a Type 1 reach have low cohesion, and because vegetation is undeveloped, the channel may shift at random during high discharge events and rework inner-flood plain deposits. Hence the position of the channel can change and lateral erosion of the arroyo walls can occur virtually anywhere under these conditions. On the other hand, channel migration or avulsion of a Type 2 reach is more restricted due to the cohesion of banks and dense riparian vegetation. Unless the entire bend is free to migrate downstream, the meander will grow to unstable proportions, leading to an avulsion. The position of former Type 2 channels can be

Table 3-1. Geometry of some high amplitude Type 2 meanders, before and after cut off.

Cross Section	L/H Ratio		r_m/W Ratio	
	Before	After	Before	After
18	0.4	1.1	1.7	2.3
25	1.2	3.2	1.6	5.4
26	0.6	1.2	1.9	3.3
28	0.9	2.1	1.9	2.5
29	1.0	1.2	1.9	3.8

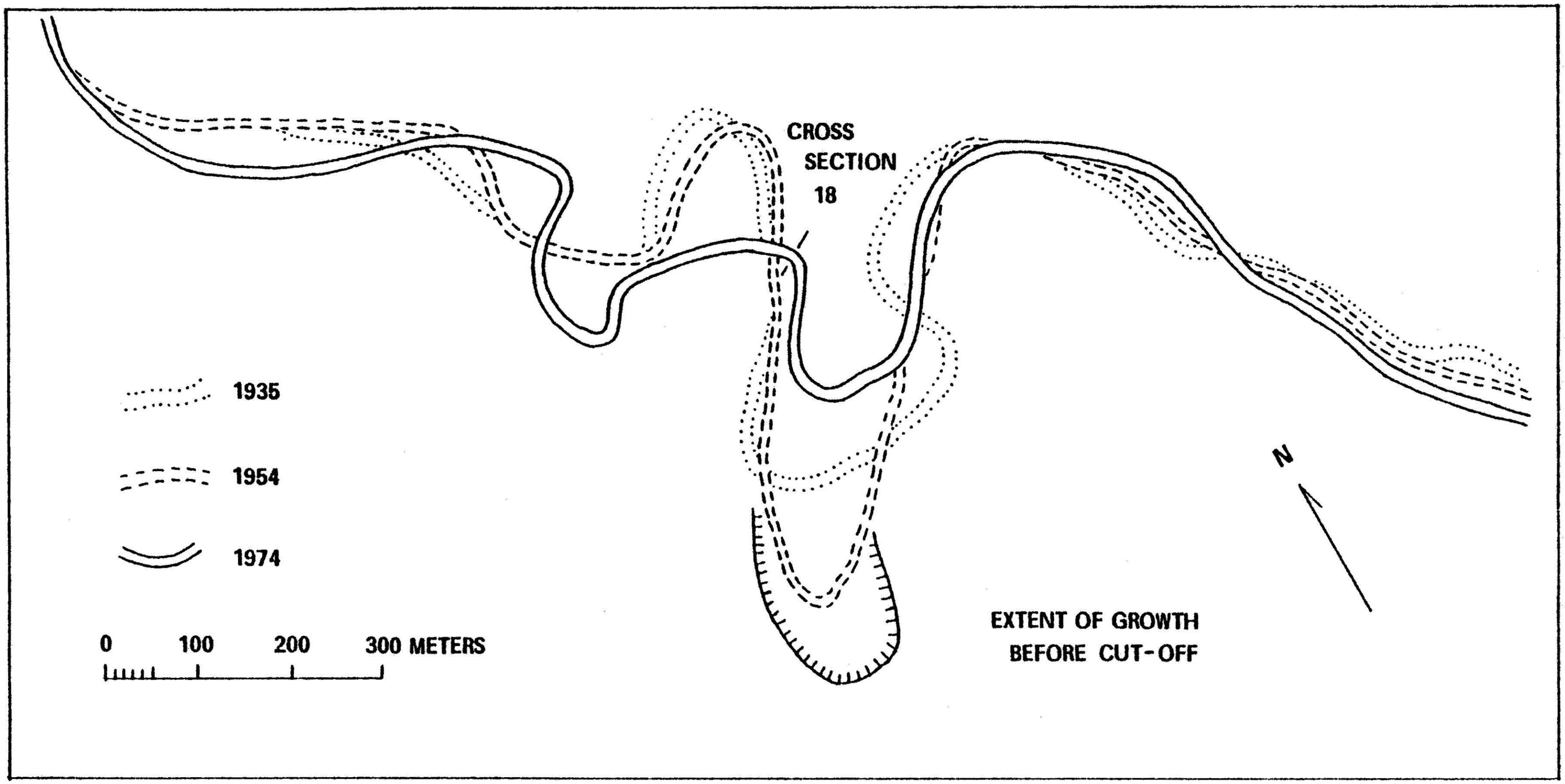


Fig. 3-6. Growth and avulsion of an incised meander, near cross section 18. See Figure 3-5.

determined from the location of parallel rows of salt cedar that once lined the banks, and from terraces that preserve the dimensions of the bend before it cut off.

Erosion of valley alluvium by the growth of high amplitude bends does contribute to the enlargement of the lower Rio Puerco arroyo, but the amount of sediment removal under these circumstances is relatively minor in comparison to that mobilized by lateral erosion in Type 1 reaches upstream. For the most part the channel in Type 2 reaches meanders through deposits of the inner-flood plain and carries predominantly fine sediments. Though a sinuous channel is not normally conducive to bedload transport (Schumm, 1963), alluvium mobilized by reworking of the flood plain or that derived from sporadic erosion of valley fill is moved through a Type 2 reach without noticeable effect on channel morphology. The perimeter of streams carrying a high percentage of silt and clay sized material, such as the lower Rio Puerco, have a great resistance to tractive force (Dunn, 1959), and when the banks of a channel are resistant to erosion, the capacity of a reach for sediment transport is increased, consequently reducing the likelihood of bedload deposition (Leopold, Wolman and Miller, 1964). In addition to enhancing the cohesion of the channel boundary, a high concentration of suspended sediment augments stream power by increasing viscosity and decreasing the fall velocity of larger sediment particles (Nordin, 1963); therefore a high percentage of fine sediment in the flow gives the stream a tremendous capacity to transport any sand that may be introduced into a Type 2 reach. Wagner (1963) has sampled suspended sediment in excess of 100,000 ppm (by weight) near Bernardo which, deposited during recessive stages, creates an armor up to 13 cm

(5 inches) thick on the bed. The small amount of sand carried by the river at this location is easily transported over the armor and out of the system.

Evolution of a Stable Channel

Several factors are responsible for the morphological changes in the lower Rio Puerco that have occurred since the early part of this century. Among them are; changes in discharge and flood peaks, changes in the quantity and nature of sediment load, deposition of cohesive material along banks, and the establishment of riparian vegetation.

In semiarid regions, many stream beds are underlain by a considerable thickness of porous sand and gravel, and a significant amount of water is lost by infiltration into this alluvium. Between the gages at Rio Puerco and Bernardo, 50 km (31 miles) downstream, drainage area increases from 13,364 km^2 (5160 mi^2) to 15,177 km^2 (5860 mi^2), but in the five years prior to 1951, discharge of the maximum annual flood event was as much as 47 percent less at Bernardo as a result of infiltration between these two locations. When discharge decreases, along with transport ability, much bedload is deposited in the channel, but fine material may be carried through. Downstream, the increased concentration of suspended sediment in many ephemeral streams may be attributed to such infiltration in sandy reaches (Leopold and Miller, 1956). Other channel parameters may be affected too if the amount of discharge reduction is sizeable; flow velocity decreases, as do width and depth, and channel slope may increase (Eq. 3-5).

Schumm (1961) has noted the progressive decrease of slope that accompanies backfilling as coarse sediments are deposited in an aggrading reach, but he also observed that much of the finer fraction is ultimately mantled on the steeper areas where the coarsest load was first laid down (Fig. 3-8). In a flume study, Schumm and Khan (1972) found banks and alternate bars became stabilized as the concentration of fine sediment was increased. Applied to a natural setting, deposition of fine sediments permits perennial vegetation to become established, further promoting the stabilization of the channel below a backfilled reach.

