The Significance of Sediment Transport in Arroyo Development

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The Significance of Sediment Transport in Arroyo Development

By DAVID F. MEYER

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CONVERSION FACTORS

For use of readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply SI units	By	To obtain inch-pound units
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
decimeter (dm)	0.3281	foot (ft)
meter (m)	3.281	foot (ft)
kilometer	0.6214	mile (mi)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
liters per second (L/s)	0.03531	cubic foot per second (ft^3/s)
kilogram (kg)	2.2046	pound (lb)
gram (g)	0.03527	ounce (oz)

The Significance of Sediment Transport in Arroyo Development

By David F. Meyer

Abstract

Arroyo widening dominates postincisional arroyo development, and the manner of widening is dependent on the grain size of bed material transported by the channel.

When bed material is predominantly gravel, subaqueous bars that alternate from one side of the channel to the other form during high flows in initially narrow, often straight, arroyos. These alternate bars grow and become coarse-grained point bars. Moderate and low flows cannot rework these coarse bars, and the channel meanders around them. Arroyo walls opposite the bars are undercut and eroded. With progressive arroyo widening by erosion of cut banks, high-flow channel width increases, and depth decreases, reducing channel competence. Gravel is deposited in midchannel bars, point bars are reworked, and the channel becomes braided. As braiding becomes dominant, both arroyo walls are eroded. This conceptual model of coarse-grained arroyo development is based on observations of arroyo development through time using physical models and interpretation of the channel and arroyo morphology and sedimentology during a short period along the San Simon, San Pedro, and Santa Cruz Rivers in southeast Arizona.

When bed material is predominantly sand, the channel pattern within initial arroyos is typically braided, and both arroyo walls are actively eroded. Alternate bars may form within single-thread, high-flow channels, but they are reworked during recessional flows, and the low-flow channel is again braided. With progressive arroyo widening, fine sand, silt, and clay carried in suspension are deposited across a flood plain within the wide arroyo, causing the channel to meander. This fine-grained arroyo development model is based on observations of arroyo development through time using physical models and interpretation of the channel and arroyo morphology and sedimentology during a short period along the Rio Puerco, New Mexico.

Experimental investigations using physical models in which incised channels were monitored through time indicate that the rate of arroyo widening is dependent on the amount of bedload transported through a reach. This is documented by the relations between the rate of arroyo erosion and the observed sediment transport, the channel slope, the channel width and the channel width-to-depth ratio. When a small amount of bed material is being transported, arroyos do not widen whether they are narrow (arroyo width-to-depth ratios between 1.5 and 3.1), intermediate (between 2.5 and 4.8), or wide (greater than 4.9). Arroyo widening resumes when a larger supply of bed material is introduced.

Arroyo widening decreases through time because with progressive increases of arroyo width, the frequency with which unstable channels within the arroyo impinge upon arroyo walls decreases. Arroyos become wider in a downstream direction in response to the cumulative effect of upstream sediment production.

INTRODUCTION

Erosion and sedimentation caused by the development of steep-walled continuous river trenches, commonly called arroyos, constrain urban, agricultural, energy, and transportation development. A period of channel incision commenced during the late 1800's and early 1900's throughout the southwestern United States. Since that time, some channels have continued to incise and some have aggraded, but nearly all have widened. Although they were initially narrow trenches, many arroyos widened to the extent that they contain flood plains. Preentrenchment flood plains are now (1987) terraces that are too far above the incised channels to receive even large flood flows. Arroyo widening introduced large amounts of sediment to the stream channels. Patterns of arroyo widening commonly differ from one arroyo to another. The processes involved in arroyo widening and the controls on them must be identified for rational consideration in future development in the vicinity of these changing landscapes.

Purpose and Scope

This report describes the results of a study to enhance the understanding of arroyo development after incision, by means of field observations and physical models. The following questions guided the investigation:

How have arroyos changed since entrenchment?

What processes caused arroyo changes?

How do grain size and rate of bedload discharge affect arroyo processes?

What grain-size and channel-geometry variables help to discriminate between stable and unstable arroyos?

Development of arroyos (defined herein as continuous, large trenches, initially formed by channel incision in major stream valleys in the arid and semiarid southwestern United States) is closely linked to bedload transport. Arroyo floors are occupied by channels and, when arroyos are wide enough, by flood plains. This report is therefore limited to a study of channel processes related to bedload transport;

other processes, such as mass movement along arroyo walls, gully formation in tributary streams, and discontinuous gully formation, are secondary.

Conceptual models developed in this study explain patterns of arroyo development. Experimental studies of processes and patterns of arroyo development were performed in the Rainfall Erosion Facility (REF) at Colorado State University. However, the experimental channels are not treated as scale models of river channels. Patterns of arroyo development observed in experimental studies were also identified in the San Simon, San Pedro, and Santa Cruz Rivers in Arizona, and the Rio Puerco in New Mexico (locations shown in figs. 7 and 8).

The processes observed in this study are not restricted to arroyos in arid and semiarid climates. Therefore, the models presented here may have applications to any stream in which lateral channel instability leads to increased sediment loads.

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History of Arroyo Entrenchment in Study Area

In the late nineteenth century, many valleys and channels in the southwestern United States commenced a period of channel incision. Channel incision formed arroyos along many valleys that had supported marshes, lush grasses, and irrigated agricultural lands. At the same time, many upland areas were dissected by smaller discontinuous gullies. Changes in precipitation amount and pattern, overgrazing, and flow diversion and concentration have all been cited as reasons for arroyo and gully formation (summarized in Cooke and Reeves, 1976; Graf, 1983; Hereford, 1984). In the arroyos studied herein (San Simon, San Pedro, and Santa Cruz in southeastern Arizona, and Rio Puerco in New Mexico), these causes were all significant to various degrees. Base level did not lower along the San Simon, San Pedro, and Santa Cruz Rivers to initiate channel incision. The Gila River, to which all three are tributary, experienced no significant vertical fluctuations of its bed, and channel widening was not of the magnitude that would increase the channel gradient of its tributaries by shortening their channel lengths (Burkham, 1972). Incision along the Rio Puerco, however, may reflect a lowering of base level (Happ, 1948).

Regional climatic fluctuations may have altered runoff and discharge patterns to initiate widespread channel incision. Stratigraphic evidence of prehistoric periods of arroyo incision that coincided with drier climates and periods of arroyo filling coinciding with wetter climates support this theory (Bryan, 1928, 1941). Since the earliest climatic records of the 1860's, rainfall patterns in Arizona and New Mexico have shifted toward a greater frequency of light rains and lesser frequency of heavy rains (Leopold, 1951; Leopold and others, 1966; Cooke and Reeves, 1976). Therefore, channel incision could reflect an increase in peak flows. Unfortunately, few preentrenchment climatic data exist (Thornthwaite and others, 1942; Hastings, 1961).

Incision of San Simon Arroyo

Marshes (locally called cienagas) were common throughout the San Simon, San Pedro, and Santa Cruz valleys during the 1860's (Hastings, 1961; Cooke and Reeves, 1976). Many marsh deposits are now capped by alluvial fan deposits of sand and gravel that thicken toward the valley sides (Melton, 1965). The tall grasses that grew in and near these marshes attracted cattle. Melton (1965) blamed overgrazing for increased erosion of uplands that produced the alluvial fans, which subsequently restricted flows to the center of the valleys. The reduction of the grass cover of the valley floors, in turn, decreased roughness. Flow was also restricted by a wagon road that ran the length of San Simon valley and, in places, by the Gila, Globe, and Northern Railway. Sometime between 1883 and 1900, a network of levees and ditches was constructed to divert floodwaters at the mouth of the San Simon River near Solomon (Olmstead, 1919; Hastings, 1961; Cooke and Reeves, 1976). Massive erosion began along the San Simon River during floods of 1905 (Burkham, 1972). During the 1930's, grass was planted and numerous water spreaders were constructed throughout the uplands to decrease runoff. Check dams were constructed along the main channel of the San Simon River as part of public works projects.

Incision of San Pedro Arroyo

The San Pedro River flowed through discontinuous trenches that alternated with marshes in the early 1860's. Early Mormon settlers at St. David described the San Pedro as flowing through a gully 6 m deep, but they had problems with malaria owing to proximity to marshes (Hastings, 1961; Cooke and Reeves, 1976). The coalescence of these discontinuous trenches into the San Pedro arroyo is not described in historical records.

Incision of Santa Cruz Arroyo

The Santa Cruz valley also contained discontinuous trenches alternating with marshes (Cooke and Reeves, 1976). Levees and ditches were constructed to divert periodic floodwaters from towns and fields (Olmstead, 1919; Hastings, 1961; Cooke and Reeves, 1976). Infiltration ditches were dug at Tucson and at San Xavier Indian Reservation to collect ground water. Floods during the 1890's enlarged these ditches into an arroyo, many meters wide, 3 to 6 m deep, and extending as far as 29 km upstream by 1912 (Cooke and Reeves, 1976).