A change in the nature of sediment transported and deposited by a river is very important in modifying the channel character. If sediment production from upstream is sufficiently moderated, the channel may gradually outgrow its braided pattern, evolving one with more stable banks and position. The metamorphosis of the lower Rio Puerco has been accompanied by a significant decrease in sediment yield measured at Bernardo, near the mouth (Patton, 1973). An average yield of 33 million tons per year for the period 1887 to 1928 decreased to six million tons per year for the period 1948 to 1968. This reduction may be attributed to: 1) a decrease in the absolute amount of sediment produced in tributaries as the basin matures, and 2) storage of sediment within the system via backfilling in the channel or over-bank deposition on the youthful inner floodplain. Schumm's (1977) relations explain other changes that accompany the evolution of a bedload channel to one that carries predominantly fine sediments,

$$Q_s^- \propto W^-, D^+, \lambda^-, S^-, P^+, \qquad \text{(Eq. 3-6)},$$

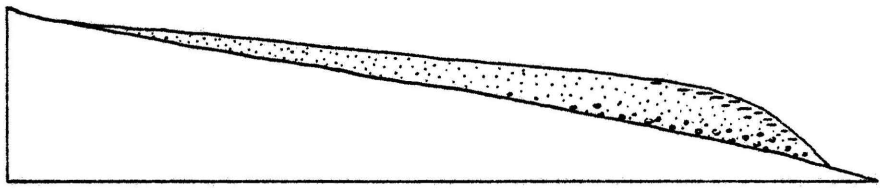


Fig. 3-7. Schematic diagram of sediment in an aggrading reach.

where: Q_s = bedload quantity

W = channel width

D = channel depth

λ = meander wavelength

S = channel slope

P = sinuosity

(+ and - indicate a relative increase or decrease in the parameter).

When bedload is reduced for any reason, the consequent increase in sinuosity and decrease in gradient reflect the stream's need to dissipate energy in excess of that expended in friction and sediment transport. Thus a more sinuous pattern is adopted in which energy is dissipated due to channel curvature (Leopold and Wolman, 1960).

The stabilization of channel configuration is also a function of the nature of water discharge. A reduction in peak annual discharge, or in bedload movement, may result in channel narrowing, a response well illustrated by the Republican River in southwest Nebraska. Drought in the early 1950's and construction of a dam combined to significantly reduce peak discharge until 1957, by which time riparian willows and cottonwoods had become firmly established, reducing the capacity of the channel by more than two-thirds (Northrup, 1965). Although annual runoff from the Cimarron River of southwest Kansas increased between 1942 and 1951, flooding was inconsequential during this time, and as a result, the average width of the Cimarron decreased from 366 meters (1200 ft.) to 17 meters (55 ft.). Anabranches were abandoned, islands coalesced and increased plant cover promoted bank stabilization and sedimentation on the new flood plain (Schumm and Lichty, 1963).

Flood Plain Development

The new flood plain of the Rio Puerco, forming within the arroyo since the incision of the 1880's has a compound origin. As the arroyo is widened, large quantities of coarse material are introduced to the stream. Some of this material is deposited on the bed as the channel becomes overwhelmed by the sheer volume of bedload it is supplied with. Initially, the inner-flood plain is constructed by vertical deposition and backfilling. Along aggrading Type 1 reaches below Cuba, Hadley (personal communication) has observed up to three meters of vertical deposition in the past 25 to 30 years. When a decrease in sediment yield and water discharge occurs the channel becomes narrow and deeper, and the flood plain is further endowed by lateral accretion of fine material along channel margins (Fig. 3-9), while vegetation that takes hold in cohesive deposits promotes additional overbank sedimentation.

Flood plain development is contingent upon several factors. The channel pattern, cross-sectional geometry and flood plain of two major rivers in eastern Colorado have undergone considerable modification following a decrease in sediment and water discharge due to drought and irrigation diversions (Nadler, 1978). Once braided, the Arkansas River, near Bent's Old Fort, today meanders through a flood plain constructed of point-bar deposits. Near Goodrich, the South Platte has been converted from a braided to a single thalweg channel

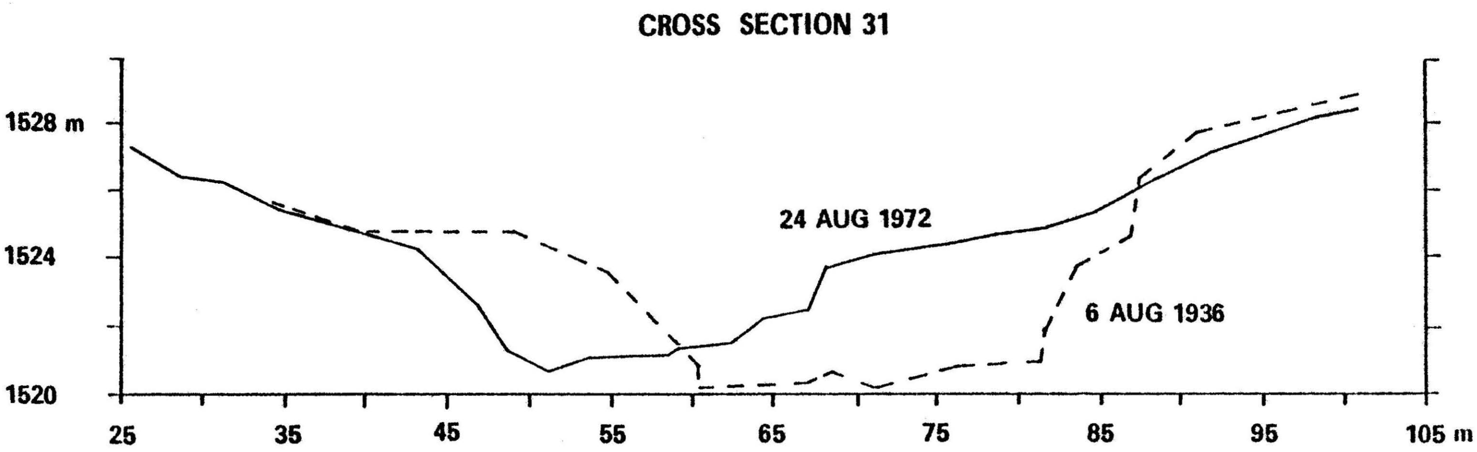


Fig. 3-8. Channel cross sections illustrating point bar development and reduction of width, near highway 6.

with a flood plain composed of a complex sequence of island and abandoned channel deposits. The primary difference in the mode of flood plain construction at these two sites is attributed to sediment type: the Arkansas at Bent's Old Fort has a very high percentage of silt and clay in the channel, while at Goodrich, on the South Platte, this percentage is very low and sediments are poorly sorted.

Transition to Type 2 conditions and flood plain construction in the lower Rio Puerco may also be closely tied to a change in water discharge. When five year moving means are plotted for discharge data from the southern most gaging sites, at Rio Puerco and near Bernardo, three trends are evident (Figures 3-10 and 3-11). To begin with, annual flood peaks decreased noticeably between the 1940's and 1950's and have remained relatively low since then. This may be a result of improved land use and water storage (Hadley, personal communication), or due to infiltration in sandy Type 1 reaches now located farther upstream. Additionally, the cyclic peaks of mean annual discharge have decreased somewhat over the period of record, and finally, the sharp decline in peak discharge coincides with an eight-year period of low mean annual discharge. As in the aforementioned studies of river metamorphosis, changes in the nature of water discharge undoubtedly played an important role in the transition of the lower Rio Puerco's character between 1935 and 1954.

The role of vegetation must also be addressed, it being both an agent and a consequence of bank stabilization and flood plain formation. Below a reach aggrading with coarser sediments, deposition of cohesive material in the channel will tend to stabilize banks and

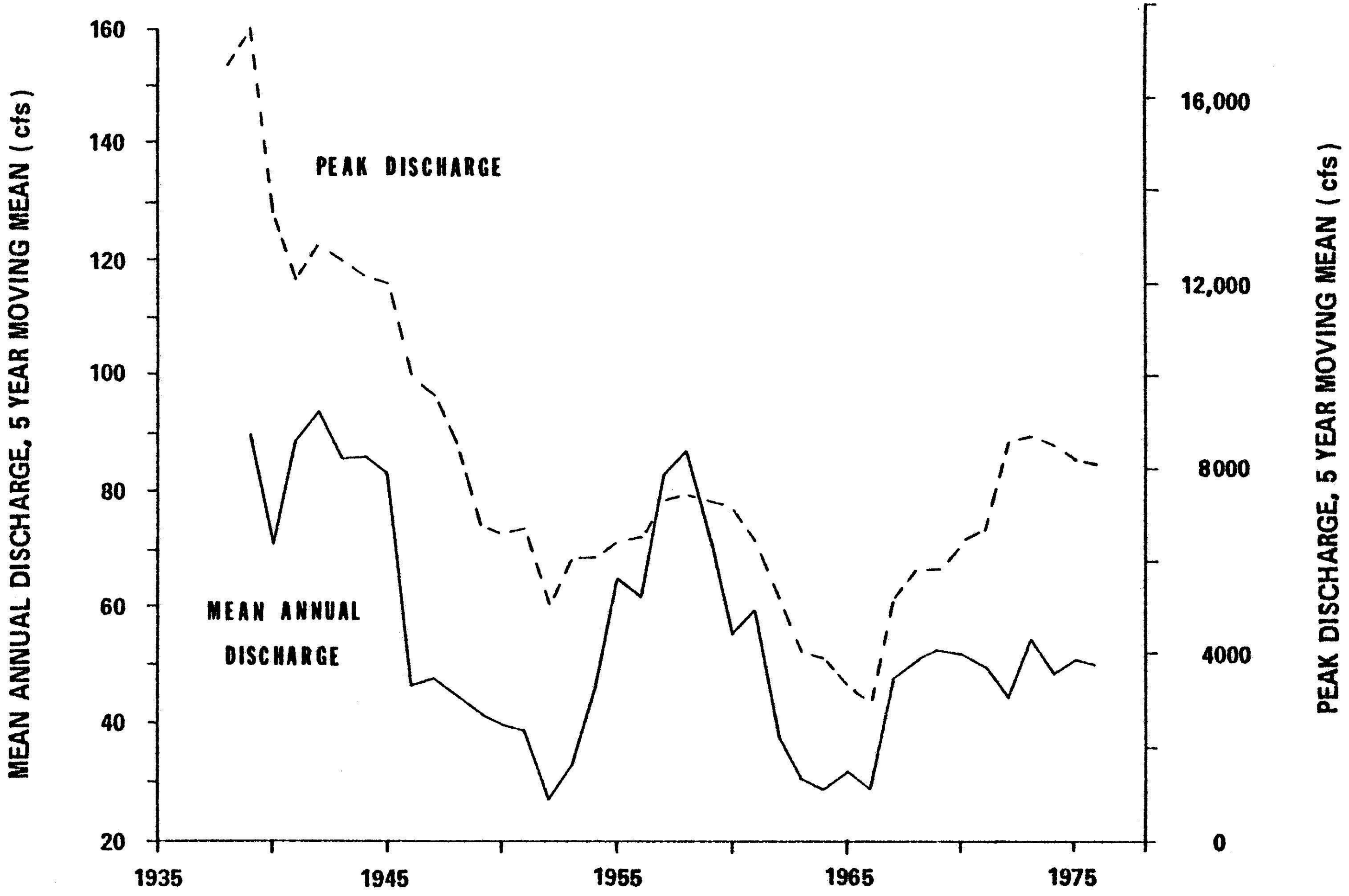


Fig. 3-9. Discharge trends, Rio Puerco at Rio Puerco.

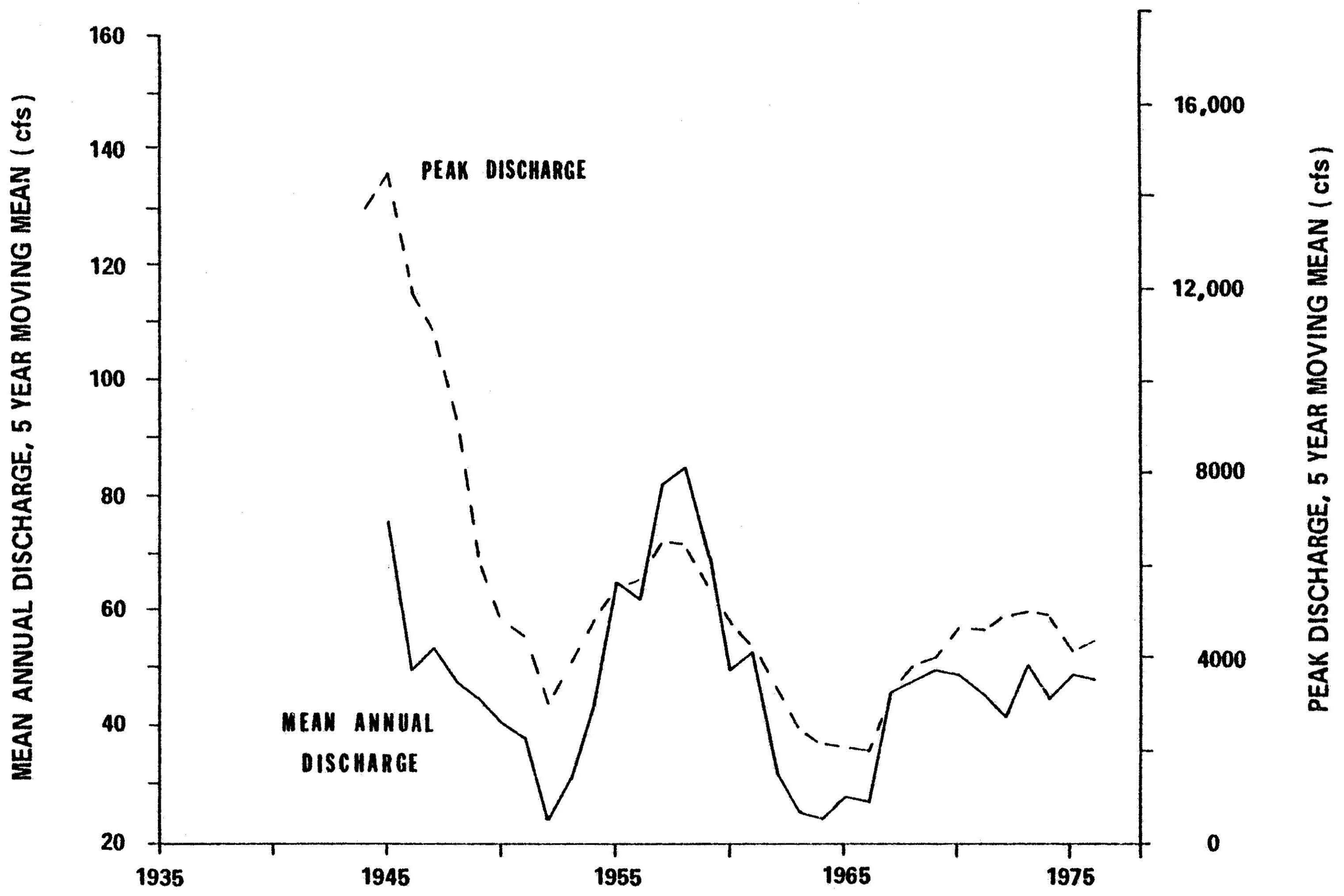


Fig. 3-10. Discharge trends, Rio Puerco near Bernardo.

bars, permitting vegetation to become established (Schumm, 1961). The presence of perennial vegetation increases roughness, prevents scour and aids in further deposition on the inner-valley floor during flood events. Hadley (personal communication) believes the influx of salt cedar in New Mexico arroyos has occurred since the 1940's; a trend visible in the aerial photographs of the lower Rio Puerco and concurrent with the decline in annual discharge values. Wagner (1963) found the roots of salt cedar effective in preventing channel erosion, and indeed this appears to be true for Type 2 reaches of the Rio Puerco where dense growths of salt cedar are almost always associated with channel segments confined by stable banks.