Incision of Rio Puerco Arroyo

The Rio Puerco began to incise continuously during the late 1800's. Prior to 1885, it flowed through discontinuous trenches and cienagas. Arroyo entrenchment probably occurred in an upstream direction from the mouth of the Rio Puerco (Bryan, 1928), perhaps in response to lowering of base level from a meander cutoff on the Rio Grande during railroad construction (Happ, 1948).

In summary, in spite of over 60 years of scientific research and discussion, the cause of the widespread arroyo cutting and coalescence of discontinuous arroyos that culminated at the end of the nineteenth century is still uncertain. Discontinuous arroyos were clearly present before Anglo-American settlement. Yet, the nearly simultaneous, widespread initiation of new arroyos, the incorporation of small natural and man-induced arroyos into long trenches extending the length of the valleys, and the trenching of previously untrenched valleys all suggest that there was an extrinsic change in the hydrologic regime of the entire Southwest. However, Anglo-American settlement must have had an important effect on the streams in the Southwest, but whether it was the ultimate cause of arroyo cutting, or whether it was a "mere trigger pull which timed a change about to take place," as Bryan (1928) asserted, still has not been resolved. Cooke and Reeves (1976, p. 16) presented a complex model of arroyo formation that involves a large number of possible combinations of factors that can lead to arroyo entrenchment.

Arroyo Widening

After initial incision, arroyos start to widen. Sequential changes in channel pattern affect the widening process. San Simon, San Pedro, Santa Cruz, and Rio Puerco arroyos contain braided, straight, and sinuous reaches, but changes from a braided channel to a sinuous channel, or from a sinuous channel to a braided channel, are a key to differences between two different widening sequences.

Some reaches of San Simon, San Pedro, and Santa Cruz arroyos contain channels that meander around coarse-grained point bars. These channels actively widen their arroyos, as indicated by vertical, raw cut-banks opposite point bars. However, other reaches along these arroyos have no raw walls. The channels in these noneroding reaches may be sinuous, straight, or braided. Actively widening reaches are interspersed between noneroding sinuous or straight reaches along these three arroyos, but most braided reaches occur at the downstream end of the channels.

The arroyo of the Rio Puerco also contains both braided and sinuous reaches, but the braided reaches are actively widening their arroyos. Braided channels and unstable arroyos are confined to upstream reaches of the Rio Puerco, whereas downstream reaches contain sinuous channels and arroyos that widen only rarely.

Development of Other Entrenched Channels

Gullies

Gullies are small, recently formed, incised channels that commonly develop where no previous channel existed. They can be formed anywhere that the erosive power of unchannelized flow exceeds the erosive resistance of the surface. This can occur as a result of concentrated flow, increased runoff, increased slope, reduced vegetative cover, or reduced shear strength of the surface. The causes of such changes are countless, and can be either natural or man-induced, but the most common is poor agricultural practices (Ireland and others, 1939; Jepson, 1939; Harvey and others, 1985). Accelerated gully erosion in the Southwest was coincident with the period of arroyo formation during the late nineteenth century. Possible causes are, for the most part, the same as the causes of arroyo entrenchment.

Small gullies, at least in the Southwest and Great Plains, seem to be relatively short-lived phenomena which exhibit an inherent trend toward stabilization (Ireland and others, 1939; Thornthwaite and others, 1942; Daniels and Jordan, 1966; Blong, 1970; Bariss, 1971; Bradley, 1980). In arid and semiarid climates, infiltration and evaporation cause a decrease in discharge downstream, resulting in deposition of sediment. As a gully headcut proceeds upvalley, the locus of deposition also moves upvalley, producing a backfilled fanlike deposit (Schumm, 1977, p. 152; Bradley, 1980). In addition, as a gully grows wide enough, material from bank caving is no longer transported during storm flows, and the gully walls reach a relatively stable configuration (Ireland and others, 1939; Blong, 1970; Bariss, 1971).

Ireland and others (1939) and Thornthwaite and others (1942) developed similar four-stage models of gully evolution. The four stages involve (1) initiation, involving channelization, coalescence of denuded areas, and sidewall cutting, (2) enlargement, involving headward erosion and vertical incision, (3) healing, in which gully sidewall slopes recede and vegetation is established on the gully floor, and (4) stabilization, in which healing continues and the gully fills.

Channelized Streams

Channelized or straightened stream channels commonly respond like gullies. Vertical incision results from concentration of flow that formerly spread over the valley floor. After or accompanying downcutting, channel side walls erode, usually by lateral channel erosion and mass wasting of vertical banks (Daniels, 1960; Daniels and Jordan, 1966; Emerson, 1971; Yearke, 1971; Barnard, 1977; Piest and others, 1977; Harvey and others, 1985; Simon and Hupp, 1986). In channelized streams, tenfold increases in channel area are common, which are attributed to both downcutting and bank-top widening. These changes result from a concentration of flood flows and increased channel gradient caused by channel straightening.

Most channelized streams evolve without major changes in channel pattern, and, after initial incision, are stable both vertically and horizontally. Channelized stream channels commonly remain straight. Alternate, midchannel, or point bars are noticeably absent. Barnard (1977) documented a notable exception along Big Pine Creek Ditch in Indiana.

METHODS OF ANALYSIS

Natural arroyo development requires tens to hundreds of years. In order to compress the time required to observe changes in arroyo morphology and the processes effecting those changes, controlled experiments were performed to document patterns of arroyo development following base level lowering. The experiments described herein model only postincisional arroyo development, and assume that this development is independent of the incision-triggering mechanism, except as discussed.

The differences between the experimental channels and real rivers or arroyos are important; therefore, a field study of arroyos also was undertaken in an attempt to verify the degree to which the experiments replicate nature. In many cases, because of the scale and the simplicity of the experimental design, either the same processes were not active in the field or they did not interact in the same manner. However, processes that have similar effects were either observed or implied by channel geometry, and the models developed during the experimental studies are analogous to the arroyos observed in the field.

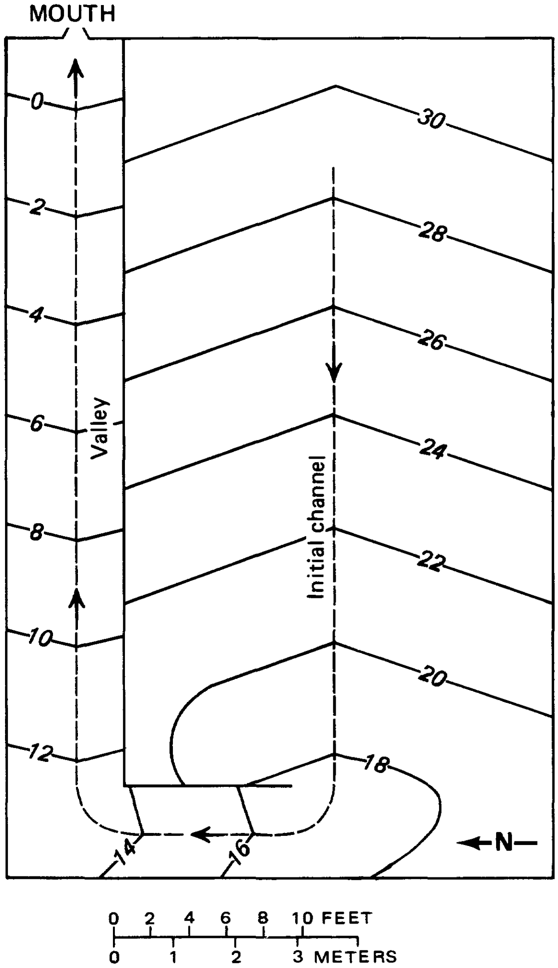


Figure 1. Initial topography in Rainfall Erosion Facility. Drainage basin, area above 18 cm elevation, comprises majority of Rainfall Erosion Facility. Valley segment runs along north wall of Rainfall Erosion Facility, at elevations below 12 cm. Precipitation was not applied to northernmost 2 m of facility

Experimental Design

Experiments were undertaken in the Rainfall Erosion Facility (REF) at Colorado State University, in Fort Collins, to study patterns of arroyo entrenchment and development. The REF is a container 15.3 m long, 9.2 m wide, and 1.8 m deep; it can be filled with various materials and can be subjected to simulated rainfall of varying intensities (Parker, 1977).

The REF was divided into a large drainage basin and a smaller valley (figs. 1, 2). The major drainage course had an initial slope of 1 percent. Precipitation was applied to the drainage basin, but not to the valley (fig. 3). The REF was filled with a mixture of 52 percent sand and 48 percent silt/clay (fig. 4) that had an average dry density of 1.53 g/cm^3. Base level was controlled by a movable weir at the outlet.