Changes in valley bottom flora are often associated with changes in flow characteristics. A greater base flow and elimination of floods are related in some instances to increased plant density on flood plains of semiarid regions (Leopold, Wolman and Miller, 1964). The establishment of dense perennial growth during periods of reduced flood activity was partly responsible for narrowing the channels of the Republican (Northrup, 1965) and Arkansas (Nadler, 1978) Rivers.

In the lower parts of the Rio Puerco the channel meanders through the older flood plain deposits, modifying them by continual bank erosion and point bar development. Patton (1973) and Hadley (personal communication) have observed that overbank deposition and lateral accretion in the lower reaches are beginning to fill the arroyo, but that the bed is not being raised (Figs. 3-9 and 3-12). Patton states that in large ephemeral drainage systems, such as the Rio Puerco, the magnitude and duration of runoff events apparently offsets the high

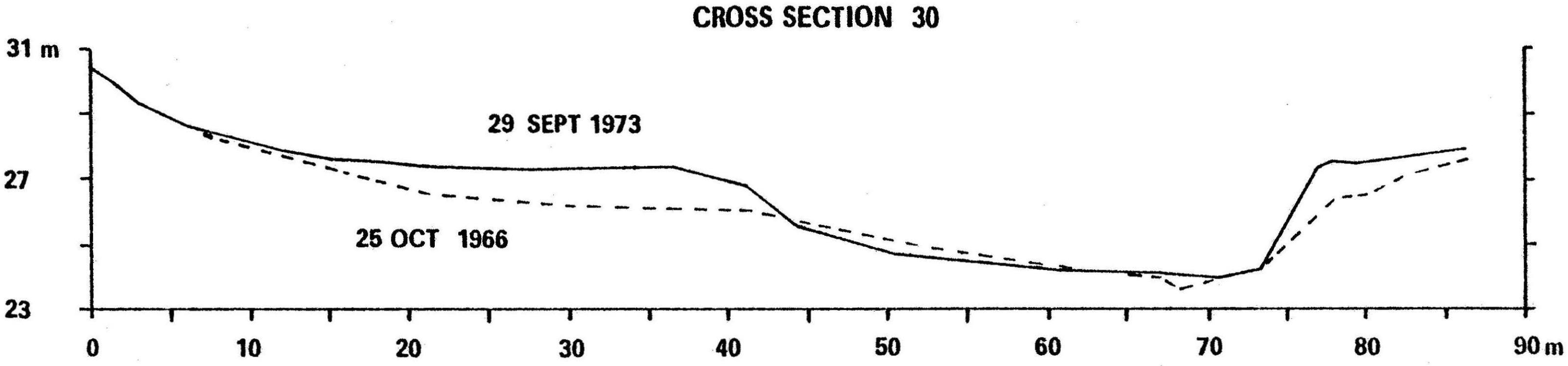


Fig. 3-11. Channel cross sections illustrating overbank deposition and lateral accretion in Type 2 reaches, above Interstate 40.

sediment load so that the stream is able to establish a more stable form than in smaller ephemeral systems. The formation of an inner valley within an extensive arroyo may therefore be analogous to the construction of a flood plain by an alluvial river.

The active portions of most flood plains are overflowed on an average of once every year or two, with inundation to a depth of about eight tenths mean bank height on the order of every 50 years (Leopold, Wolman and Miller, 1964). Continued overbank deposition should cause the elevation of a flood plain to increase over time, but this does not appear to be the case. Discharges greater than bankfull are often deficient in sediment because the concentration of fine material is greatest during the rising stage of a flood (Leopold and Wolman, 1957). In addition, flow over the surface of the flood plain is often irregularly distributed resulting in localized scour, rather than deposition (Leopold, et al., 1964).

Eighty to ninety percent of a meandering river's flood plain is composed of laterally accreted point bar deposits (Wolman and Leopold, 1957). When a wide range of grain sizes are available these sedimentary structures generally exhibit fining-up sequences in grain size and structural scale. Most fine sediments are deposited in the upper part of a point bar sequence, but often they come to rest in the deposits of natural levees or abandoned channels (Reineck and Singh, 1975). Though Schumm and Lichty (1963) observed a fining-up trend in the recently formed Cimarron flood plain, this propensity may be obscured in the stratigraphy of many flood plains due to the random distribution of point bars within the valley at any given time, the shifting nature of channel position and occasional scour by over-bank flows. Other processes, such as mass movement and construction of low angle tributary fans, tend to confuse the stratigraphy of the flood plain, but nonetheless contribute to its formation and modification (Wolman and Leopold, 1957).

Many discontinuous terraces have been created during the enlargement of the Rio Puerco's arroyo. Because the channel in a youthful arroyo is incised, developing meander bends will inevitably remove valley alluvium. Scalloped features created by lateral erosion of meander loops mirror the pattern of the channel that formed them. Occasional shifts and cut-offs, or confinement of the channel as the flood plain evolves result in the abandonment of some channel segments whose form and bed material are then preserved as broad terraces along the margins of the inner-valley.

In the lower reaches of the Rio Puerco, the oldest terraces often reveal a plan geometry similar to that of active Type 1 river segments, suggesting that most widening of the arroyo occurred at a time when Type 1 channels occupied these reaches, (Fig. 3-13). Except when contemporaneous terrace formation is verified in aerial photographs, correlation of these terrace remnants from valley to valley, or even along the same stream, is made difficult if not impossible by the lack of continuity of individual terraces. Lateral channel shifting within the broadening arroyo has obliterated many higher terraces and those that remain are seldom traceable for more than a kilometer or two.

In summary, the behavior of large ephemeral channels during a cycle of erosion is different than that of smaller-scale, discontinuous

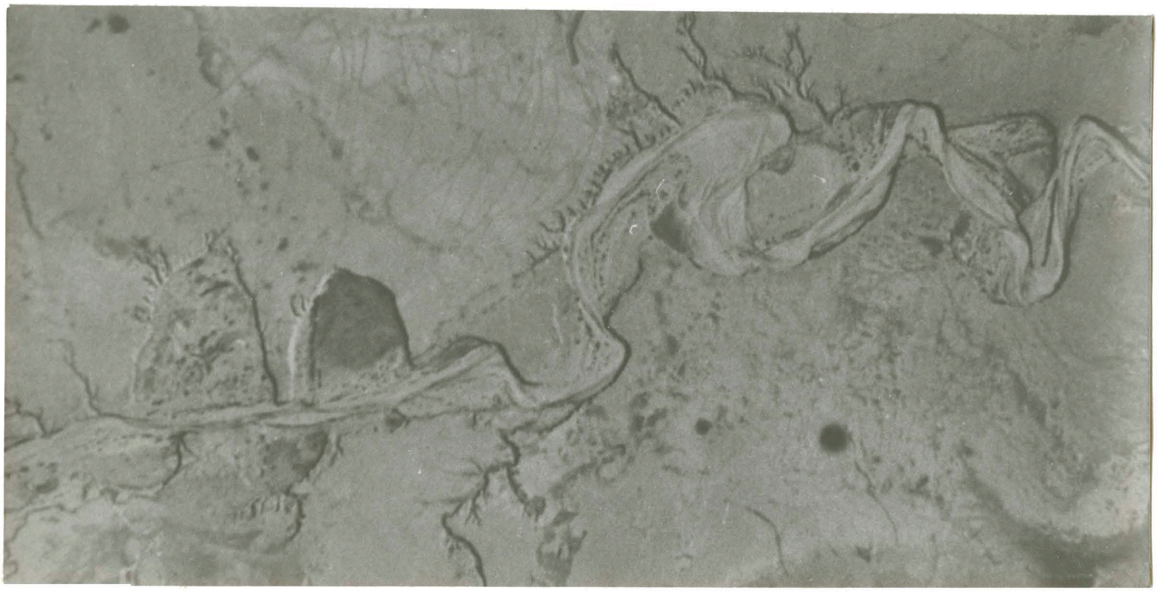


Fig. 3-12. Terrace formation following pattern adjustment and channel confinement; section 16, T11N, R1W. Top, S.C.S. photo, 1935; bottom, A.M.S. photo, 1954.

arroyos. While the gullying of small channels may soon be followed by aggradation to the level of the former valley floor, there exists a tendency for the arroyos of larger fluvial systems to become valley-like over a period of several decades. Such widening occurs so that the arroyo may attain a geometry that will accommodate discharge events of widely differing magnitudes without involving the walls in destructive lateral erosion (Cooke and Reeves, 1976), thereby averting an overloading of the channel with large amounts of locally introduced alluvium. In the lower part of the study area, several kilometers of the channel meander through a wide, inner-flood plain; seldom, if at all, does the river mobilize large masses of alluvium by intercepting the margin of the arroyo. In essence the Rio Puerco in these parts behaves much like any non-incised, alluvial river.

In contrast to the laterally eroding upstream reaches, the stable appearance of the lower Rio Puerco implies that some optimal valley dimensions must exist for each ephemeral fluvial system. Within such a valley, the stream or river meanders and reworks its flood plain as does any equilibrium channel. In most stable alluvial systems, the channel flows through a previously established flood plain, while a rejuvenated river, not confined by bedrock, must first enlarge its arroyo and form a flood plain within the new "inner-valley" before its channel may adopt a more stable pattern.

Following rejuvenation, the initial trench is quickly widened by lateral erosion of floodwaters. Sediment produced in headwaters and stored in the main channel causes the stream to shift laterally, further enlarging the arroyo (Figs. 3-3 and 3-4). When the breadth of an arroyo is not great, the channel should be expected to braid, shift and attack the bases of the scarps until it has planed off sufficient amounts of valley alluvium, thereby enlarging the arroyo to the "optimum" dimensions. By ultimately increasing the arroyo width to some scale, fewer bends of the channel would intercept the walls and less valley fill would be mobilized. Thus, the former bedload channel could become narrower and more sinuous, and the new flood plain forming within the arroyo would be of sufficient proportions such that random flood events would flow predominantly on it, doing a minimal amount of damage to the arroyo sides.

Although no empirical relations have been tested among arroyo width, discharge or channel width, the inner-valley of the lower Rio Puerco, where lateral erosion of the old valley alluvium has abated to a large degree, often exceeds 350 meters in breadth (Figs. 2-7 and 2-8). Upper reaches of the main channel flow through an arroyo whose width is usually well below 200 meters (Fig. 2-5), and it is along these segments that arroyo widening is most active. The propensity for incised channels to create broad valleys was evident in Parker's (1977) experimental study.

The transition from a shifting bedload channel into one that meanders and transports mostly suspended sediment occurs as a result of several factors; some are cyclic in nature, others are coincidental. Braiding may not be sustained if the amount of sediment introduced to a reach is sufficiently reduced, either because production in tributary headwaters has decreased with maturity of the basin, or because the arroyo has been broadened to such dimensions that lateral erosion becomes an insignificant agent in mobilizing alluvium. Infiltration in a sandy length of channel reduces water discharge and bedload movement. Fine grained material passing through backfilling reaches is deposited downstream, stabilizing banks and bars. Vegetation may flourish on cohesive alluvial deposits if floods are not of such magnitude and recurrence as to eradicate it.

Metamorphosis of the river and enlargement of the arroyo have not proceeded at similar rates in different reaches of the Rio Puerco. Evolution of the channel appears to have begun in the lower reaches and is, for the most part, migrating upstream as did the 19th century headcuts. Assuming Type 1 channel conditions preceeded the Type 2 environment in lower reaches, a substitution of space for time has been made. The theory is proffered that Type 2 conditions will, in time, come to replace Type 1 conditions in the upper parts of the basin as well.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The stability of rivers and streams has a profound effect on water quality, agriculture, engineered structures and the ecology of watersheds in semiarid regions of the world. Periodically, the hydrology and geomorphology of these fluvial systems are drastically altered when conditions of hydraulic equilibrium are no longer sustained. Cyclic erosion has been common in the southwestern United States, spanning several millennia and it was one factor in the demise of Anasazi culture in many valleys (Euler, et al., 1979). Likewise, the most recent period of erosion, beginning in the late 19th century, has adversely affected contemporary agrarian economies. Climatic and geomorphic conditions, and the effects of human habitation have been determined to be important factors in the deterioration of basin stability and formation of arroyos (Schumm, 1977; Antevs, 1952; Leopold, 1951; and others).

In nearly a century since the rejuvenation of southwestern watersheds sufficient time has elapsed for many long-term adjustments in channel and valley morphology to become apparent. Visible trends in physical and hydrologic changes indicate the Rio Puerco, and perhaps other large ephemeral systems, are adjusting physical parameters to entirely new equilibrium conditions rather than fluctuating about a mean. Whereas the gullying of small channels may soon be succeeded by aggradation and healing during a cycle of several decades, the behavior of large, continuous arroyos over the last century implies the existence of a much longer and more elaborate erosional development. The breadth of the Rio Puerco's arroyo has been greatly increased along most of its course and the formation of a new flood plain within it gives many reaches a form more valley-like than the precipitous trench observed by early investigators.

The complex response of Parker's (1977) experimental watershed to rejuvenation has a parallel in large, ephemeral river systems. Drastic changes in channel morphology accompany the rejuvenation of a drainage basin. Initially, material excavated near the mouth is quickly removed from the system, but as nickpoints extend into increasingly numerous tributaries more sediment is mobilized than the main channel can manage and these reaches soon become sites of deposition and storage. Aggradation in the lower channel of the experimental watershed was accompanied by braiding and widening of the trench through which it flowed. As the rate of sediment production eventually declined with maturity of tributaries, the channel became narrower and deeper, and secondary incision resulted in the emergence of terraces that were formerly the bed of the stream when it was broad and braided.

Lower reaches of the Rio Puerco, denoted "Type 2" for clarity, were the first to be rejuvenated and at this date they exhibit a more advanced stage of evolution than do upper reaches. Here the arroyo is broad and valley-like, and the channel narrow and meandering. The upper, or "Type 1" reaches of the Rio Puerco are generally in an aggraded state. The channel is prone to abrupt shifting and is actively enlarging the arroyo through which it flows.

Because the morphological differences between the upper and lower arroyo are due presumably to stage of development, spatial differences have been substituted for chronologic stage in developing a hypothetical sequence of form and process for this study area. Visual peculiarities in channel and arroyo form were substantiated statistically with the application of multiple discriminant function analysis. Of several variables sampled, width-depth ratio (W/D), channel slope (S), weighted mean percent silt and clay in the channel perimeter (M), and means radius of channel curvature (r_m) proved to be the best discriminators of morphological type.

In the Rio Puerco, Type 1 channel and arroyo segments represent an intermediate stage of arroyo metamorphosis. Main channels have been incised and high rates of sediment production in the upper basin strongly influence form and process downstream. The river in Type 1 reaches is broad and shallow, and low flow channels are often multiple and anastomosing. Fluctuating discharge and a high sediment load tend to maintain its braided appearance. Regression of W/D and M data indicates that Type 1 channel segments are unstable and aggrading with respect to Schumm's (1960) equation: $F = 225\ M^{-1.08}$. Non-cohesive banks and paucity of vegetation permit channel position within the arroyo to change abruptly during high stages. Because of this lateral instability, the walls of the arroyo are subject to frequent erosive attacks and it is under these circumstances that most enlargement of the arroyo occurs.