The experiments were continued in a variable-slope flume, 20 m long and 1.5 m wide. Streamflow was simulated by recirculating water from a settling basin to the head of the flume. Both installations contained movable carriages so that measurements of position and elevation could be made at any point along the channels.

The flume was filled with a mixture of 73 percent sand and 27 percent silt/clay (fig. 4) that had an average dry density of 1.81 g/cm^3. Adjustable with jacks, the flume was

Figure 2. Valley portion of Rainfall Erosion Facility with entrenched channel. The strings mark 1-m increments. Person standing in background is about 1.8 m tall. Flow is from bottom to top.

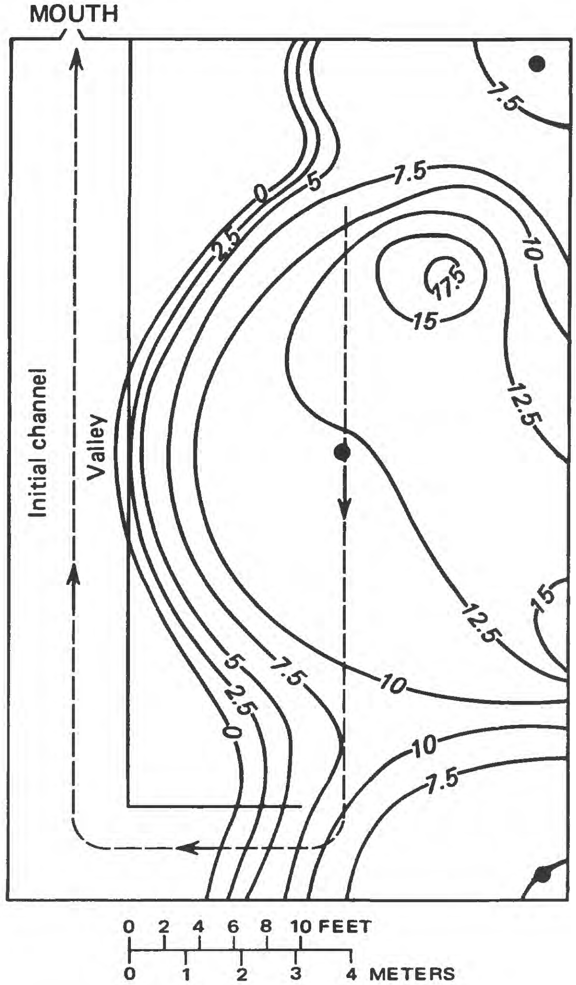


Figure 3. Precipitation distribution in Rainfall Erosion Facility and location of sprinkler nozzles.

tilted to a 1-percent slope. A tail box (fig. 5) at the mouth of the flume acted as a settling basin. The settling basin removed sand- and silt-sized particles so that the effect of clear-water discharge could be studied independent of headwater erosion, and to prolong the life of the recirculating pumps. When the effect of an upstream sediment supply was desired, sediment was fed into the channel from a vibrating sediment feeder. Base level was controlled by a movable weir at the outlet.

Differences in grain size between the REF and the flume were fortuitous. Material to fill both facilities came from a local quarry where material was described as sand and "topsoil." The sand and topsoil had been used in earlier experiments (Parker, 1977) and produced ample quantities of bed material and reasonable bank cohesion. The proportions of sand and topsoil were the same in the REF and flume, but it was found that the two shipments of topsoil were quite different (fig. 4). Nevertheless, both mixtures produced relatively high cohesion, as banks were commonly stable when undercut.

Experimental Procedure

The experiments in the REF and in the flume were divided into runs. In this report, the term "run" is used to denote a series of flows during which most extrinsic variables, such as base level or discharge, were held constant. After periods ranging from 30 minutes to 10 hours, precipitation or flow (depending on whether the REF or flume was being used) was stopped to allow measurement of cross sections and longitudinal profiles of the channel by means of a point gauge mounted on the carriage. Because stoppage and startup of the flow were gradual, neither produced an appreciable effect on arroyo morphology. The cross sections

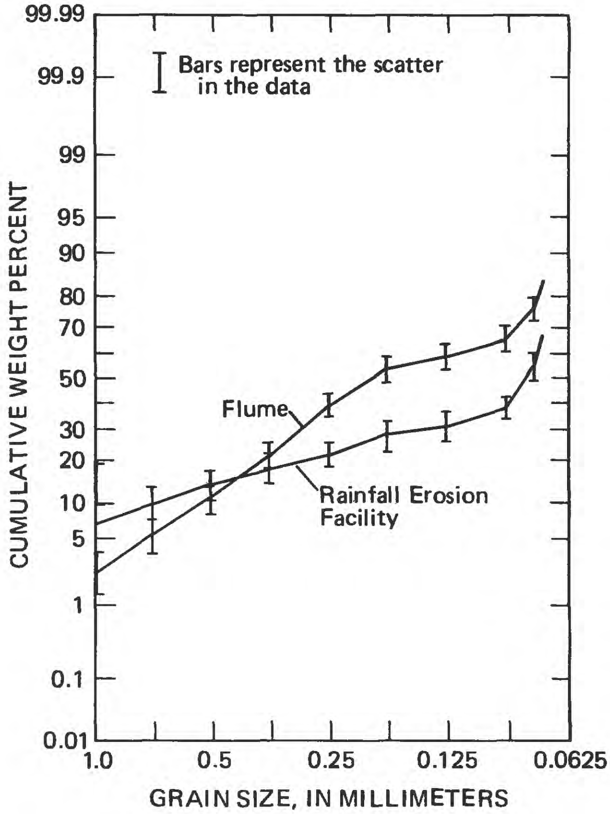


Figure 4. Cumulative grain-size distribution of Rainfall Erosion Facility and flume-source materials.

were measured at 1-m intervals along the valley, with cross-valley stationing of 5 cm or less. Water surface elevation from the time of the last measured discharge was recorded during the cross-section measurements. Longitudinal profiles were measured along the thalweg of the channel. During surveys, measurements were frequently taken at shorter distances in order to record small-scale features, such as scours, bars, or undercut banks.

Water and sediment discharge were measured in the same manner in both the REF and flume. A 20-L bucket was placed under the outlet of the channel, and the time required to fill the bucket was measured with a stopwatch. Water discharge was measured and recorded at 15- to 30-minute intervals, and the discharge was maintained at a fairly uniform rate. Random fluctuations in the pressure caused about a ±7 percent fluctuation (coefficient of variation) of discharge during a run. At the end of each run, the final discharge was recorded and the cross sections and the longitudinal profile were resurveyed.

Sediment samples were collected in a 3.8-L jar as the 20-L samples were too large to handle efficiently. The time required to fill the jar was measured with a stopwatch. The water-sediment mixture was allowed to settle for 5 to 24 hours, then it was filtered through 0.024-mm filter paper. The sediment was dried and weighed to compute sediment discharge.

The discharge, cross-section, and longitudinal profile measurements were processed by a computer program written for this purpose. The program corrected the measurements for elevation discrepancies in the REF and the flume. Channel cross-sectional area was corrected for the angle between the thalweg and the downvalley direction. From the cross sections and longitudinal profiles, various channel characteristics were calculated (fig. 6), including the following (appendix 1): wetted perimeter, hydraulic radius, channel top-width, maximum depth, average depth, width-to-depth ratio, water elevation, local slope of the thalweg, minimum and average bed elevation, energy slope between adjacent cross sections, and sinuosity of the channel downstream from each cross section. In addition, arroyo top-width, maximum depth, and area were measured from cross sections.

Time was recorded during all runs, but it was recorded differently in the REF and the flume. A summary of the various runs is listed in table 1. In the REF, flow time was initiated at the start of run 2 (flow time 0:00); run 3 started at flow time 38:00. In the flume, flow time was measured from the start of each run, so that each run (with the exception of run 17) started at flow time 0:00; run 17 was started at flow time 11:00 of run 16.

Field Procedure

The San Simon, San Pedro, and Santa Cruz Rivers (fig. 7) were studied in southeastern Arizona to identify the different phases of the development of arroyos, with specific regard to arroyo widening. They were chosen because they are long, continuous, somewhat sinuous trenches, similar to those studied during the experimental phase of this study, and because their early history is documented (Cooke and Reeves, 1976).

Five sites were studied on each of the three rivers (fig. 7, appendix 2). Sites were selected to represent the various types of reaches common to the three rivers. Additional considerations in site selection were ease of accessibility, minimal influence from tributaries, bedrock or manmade structures, and geographic variability along each of the three rivers. The San Simon River near Tanque, Arizona (sites 5 and 6), was controlled by structures (R.F. Hadley, written commun., 1985), but the effect of this control was not apparent.