Creation of an inner-valley is at an early stage during the Type 1 phase. The dimensions of the arroyo are greatly increased by channel shifting and construction of the new flood plain commences with vertical aggradation and backfilling of coarser material. Formerly occurring in lower parts of the watershed, these conditions are active today in upper parts of the basin, below Cuba, or where tributary contribution of bedload is very high, such as below the confluence of Chico Arroyo near Guadalupe.

A more advanced stage of arroyo evolution is represented by Type 2 arroyo segments. Channels in these reaches have a lower W/D and slope than do those of Type 1 segments, and bends are characteristically smaller in radius of curvature. A high proportion of silt and clay in the bed and banks and dense riparian vegetation tend to discourage abrupt relocation of the channel, although meanders may grow to unstable proportions and become prone to cutoff. With the exception of a few ingrown meanders near the margin of the arroyo, the channel generally behaves as an alluvial river, meandering through flood plain deposits. Because there is less channel shifting and contact with the arroyo wall in Type 2 reaches, sediment production from erosion of older valley fill is relatively low in these areas.

Reduced flood peaks and bedload transport from infiltration and sediment storage upstream in Type 1 reaches have brought about the inception and maintenance of the meandering Type 2 channel. In many areas the arroyo is broad and valley-like. Terrace scarps formed during Type 1 conditions have become somewhat obscured from gullying and slope retreat, but nonetheless, their plan geometry is still discernable in air photos. The inner-flood plain supports some vegetation, especially dense near the channel, and it is added to and modified by point bar construction.

Long-term changes in the main valley of a large-scale ephemeral system are illustrated in the following model and Figures 3-3 and 3-4. After initial vertical incision, highly erosive flows attack walls of the youthful arroyo increasing its width and reducing irregularities in its pattern. Accelerating sediment production in tributaries soon overburdens the main channel which responds by adopting a shifting, braided pattern. The unstable disposition of the channel perpetuates vigorous lateral erosion and the width of the arroyo is considerably increased. High or variable water and sediment discharges perpetuate these unstable conditions. Sediment load is augmented by undercutting of the walls as channel position changes with each flood event. Type 1 channel and arroyo conditions prevail in a reach until some optimal inner-flood plain width has been attained whereby high flows will intercept the arroyo wall only sporadically.

A transition to the Type 2 arroyo and channel phase may also begin when sediment production in headwaters begins to decline, or as sediment is stored in the channel or on the flood plain upstream. Moderation of mean annual and peak annual discharges allow vegetation to become more firmly established and it, in turn, stabilizes banks and induces more deposition of fine material. Areas of the inner-flood plain that have undergone backfilling in the Type 1 phase sustain meandering channels in the Type 2 phase after bedload transport has been greatly reduced. The new flood plain is modified and further added to by bend migration and point bar deposition. The river and inner-valley in a Type 2 reach generally has the appearance of a "stable" alluvial river and flood plain, but in some areas, where the channel intercepts thick valley alluvium, meander loops may become ingrown to unusual proportions.

Channel incision and arroyo development begin near the mouth and are perpetuated upstream much in the way headcuts migrated upstream when the basin was first rejuvenated (Bryan, 1928 b; Parker, 1977). Local exceptions to this trend may occur where tributaries introduce bedload at unusually high rates or where valley slope is great. By the 1950's the lower channel of the Rio Puerco was characterized by Type 2 conditions and at the time of this writing many more segments of the arroyo have undergone the transition to this phase of development. While abstraction of the Rio Puerco's headwater tributaries continues and as the upper arroyo is sufficiently widened, the relatively stable conditions of the Type 2 phase should be found progressively higher in the basin. This natural trend is encouraged by sediment storage within the arroyo upstream, improved water management and the spread of salt cedar and other vegetation.

The evolution of most geomorphic features involves considerable time, and hence the modification of the Rio Puerco's valley has been, at best, partially observed. With the exception of conditions that have been documented prior to and immediately following the incision of the Rio Puerco, only two phases of development have been witnessed in this study; Type 1 and Type 2 arroyo development described previously. Evidence to substantiate the existence of evolutionary states beyond the Type 2 phase have not, at this date, been found in the Rio Puerco watershed, but Patton (1973) noted the channel near Bernardo was in "an advanced state of aggradation." In this reach the bed of the river is only four meters below the level of the former valley floor, which is about half the relief of Type 2 reaches upstream. This suggests that the Bernardo reach has continued to aggrade, approaching the level of the former valley floor. But careful scrutinization of air photos reveals that, at least since 1935, the arroyo here has had a depth less than that of the arroyo upstream, possibly due to local influence from the Rio Grande. Aside from differences in relief between the oldest terrace and the channel bed, the Bernardo reach visually resembles a Type 2 reach. Although the channels of smaller basins may experience aggradation and healing after a period of arroyo formation, the magnitude of discharge in drainage basins the size of the Rio Puerco offsets the tendency for the channel to aggrade to its former level (Patton, 1973; Hadley, personal communication). Continued investigation of changes in the inner-valley are needed to confirm or deny this supposition.

The theory that arroyos of large fluvial systems will eventually be transformed into valley-like forms finds considerable support in changes observed in the Rio Puerco since 1880. Following rejuvenation, the initial alterations of the channel and valley floor proceed at a rapid rate. Headcut advances of eight to 20 kilometers per year were observed in Arizona by Antevs (1952), and Bryan and Post (1927) estimated the amount of sediment removed from the Rio Puerco arroyo to have averaged $1.16 \times 10^7 m^3$ (9400 a.f.) per year during the first 42 years after incision. Metamorphosis from arroyo to valley continues at a slower rate. The earliest transition from Type 1 to Type 2 conditions, in the lower Rio Puerco, is documented photographically three quarters of a century after rejuvenation.

Most lower reaches of the Rio Puerco today are relatively stable, but in places the inner-valley continues to be enlarged by lateral erosion. Valley transformations succeeding the Type 2 phase may require even longer periods of time as the means of change become more subtle. Additional observation of the lower reaches could shed light on the rate and nature of ensuing modifications in channel and valley morphology. Ecologic studies, particularly concerning the succession of inner-valley flora, would be useful in determining the agricultural potential of rehabilitated reaches.

Awareness of the succession and timing of events in the evolution from arroyo to valley is necessary in order to adequately plan for aberrations in water and land quality, and to ensure proper design of engineering projects. Ecological studies might also benefit from this information. The anticipation of a change in discharge, or in sediment quantity and composition is an important consideration in planning water diversion or storage facilities. Furthermore, as a rejuvenated channel enters the Type 2 developmental phase, the task of delineating flood plains and other potentially hazardous areas near the new valley is made easier. By this phase, areas subject to flooding, channel shifting or additional lateral enlargement can be inferred, and construction in these areas avoided.

Appendix I. Location of Cross Sections

Cross Section	Latitude	Longitude	Township and Range
1	35°58'13"	106°59'25"	ne 1/4, ne 1/4, Sec 1e, T20N, R2W
2	35°56'35"	106°59'15"	sw 1/4, sw 1/4, Sec 19, T20N, R1W
3	35°56'30"	106°59'12"	sw 1/4, sw 1/4, Sec 19, T20N, R1W
4	35°55'50"	106°59'00"	se 1/4, sw 1/4, Sec 30, T20N, R1W
5	35°55'05"	106°59'20"	nw 1/4, sw 1/4, Sec 31, T20N, R1W
6	35°55'00"	106°59'33"	nw 1/4, se 1/4, Sec 36, T20N, R2W
7	35°54'50"	106°59'22"	sw 1/4, sw 1/4, Sec 31, T20N, R1W
8	35°53'42"	106°58'30"	sw 1/4, ne 1/4, Sec 7, T19N, R1W
9	35°53'45"	106°58'38"	nw 1/4, ne 1/4, Sec 7, T19N, R1W
10	35°53'38"	106°58'32"	sw 1/4, ne 1/4, Sec 7, T19N, R1W
11	35°39'42"	107°03'43"	2.7 km sw of San Luis
12	35°32'58"	107°09'05"	.8 km n of Guadalupe
13	35°32'22"	107°08'38"	at Guadalupe
14	35°32'22"	107°08'30"	at Guadalupe
15	35°04'18"	106°57'00"	ne 1/4, nw 1/4, Sec 28, TloN, R1W
16	35°03'28"	106°57'05"	ne 1/4, nw 1/4, Sec 33, T10N, R1W
17	34°47'58"	106°59'25"	.4 km above Highway 6 bridge
18	34°46'33"	106°58'50"	sw 1/4, ne 1/4, Sec 6, T6N, R1W
19	34°45'30"	106°57'15"	nw 1/4, sw 1/4, Sec 9, T6N, R1W
20	34°38'08"	106°54'00"	nw 1/4, nw 1/4, Sec 25, T5N, R1W
21	34°37'50"	106°54'13"	nw 1/4, sw 1/4, sec 25, T5N, R1W
22	34°36'13"	106°53'58"	se 1/4, nw 1/4, Sec 1, T4N, R1W
23	34°36'20"	106°54'02"	nw 1/4, nw 1/4, Sec 1, T4N, R1W