Surveys were made at each site using a level and rod to determine the size and shape of the arroyo and channel cross section, and the local gradient of the channel. Where the channel was meandering, cross sections were measured at the apex of a point bar perpendicular to the arroyo, and at an adjacent velocity crossover perpendicular to the channel.

Channel banks were defined as the location of the first substantial growth of perennial vegetation. This usually consisted of cottonwood trees, but occasionally banks were defined by willow, salt-cedar, or mesquite trees. Width-to-depth ratios (F) were calculated from the cross sections as

Figure 5. Recirculating flume used in second series of experiments. Flume is 1.5 m wide.

the distance between the two banks (often one bank was a cut bank in alluvium with no vegetation) divided by the maximum depth of the channel (the difference in the elevation of the bank and the lowest part of the channel).

Some studied arroyos contain flood plains as well as active channels. Therefore, arroyo dimensions should be considered separately from channel dimensions. Arroyo dimensions reflect the history of entrenchment and channel migration, whereas channel dimensions reflect recent water and sediment discharge regimes (Graf, 1983).

Sediment samples were collected from channel deposits at each site and (when present) from the point-bar, bank, and flood-plain deposits, and from alluvium exposed in the arroyo wall. Five samples taken at equally spaced intervals along the channel, point bar, and flood plain were combined to form composite samples for each environment, ranging from 1 to 4 kg. Commonly the channel, and especially the point bar, was composed of cobbles and boulders with a matrix of sand and gravel. In these cases, a 10-decimeter by 10-decimeter grid was placed over a representative area. Where boulders or large pebbles were located at more than 25 percent of the grid points, a random number table was used to select 25 points at which the short, intermediate, and long axes of the grain underlying each of the grid points selected were measured. Where boulders or large pebbles underlay less than 25 percent of the grid points, every grain corresponding to a grid point was measured. Only grains longer than 2.5 cm were measured; smaller grains were sampled by the composite channel and point-bar samples described above. The measurements of pebble and boulder size were converted to weight using an average specific weight of 2.7 g/cm^3.

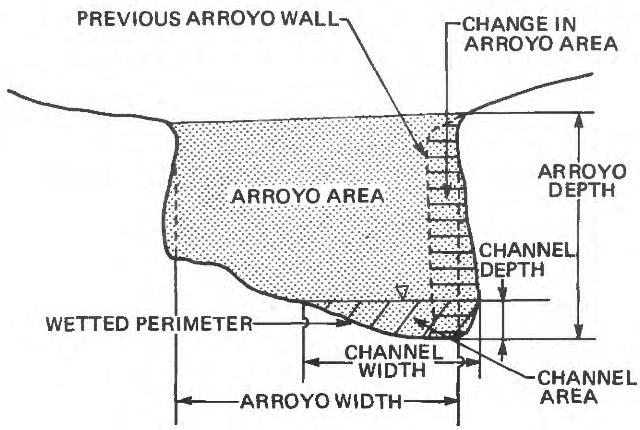


Figure 6. Definition sketch of arroyo and channel parameters.

Table 1. Summary of Rainfall Erosion Facility and flume runs

Run	Flow time (h)	Comments
		Rainfall Erosion Facility
1	No time record	The new sprinkler system was tested and evaluated with regard to record precipitation distribution and intensity. Various methods of measurement of discharge and sediment yield from the channel and the drainage basin were evaluated, and the methods described in the text were found to be the most accurate as well as the simplest.
2	0:00-38:00	The outlet weir was at grade with the channel. Precipitation intensity was variable, although even the highest intensities did not produce the expected discontinuous erosion. Several artificial headcuts were initiated in the channel, but these were quickly filled. Localized minor scour and fill produced a sinuous alluvial channel.
3	38:00-42:00	Base level was lowered by 1.25 cm. The channel straightened and became better defined, but it did not incise.
3.5	42:00-44:00	Base level was lowered by 3.5 cm. The channel incised into a single narrow trench and alternate bars were built within this channel. Sinuosity increased. The knickpoint produced by the lowered base level disappeared about 6 m above the mouth, without rejuvenating the drainage basin. The channel was stable after 2 hours.
4	44:00-56:00	Base level was lowered by 6.1 cm. Primary and secondary headcuts were formed, and they migrated upchannel, producing an excess of sediment which was deposited as alternate bars. Incision in the upper portions of the channel involved flattened knickpoints and generalized scour which produced less sediment than headcuts. Periods of high sediment production were marked by alternate bar and point-bar building with bank erosion and arroyo widening. Low sediment production caused straightening of the channel with little bank failure.
5	56:00-86:00	Base level was lowered by 7.5 cm. Unstable banks were higher than in previous runs, and bank failures produced large amounts of sediment, which induced more point-bar building than before. Alternate bar building and arroyo widening occurred throughout the channel. A 3-m reach near the mouth was braided.
6	86:00-103:00	The channel between the upper end of the valley and the mouth of the drainage basin was shortened and confined to rejuvenate the drainage basin. The increase in sediment delivery from the drainage basin, if present, had little effect on the channel.
7	103:00-108:00	Precipitation was increased, and average discharge increased by about 50 percent. Some bank failure occurred, but channel changes were minor.
		Flume
10	No time record	The flume was tested and discharge and sediment sampling procedures refined. The final channel was mostly alluvial and wide.
11	0:00-22:00	Base level was lowered by 7.2 cm. The initial headcut was wide, but further degradation after passage of the headcut left a narrow channel. Bed armor formed, limiting degradation. As knickpoint migration slowed, sediment production decreased, stopping point-bar building. Thus the channel stabilized.
12	0:00-17:00	Base level was lowered by 7.5 cm. As sediment production from knickpoint migration decreased, point bars were eroded. Downvalley migration of meanders was responsible for much arroyo enlargement in the lower channel.
13	0:00-8:30	Bed armor was removed in every other 2-m reach. Mobilization of fine material followed and induced further point-bar building and arroyo widening. The knickpoint which had stalled in run 12 migrated upvalley about 2 m.
14	0:00-11:30	Sediment was fed into the stable channel from run 13. Point-bar building was again reinitiated with accompanying arroyo widening.
16	0:00-11:00	The channel was regraded and subjected to an initial base level 5 cm lower than grade. After 7 hours, sediment was fed into the channel, producing results similar to run 14.
17	11:00-26:30	Base level was lowered by 4.1 cm. After 6 hours sediment was fed into the channel with effects similar to runs 14 and 16.

Where channel banks were definable and distinct from the point bar and arroyo walls, two samples were combined from each bank to form a composite bank sample. Where the cut bank was eroding alluvium, composite alluvium samples were made from five samples taken at equally spaced intervals from the cut banks.

Samples were dried, split, and sieved in the laboratory. After drying, the samples were split into samples of about 100 g, which were sieved for 15 minutes using 0.5 phi interval sieves in a standard Ro-Tap, following procedures outlined by Folk (1974). When the samples contained gravel coarser than 4.0 mm, the entire sample was sieved by hand to determine the percentage by weight of the coarsest fraction. The fraction of the sample finer than 4.0 mm was then split and sieved as described above.

The boulder point-count data were combined with the matrix-sieve data by weighting the matrix-sieve data according to the surface distribution obtained by the point count. The weight percentage in each size fraction of the combined boulder point count and matrix samples was used to compute mean grain size (M_Z) (Folk, 1974). Cumulative log-probability curves were plotted using grain size in phi units as the abscissa and cumulative weight in percent coarser than a given size as the ordinate.

The percentage of silt and clay in the channel perimeter (M) was calculated using the following equation:

$$M=\frac{(SC_c \times W)+(SC_b \times 2D)}{W+2D}$$

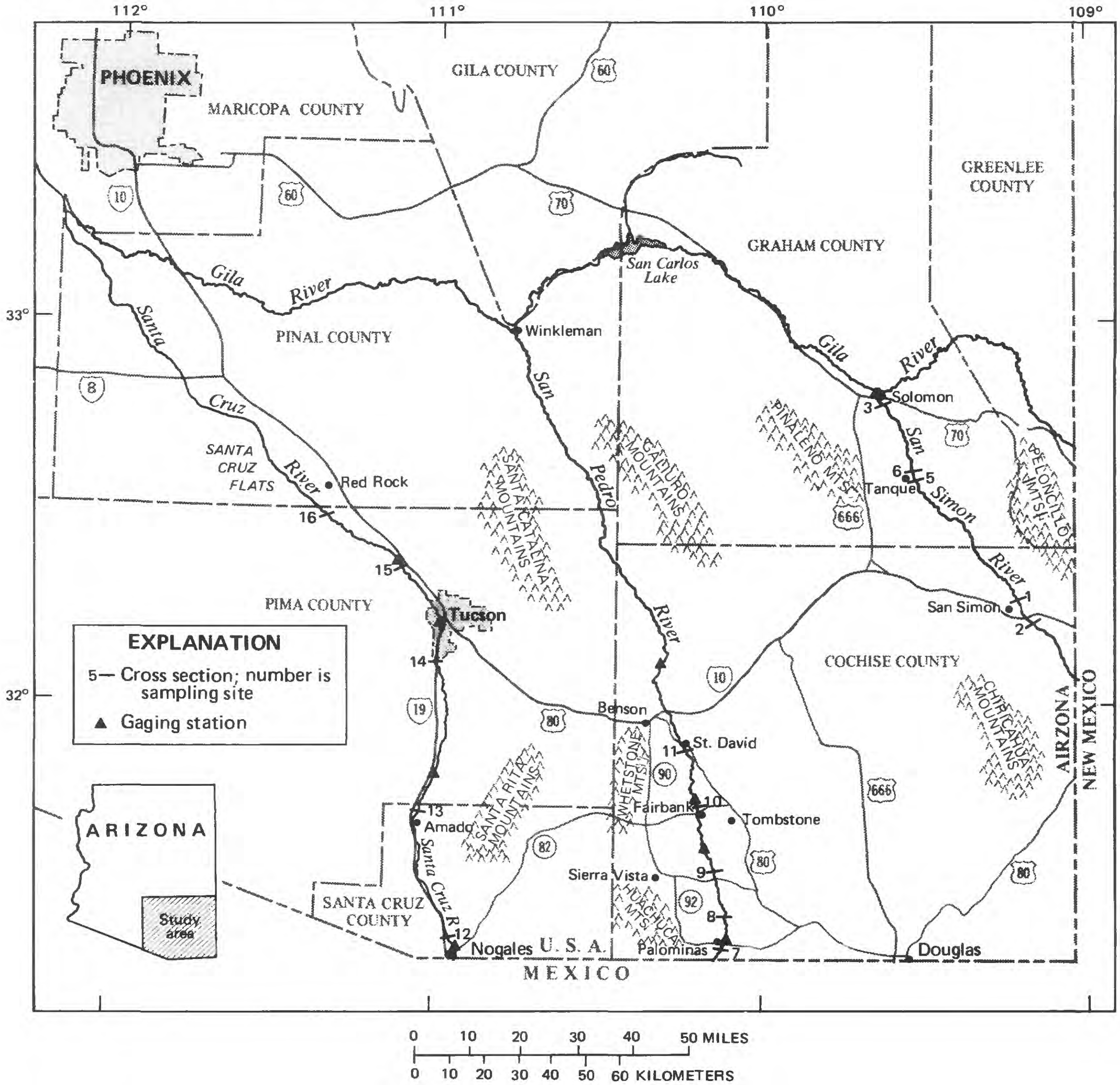


Figure 7. Location of study area and sampling sites along San Simon, San Pedro, and Santa Cruz Rivers, southeast Arizona.

where SC_c and SC_b are the percentage of material passing the No. 200 mesh sieve (0.074 mm) from the composite channel and bank samples, respectively, W is the width of the channel, and D is the maximum depth of the channel (Schumm, 1960).

Channel sinuosity (P), valley slope (S_v), and channel slope (S_c) were measured along 1- to 6-km reaches from 1:24,000 and 1:62,500 scale topographic maps. Reaches were chosen to represent conditions at arroyo cross-section sites.

The fieldwork of John Elliott (1979) on the Rio Puerco in New Mexico (fig. 8) closely parallels the author's fieldwork in southeastern Arizona. The Rio Puerco basin receives slightly greater amounts of precipitation than southeastern

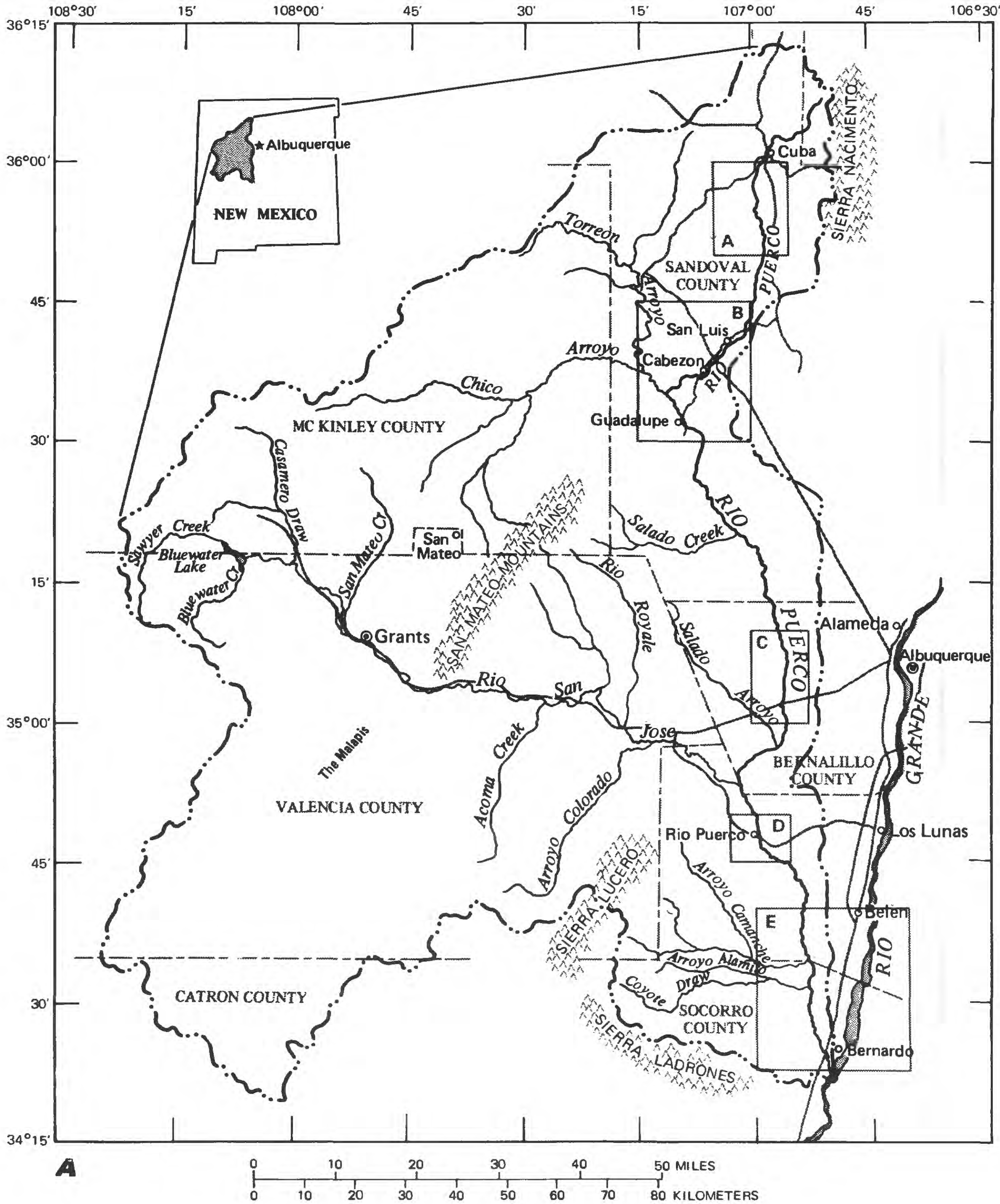


Figure 8. Rio Puerco drainage basin. *A*, Areas where sampling sites are located. *B* (facing page), Areas enlarged from *A*, showing approximate locations of cross-section sampling sites along Rio Puerco studied by Elliott (1979).