Appendix I. Continued.

Cross Section	Latitude	Longitude	Township and Range
24	34°36'12"	106°54'05"	sw 1/4, nw 1/4, Sec 1, T4N, R1W
25	34°36'15"	106°54'00"	sw 1/4, nw 1/4, Sec 1, T4N, R1W
26	34°36'07"	106°53'32"	sw 1/4, ne 1/4, Sec 1, T4N, R1W
27	34°35'03"	106°53'13"	nw 1/4, sw 1/4, Sec 7, T4N, R1E
28	34°35'00"	106°53'10"	sw 1/4, sw 1/4, Sec 7, T4N, R1E
29	34°35'05"	106°53'05"	nw 1/4, sw 1/4, Sec 7, T4N, R1E
30	35°05'27"	106°56'45"	se 1/4, Sec 16, T10N, R1W
31	34°47'10"	106°59'20"	sw 1/4, Sec 31, T7N, R1W

Appendix II. Basic Data

Cross Section	W (m)	D (m)	W/D	S (m/m)	P	M (%)	L/H	r_m (m)	S_v (m/m)
1	48.2	0.5	96.4	.0034	1.6	36.6	2.2	62.5	.0052
2	23.7	0.5	47.4	.0036	1.3	17.2	1.8	75.0	.0033
3	21.3	0.6	35.5	.0044	1.3	25.4	3.3	87.5	.0033
4	58.9	0.3	196.3	.0045	1.1	24.1	10.0	-	.0030
5	58.4	0.6	97.3	.0029	1.7	-	2.6	125.0	.0036
6	26.5	0.7	37.9	.0034	1.7	11.2	2.8	125.0	.0036
7	40.3	0.6	67.2	.0028	1.7	42.6	1.9	125.0	.0036
8	27.6	0.7	39.4	.0056	2.0	30.6	0.9	50.0	.0021
9	16.4	0.6	27.3	.0024	2.0	9.1	1.4	75.0	.0021
10	23.1	0.6	35.5	.0033	2.0	8.5	3.2	125.0	.0021
11	33.2	1.2	27.7	.0023	1.4	26.4	2.6	56.2	.0050
12	33.4	0.3	111.3	.0022	1.0	13.5	15.0	-	.0033
13	68.4	0.5	136.8	.0014	1.8	42.4	1.8	125.0	.0030
14	45.0	0.5	90.0	.0024	1.8	-	0.9	100.0	.0030
15	23.6	1.6	14.8	.0013	1.5	41.0	2.3	68.8	.0020
16	24.3	1.8	13.5	.0017	1.4	26.4	4.1	62.5	.0022
17	29.7	1.8	16.5	.0012	1.5	37.1	2.9	56.2	.0036
18	22.5	1.7	13.2	.0022	1.7	23.9	1.1	50.0	.0024
19	21.0	1.8	11.7	.0008	1.7	35.2	2.3	56.2	.0019
20	19.3	1.9	10.2	.0006	1.1	58.1	4.3	87.5	.0018
21	25.0	2.1	11.9	.0010	1.4	54.9	2.4	75.0	.0014
22	21.4	1.9	11.3	.0009	1.2	59.1	4.4	100.0	.0014
23	25.3	1.7	14.9	.0012	1.2	62.6	5.8	100.0	.0014

Appendix II. Continued.

Cross Section	W (m)	D (m)	W/D	S (m/m)	P	M (%)	L/H	r_m (m)	S_v (m/m)
24	16.3	1.6	10.2	.0010	1.4	54.3	1.2	37.5	.0014
25	16.7	1.6	10.4	.0022	1.2	40.8	3.2	125.0	.0014
26	18.7	1.7	11.0	.0018	1.7	45.7	1.2	62.5	.0014
27	20.0	1.9	10.5	.0012	2.2	44.0	0.9	37.5	.0022
28	13.9	1.0	13.9	.0030	1.7	52.8	2.1	50.0	.0022
29	19.7	2.3	8.6	.0012	2.2	38.2	1.2	75.0	.0022

Appendix III. Multiple Discriminant Function Analysis.

Initially, 29 sample reaches were assigned to three predetermined groups: Type 1, Type 2 and Intermediate. Twelve variables were sampled at each site, and they were subdivided into the categories: Channel Geometry, Sediment and Pattern. The variables in each category were then analyzed to determine their ability to assign samples to the proper group. Having identified the best discriminating variables from each category, different combinations of these variables were tested in a similar fashion. In the second stage of multiple discriminant function analysis, samples were assigned to only two groups: Type 1 and Type 2.

Category	Rank	Variable	Individual *F-value
Channel Geometry	1	S_v	21.74
	2	S	8.88
	3	W/D	6.01
	4	P	1.16
Sedimentology	1	M_{zc}	9.78
	2	M	1.44
	3	M_{zb}	0.33
Pattern	1	L/H	4.23
	2	r_m	4.17
	3	$\overline{L/H}$	0.89
	4	L	0.78
	5	H	0.42

Appendix III. Continued.

Variable Combination	Rank	Variable	Individual *F-value
W/D, M, r_m	1	W/D	24.67
	2	M	18.01
	3	r_m	1.83
W/D, S, r_m, L/H	1	W/D	33.28
	2	S	30.67
	3	r_m	4.23
	4	L/H	1.39

*The Individual F-value is an expression of the relative importance of each variable in the discriminant function, and may be defined as the ratio of "between groups variation" to "within group variation."

S = channel slope

S_v = valley slope

W/D = width to depth ratio

P = sinuosity

M = weighted mean percent silt and clay in channel perimeter

M_{zc} = graphic mean grain size of bed material

M_{ab} = graphic mean grain size of bank material

L = distance between meander loop inflection points

H = height, or amplitude of meander loop

L/H = length to height ratio

$\overline{L/H}$ = mean of reach L/H ratios

r_m = mean radius of bend curvature

REFERENCES CITED

Antevs, E., 1952. Arroyo-cutting and filling: Jour. Geology, v. 60, pp. 375-378.

Bagnold, R. A., 1966. An approach to the sediment transport problem from general physics: U.S. Geol. Survey Prof. Paper 422-I, 37 p.

Brice, J. C., 1964. Channel patterns and terraces of the Loup Rivers in Nebraska: U.S. Geol. Survey Prof. Paper 422-D, 41 p.

Brice, J. C., 1974. Evolution of meander loops: Geol. Soc. Amer. Bull., v. 85, pp. 581-586.

Bryan, K., 1928 a. Historic evidence of changes in the channel of the Rio Puerco, a tributary of the Rio Grande, New Mexico: Jour. Geology, v. 36, pp. 265-282.

Bryan, K., 1928 b. Change in plant associations by change in ground water level: Ecology, v. 9, pp. 474-478.

Bryan, K., 1929. Flood-water farming: Geographical Review, v. 19, pp. 444-456.