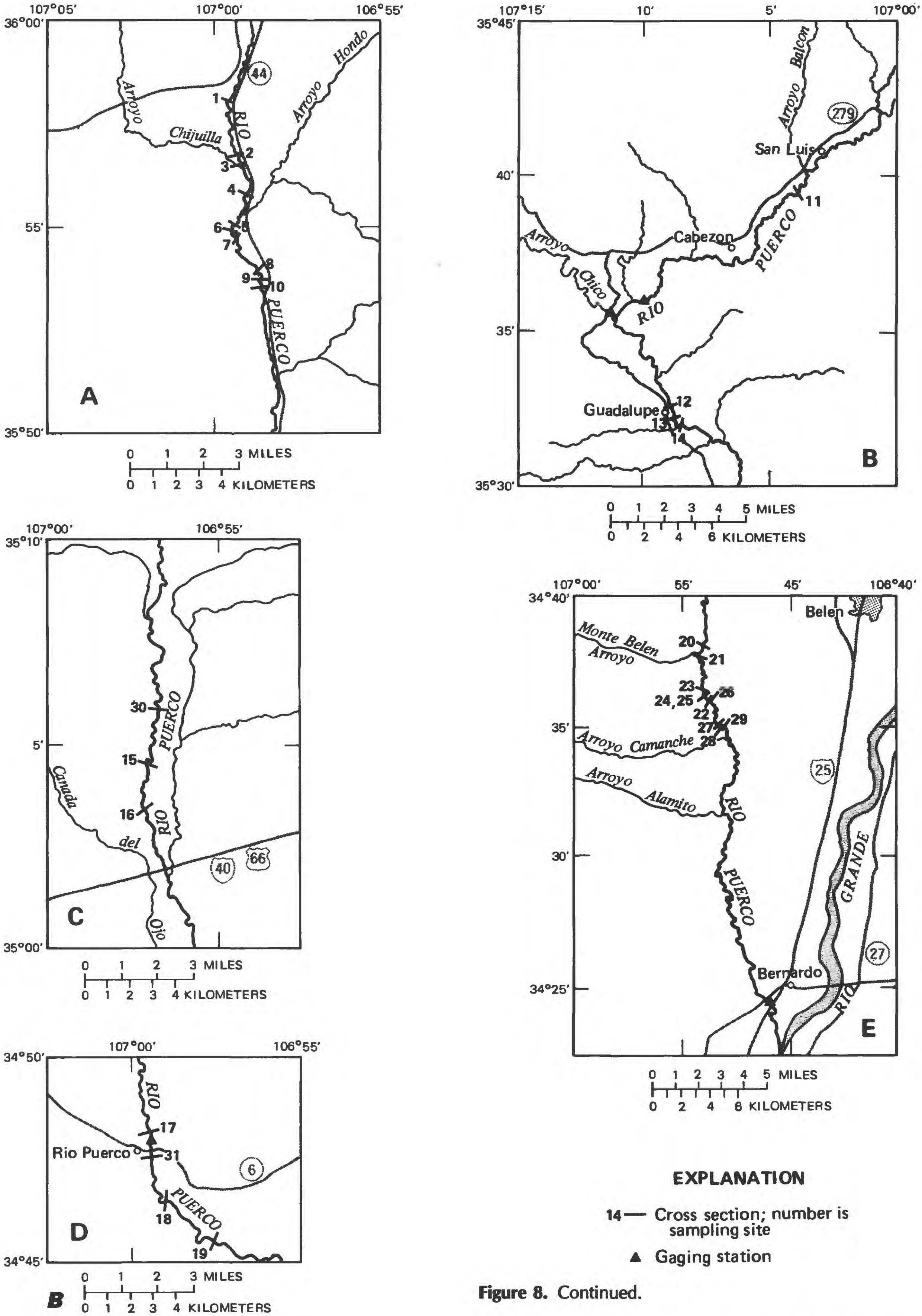


Figure 8. Continued.

Arizona, but rainfall patterns are similar. The most significant difference between arroyos of the Rio Puerco and those of southeastern Arizona is that Rio Puerco arroyos are entrenched into predominantly sand-size sediment.

Description of Field Area

The San Simon, San Pedro, and Santa Cruz Rivers are tributary to the Gila River (fig. 7). The San Simon River originates in New Mexico and flows north-northwest to its mouth on the Gila River near Solomon. The San Pedro River begins in Mexico, enters Arizona near Palominas, and flows north-northwest to join the Gila River at Winkleman. The Santa Cruz River originates 35 km east of Nogales, Arizona, flows south into Mexico, then back north into Arizona. After passing through Tucson, it flows onto Santa Cruz Flats, then into the Gila River south of Phoenix. Most of the flow of the Santa Cruz River is lost to infiltration and evaporation on Santa Cruz Flats. No dominant channel can be identified northwest of Red Rock, but a series of anastomosing channels eventually reach the Gila River.

Geology

The geology of southeastern Arizona is complex, and the rocks in the study area range in age from Precambrian to Holocene. Structurally and physiographically, the area is part of the Basin and Range province, which is characterized by isolated, subparallel mountain ranges that rise above adjacent desert plains (Thornbury, 1965).

Tertiary and early Quaternary normal faulting resulted in the Basin and Range topography, which has been modified since movement ceased along these faults. The faults that form the boundary on one or occasionally both sides of the north-south-trending mountain ranges are buried beneath Quaternary basin-fill gravel.

During early phases of fault-block movement, the basin occupied by the San Pedro River and probably the basin occupied by the Santa Cruz River had internal drainage. During this time, boulder, cobble, and pebble gravel filled the basins to as much as 1,000 m in thickness (Gilluly, 1956; Drewes, 1972).

Three Pleistocene erosional surfaces were identified in both Santa Cruz and San Pedro Valleys (Bryan, in Gilluly, 1956; Drewes, 1972). Each younger surface is 6 to 30 m lower than its older surface. The erosional surfaces are interpreted as being formed by changes in local base level produced by integration of drainage with the Gila River. Melton (1965) found evidence for lowering of base level induced by drainage integration in San Simon Valley, although he did not identify erosional surfaces.

Hydrology

The climate in southeastern Arizona is typical of the Sonoran Border Zone (Thomas, 1962) and is characterized by hot, dry summers and mild, dry winters. Within a drainage basin, the effect of elevation dominates local climatic conditions. Average annual rainfall ranges from 230 to 635 mm per year (Sellers and Hill, 1974). Desert plains, such as at San Simon, Arizona, receive small amounts of rainfall, while mountain ranges, such as the Pinaleno, Chiricahua, Huachuca, Santa Rita, and Santa Catalina Mountains (fig. 7), receive larger amounts of rainfall. Most rainfall occurs during July, August, and September as the product of convective storms. These thunderstorms which are generally of short duration and limited aerial extent produce only local runoff.

In contrast to these convective storms, larger storms capable of producing large floods are rare. The largest recorded rainfalls occur during August and September, and result from tropical hurricanes originating in the Pacific Ocean and Gulf of California. These storms are infrequent, however, occurring an average of once every five years (Sellers and Hill, 1974). Winter precipitation amounts are generally small. Occasionally, however, winter storms, often one after another, pass through Arizona. These storms produce light rains that last for about two days (Sellers and Hill, 1974). When several of these storms pass through Arizona in succession, severe flooding can occur.

Evaporation is as important in long-term water budgets as precipitation. Land pan evaporation (the amount of water evaporated from a large pan mounted 15.2 cm above the ground) ranges from 200 to 270 mm per year (Sellers and Hill, 1974). Clearly, most of the precipitation in this area is lost to evaporation.

Cooke and Reeves (1976) analyzed long-term records available for southeastern Arizona to identify changes that might have induced the period of accelerated erosion during the late 1800's. They came to the following conclusions regarding precipitation trends since the 1860's (Cooke and Reeves, 1976, p. 78–79): (1) there were no statistically significant changes in annual, annual summer, or annual nonsummer precipitation; (2) drought (periods of three or more years of below-normal precipitation) and wet periods are a feature of the precipitation pattern, and droughts are, at times, followed by wet years; (3) there was a statistically significant increase in the frequency of light rains (0.25 to 12.49 mm per day) during the period of record; and (4) there was a slight decrease in heavy rains (greater than 25.40 mm per day) during the period of record.

The San Simon, San Pedro, and Santa Cruz Rivers are fairly typical of rivers in an arid climate. Streamflow is intermittent and floods are flashy. Correlations between average or maximum discharge and drainage basin area are poor (table 2). Computations of average flows bear little relation to the floods that excavate the arroyos in which these rivers flow.

Nearly all of the maximum floods of record occurred during August, September, October, or December (U.S. Geological Survey, 1975). Those occurring during August, September, and October result from tropical hurricanes that

Table 2. Flow characteristics of San Simon, San Pedro, and Santa Cruz Rivers, Arizona, and Rio Puerco, New Mexico
[Mean annual and maximum discharge data from U.S. Geological Survey, Water Resources Data for Arizona]

Station	Mean annual discharge (m^3/s)	Maximum discharge (m^3/s)	Bankfull discharge[1] (m^3/s)	Mean annual flood[2] (m^3/s)	Drainage area (km^2)	Period of record (yr)
San Simon R. near Soloman	0.354	779	137	158	5,677	43
San Pedro R. at Palominas	.864	623	177	198	1,919	35
San Pedro R. at Charleston	1.68	2,780	212	237	3,157	66
San Pedro R. near Tombstone	1.15	524	215	250	4,507	10
San Pedro R. near Benson	.830	232	176	208	6,475	11
Santa Cruz R. near Nogales	.651	484	153	189	1,380	58
Santa Cruz R. at Continental	.498	510	138	161	4,305	32
Santa Cruz R. at Tucson	.598	470	142	188	5,755	72
Santa Cruz R. at Cortaro	1.03	481	210	236	9,070	34
Rio Puerco near Guadalupe	.365	196	68.8	81.8	1,088	30
Rio Puerco at Rio Puerco	1.61	1,070	270	340	17,068	43
Rio Puerco near Bernardo	1.30	532	151	182	19,036	42

[1] Bankfull discharge is flood with a recurrence interval of 1.5 yr (Leopold and others, 1964).
[2] Mean annual flood is flood with a recurrence interval of 2.33 yr (Leopold and others, 1964).

occasionally pass through Arizona, while the floods occurring in December result from winter storms producing light rains, but occurring one after another within several days (Sellers and Hill, 1974). Large floods also occur occasionally in July but rarely in March (U.S. Geological Survey, 1975).

CHANNEL PATTERN AND ARROYO DEVELOPMENT

Unstable Arroyos with Sinuous Channels—Experimental Examples

Following rejuvenation of the channels in the REF and flume, knickpoints formed and migrated upstream, producing narrow, entrenched channels. Incision of the channel at a given cross section was not always instantaneous, but it did proceed rapidly as a knickpoint passed, followed by a decreasing rate of incision until incision ceased (Begin and others, 1980, 1981). As the rate of incision decreased, sediment that was produced upstream of a given reach was stored, first in alternate bars, later in point bars. When incision was sufficiently deep to create unstable oversteepened banks, bank failure and point-bar growth reinforced one another.

The first run in which incision was sufficiently deep to create potentially unstable banks was run 4. Runs 3 and 3.5 had been initiated by dropping the base level of the REF channel by 1.3 and 3.5 cm, respectively (table 1). At the start of run 4 (flow time 44:00), base level was lowered an additional 6.1 cm so that the channel near the mouth was entrenched 10.9 cm below the original valley floor.

Almost immediately after passage of the primary knickpoint produced by lowering base level at the start of run 4, the arroyo walls began to fail. Arroyo wall failure occurred rapidly between 1.0 and 2.0 m above the mouth. At this time, the right bank was at the outside of a bend between 1.0 m and 2.2 m. The flow was directed against this bank, which it undercut, causing the bank to fail. By flow time 46:00, the arroyo had widened further by undercutting and bank failure, but upstream migration had slowed, causing a reduction in sediment load (fig. 9). The reduced sediment load induced point-bar erosion, which caused the channel to straighten, to degrade somewhat, and to abandon the sinuous course that had directed the flow against the arroyo wall. The arroyo 0.96 m above the mouth was 45 cm wide and 10.2 cm deep at flow time 46:00 (fig. 10).

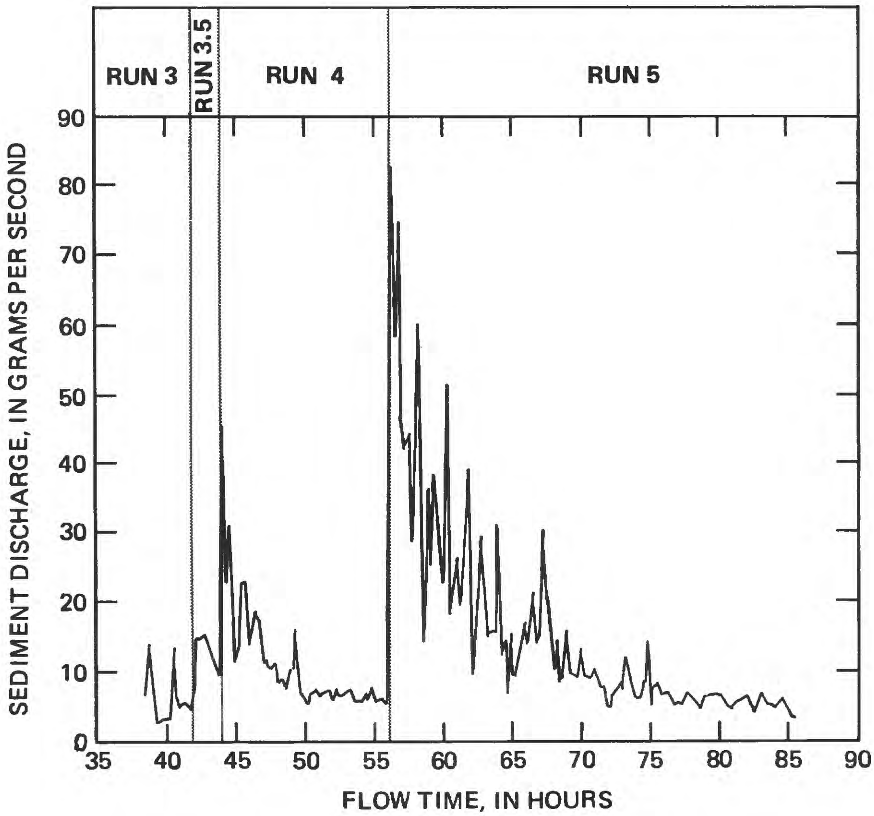


Figure 9. Sediment discharge at mouth of Rainfall Erosion Facility during runs 3 through 5.

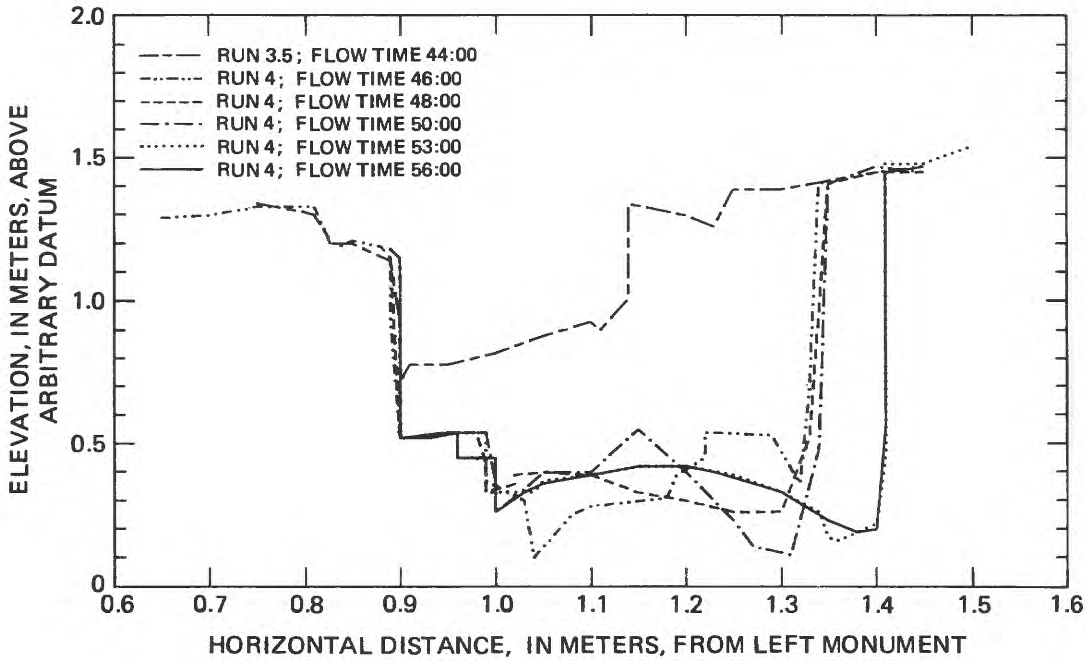


Figure 10. Development of arroyo at 0.96 m during run 3.5, flow time 44:00, through run 4, flow time 56:00. Vertical exaggeration 3×.

After the initial overloading of the channel with sediment produced by knickpoint migration and arroyo wall failure, the channel degraded steadily until a stable level was reached. Degradation was generally accompanied by lateral shift of the thalweg. As measured by the average bed elevation of the channel, this stable level was reached by flow time 46:00 at 0.96 m, 48:00 at 1.96 m, and 50:00 at 2.95 m and 3.96 m. Above 4 m, the channel continued to degrade throughout run 4.

Once a stable elevation was reached at a given point, the thalweg continued to shift laterally (fig. 10). Lateral migration of the thalweg was self-perpetuating. As the flow undercut a bank, the bank failed, and the failed material partially blocked the channel. Sediment moving as bedload was deposited behind this material, generally as a uniformly thick sheet on the point bar and channel (fig. 11). This sediment was coarser than sediment normally deposited on point bars. As the failed block was eroded away and the velocity in the thalweg returned to normal, the thalweg portion of the channel was scoured, and sediment deposited on the point bars was too coarse to be moved. This accretion of the point bar forced the channel even further against the original cut-bank wall. This process of point-bar formation is dependent on bank failure, and it is, therefore, different from the processes responsible for formation of point bars in some other experiments that modeled river meanders (Friedkin, 1945; Schumm and Khan, 1972).