Bryan, K., 1941. Pre-Columbian agriculture in the southwest as conditioned by periods of alluviation: Annals of the Assn. of Amer. Geographers, no. 4, pp. 219-242.

Bryan, K. and Post, G., 1927. Erosion and control of silt on the Rio Puerco, New Mexico: Unpubl. Report to the Chief Engineer, Middle Rio Grande Conservancy Dist. Albuquerque, New Mexico.

Burkham, D. E., 1966. Hydrology of Cornfield Wash area and the effects of land treatment practices, Sandoval County, New Mexico, 1951-1960: U.S. Geol. Survey Water-Supply Paper 1831, 87 p.

Chien, N., 1961. The braided stream of the lower Yellow River: Scientia Sinica, v. 10, no. 6, pp. 734-754.

Cooke, R. U. and Reeves, R. W., 1976. Arroyos and environmental change in the American southwest: Oxford Res. Studies in Geog., Clarendon Press.

Dunn, I.S., 1959. Tractive resistance of cohesive channels: Jour. Soil Mech. and Foundations Div., Amer. Soc. Civil Engineers, Proceedings, v. 85, no. SM3, pp. 1-24.

Euler, R. C., Gumerman, G. J., Karlstrom, T. N. V., Dean, J. S., Hevly, P. H., 1979. The Colorado Plateaus: cultural dynamics and paleoenvironment: Science, v. 205, no. 4411, pp. 1089-1101.

Fanestock, R. K., 1963. Morphology and hydrology of a glacial stream: U.S. Geol. Survey Prof. Paper 422-A, 70 p.

Folk, R. L., 1974. Petrology of sedimentary rocks: Univ. Texas.

Friedkin, J. F., 1945. A laboratory study of the meandering of alluvial rivers: U.S. Waterways Engr. Exper. Sta., 40 p.

Gregory, K. J. and Walling, D. E., 1973. Drainage basin form and process: John Wiley and Sons, New York, 458 p.

Hack, J. T., 1942. The changing physical environment of the Hope Indians of Arizona: Papers of the Peabody Museum of Amer. Archaeology and Ethnology, Harvard Univ., v. 35, no. 1.

Happ, S. C., 1948. Sedimentation in the middle Rio Grande valley, New Mexico: Geol. Soc. Amer. Bull. v. 59, pp. 1191-1216.

Herold, J., 1961. Prehistoric settlement and physical environment in the Mesa Verde area: Utah Univ. Dept. Anthropology, Anthropological Papers, no. 53.

Hickin, E. J., 1974. Development of meanders in natural river-channels: Amer. Jour. Science, v. 274, pp. 414-442.

Judd, N. M., 1964. The architecture of Pueblo Bonito: Smithsonian Misc. Collections, v. 147, no. 1.

Lane, E. W., 1937. Stable channels in erodible material: Amer. Soc. Civil Engineers, Transactions, v. 102, pp. 123-143.

Langbein, W. B. and Leopold, L. B., 1966. River meanders-theory of minimum variance: U.S. Geol. Survey Prof. Paper 422-H, 15 p.

Langbein, W. B. and Leopold, L. B., 1968. River channel bars and dunes - theory of kinematic waves: U.S. Geol. Survey Prof. Paper 422-L, 20 p.

Leighly, J., 1936. Meandering arroyos of the dry southwest: Geol. Review, v. 36, pp. 270-282.

Leopold, L. B., 1951. Rainfall frequence: an aspect of climatic variation: Trans. Amer. Geophys. Union, v. 32, pp. 347-357.

Leopold, L. B. and Maddock, T., Jr., 1953. The hydraulic geometry of stream channels and some physiographic applications: U.S. Geol. Survey Prof. Paper 252 57 p.

Leopold, L. B. and Miller, J. P., 1956. Ephemeral streams, hydraulic factors and their relation to the drainage net: U.S. Geol. Survey Prof. Paper 282-A, 37 p.

Leopold, L. B. and Wolman, M. G., 1957. River channel patterns: braided, meandering and straight: U.S. Geol. Survey Prof. Paper 282-B, pp. 39-84.

Leopold, L. B. and Wolman, M. G., 1960. River meanders: Geol. Soc. Amer. Bull., v. 71, pp. 769-794.

Leopold, L. B., Wolman, M. G. and Miller, J. P., 1964. Fluvial processes in geomorphology: Freeman Co., San Francisco.

Malde, H. E. and Scott, A. G., 1977. Observations of contemporary arroyo cutting near Santa Fe, New Mexico, U.S.A.: Earth Surf. Processes, v. 2, no. 1., pp. 39-54.

Nadler, C. T., Jr., 1978. River metamorphosis of the South Platte and Arkansas Rivers, Colorado [M.S. thesis]: Colorado State Univ., Fort Collins, 151 p.

Nordin, C. F., Jr., 1963. A preliminary study of sediment transport parameters, Rio Puerco near Bernardo, New Mexico: U.S. Geol. Survey Prof. Paper 462-C, 21 p.

Nordin, C. F., Jr., 1964. Study of channel erosion and sediment transport: Jour. Hydraulics Div., Amer. Soc. Civil Engineers, v. 90, no. HY 4, prt. 1.

Northrup, W. L., 1965. Republican River channel deterioration: U.S. Dept. Agric. Misc. Pub. 970, pp. 409-424.

Parker, R. S., 1977. Experimental study of drainage basin evolution and its hydrologic implications: Hydrol. Papers, Colorado State Univ., Fort Collins, Colo., no. 90.

Patton, P. C., 1973. Gulley erosion in the semiarid west (thesis): Colorado State Univ., Fort Collins, Colo.

Reineck, H. E. and Singh, I. B., 1975. Depositional sedimentary environments: Springer-Verlag, New York, 439 p.

Schoenwetter, J. and Dittert, A. E., Jr., 1968. An ecological interpretation of Anasazi settlement patterns: Anthro. Soc. of Washington/Anthropological Archaeo. in the Americas, pp. 41-66.

Schumm, S. A., 1960. The shape of alluvial channels in relation to sediment type: U.S. Geol. Survey Prof. Paper 352-B, pp. 17-30.

Schumm, S. A., 1961. Effect of sediment characteristics on erosion and deposition in ephemeral-stream channels: U.S. Geol. Survey Prof. Paper 352-C, pp. 31-70.

Schumm, S. A., 1963. Sinuosity of alluvial rivers in the Great Plains: Geol. Soc. Amer. Bull., v. 74, pp. 1089-1099.

Schumm, S. A., 1977. The fluvial system: John Wiley and Sons, New York, 338 p.

Schumm, S. A. and Hadley, R. F., 1957. Arroyos and the semiarid cycle of erosion: Amer. Jour. Science, v. 225, pp. 161-174.

Schumm, S. A. and Khan, H. R., 1972. Experimental study of channel patterns: Geol. Soc. Amer. Bull., v. 83, pp. 1755-1770.

Schumm, S. A. and Lichty, R. W., 1963. Channel widening and flood-plain construction along Cimarron River in southwestern Kansas: U.S. Geol. Survey Prof. Paper 352-D, pp. 71-88.

Simons, D. B. and Richardson, E. V., 1966. Resistance to flow in alluvial channels: U.S. Geol. Survey Prof. Paper 422-J, 61 p.

Smith, N. D., 1971. Transverse bars and braiding in the lower Platte River, Nebraska: Geol. Soc. Amer. Bull., v. 82, pp. 3407-3420.

Stevens, M. A., Simons, D. B. and Richardson, E. V., 1975. Non-equilibrium river form: Jour. Hydraulics Div., Amer. Soc. Civil Engineers, v. 101, pp. 557-566.

Wagner, L. H., 1963. Origin of some recent tractional sedimentary structures in the Rio Puerco near Bernardo, New Mexico (thesis): Univ. New Mexico, Albuquerque.

Wolman, M. G., and Leopold, L. B., 1957. River flood plains: some observations on their formation: U.S. Geol. Survey Prof. Paper 282-C.