Periods of arroyo widening commonly were preceded by, or accompanied by, increases in channel width (W_c) and width-to-depth ratio (F_c) (figs. 12, 13). Periods of channel incision, and to a lesser extent, periods of arroyo stability, were characterized by relatively narrow channels. F_c was low during the period of downcutting at the cross section measured at 0.96 m above the mouth (flow time 44:00 to 46:00). The period of maximum point-bar deposition at the cross section at 0.96 m (flow time 48:00 to 50:00) corresponds to the largest channel widths and width-to-depth ratios observed in run 4. As the rate of point-bar formation decreased, the width and width-to-depth ratio of the channel began to decrease. After flow time 53:00, the point bar ceased to grow, the arroyo did not widen, and both channel width and width-to-depth ratio continued to decrease for the remainder of run 4. The width-to-depth ratio of the arroyo increased from about 3.7 at flow time 44:00 to 4.4 at flow time 46:00. The width-to-depth ratios of the arroyo at 0.96 m and at 1.96 m (fig. 13) stayed within this range throughout run 4 as increases in arroyo width were offset by increases in arroyo depth.

During specific times during run 4, the slope of the energy line fluctuated significantly (fig. 14). Observations

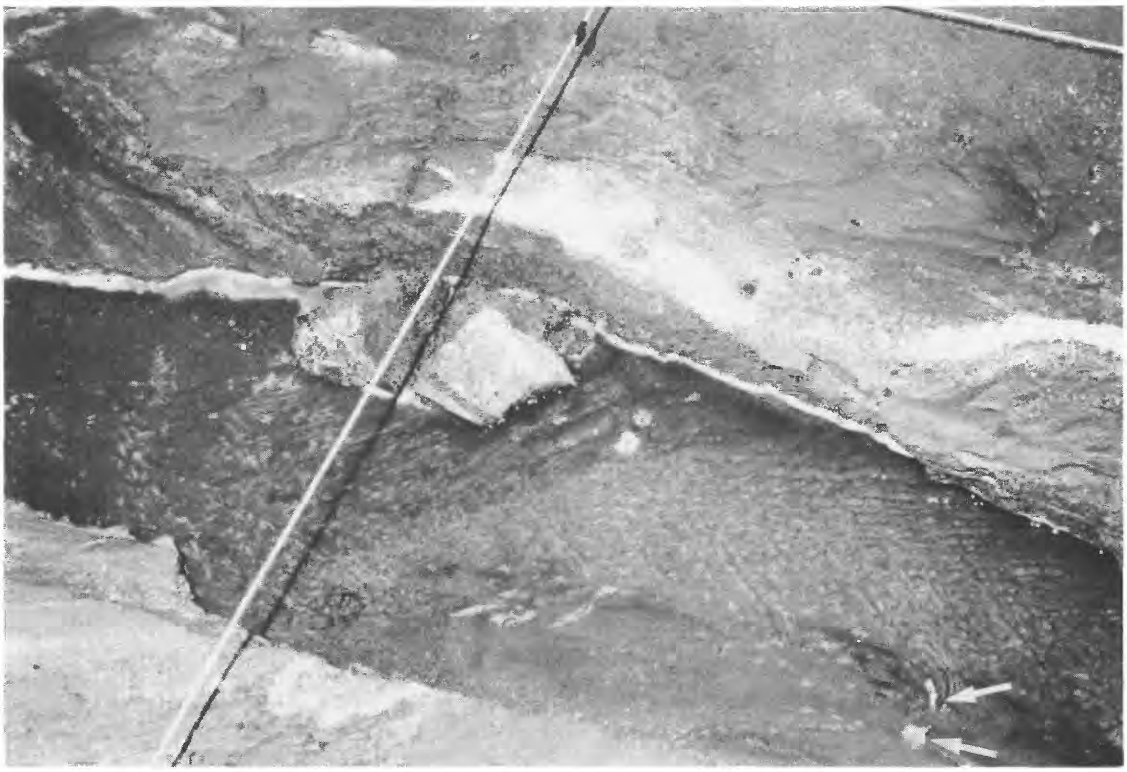


Figure 11. Recently failed block of bank material blocks channel in Rainfall Erosion Facility at 2 m, at about flow time 45:00. White flags in lower right corner (arrows) mark left water surface prior to bank failure and are covered by about 1 cm of water dammed behind failed material. Relatively light colored sand bedload is deposited upstream of failed bank material. Channel is about 30 cm wide at string. Flow is from right to left.

indicate that the energy slope was as high as 0.1 immediately following lowering of base level (flow time 44:00). Measurements indicate that the energy slope was 0.026 at flow time 46:00. During these first two hours of run 4, the maximum downcutting and sediment production rates were observed, but, because of the high slope, no sediment storage occurred. However, when the energy slope dropped below 0.019, sediment began to be stored as an alternate bar.

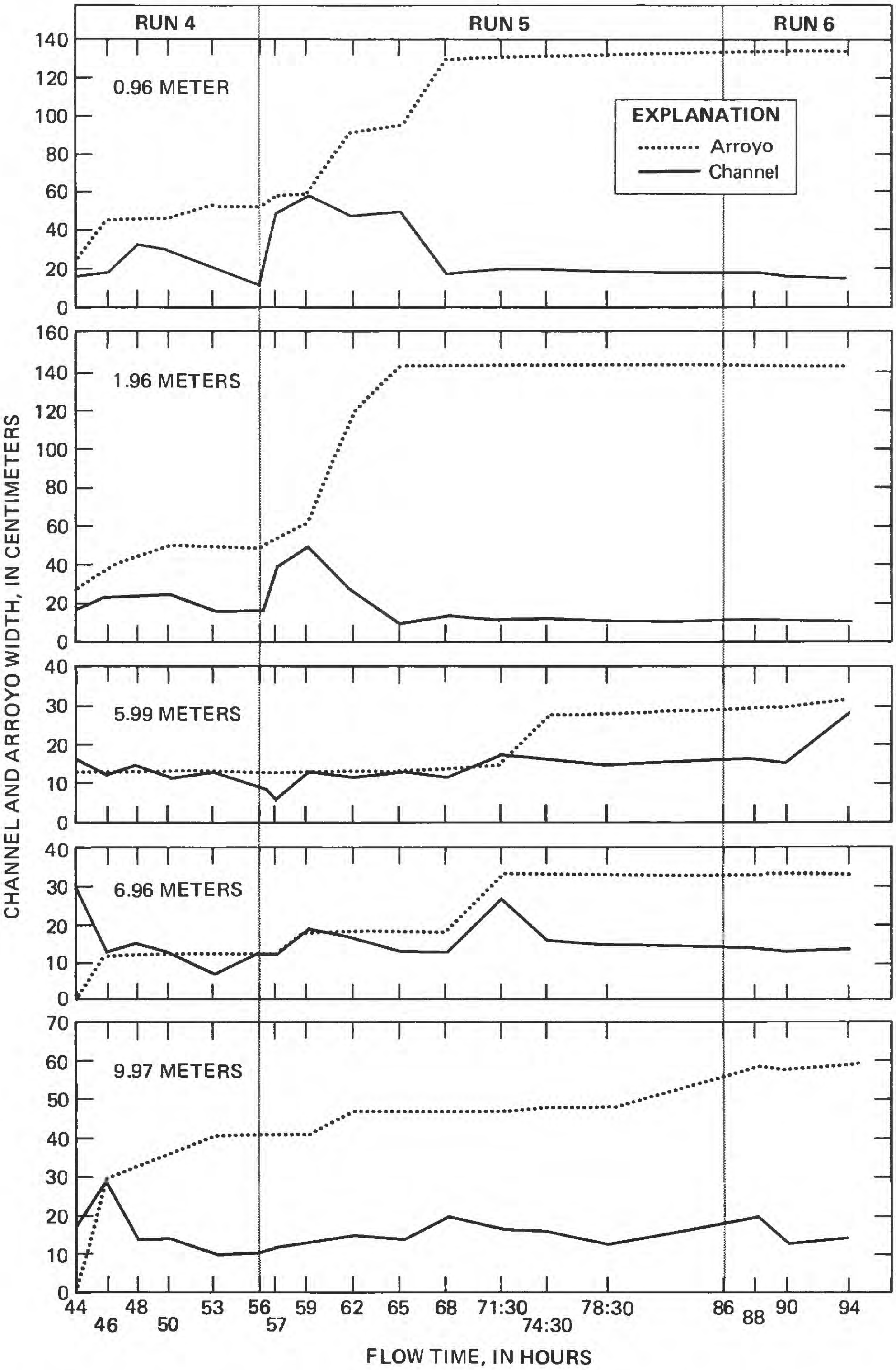


Figure 12. Changes in channel width (W_c) and arroyo width (W_a) with time at selected cross sections, runs 4 through 6 in Rainfall Erosion Facility. Vertical scale differs from plot to plot.

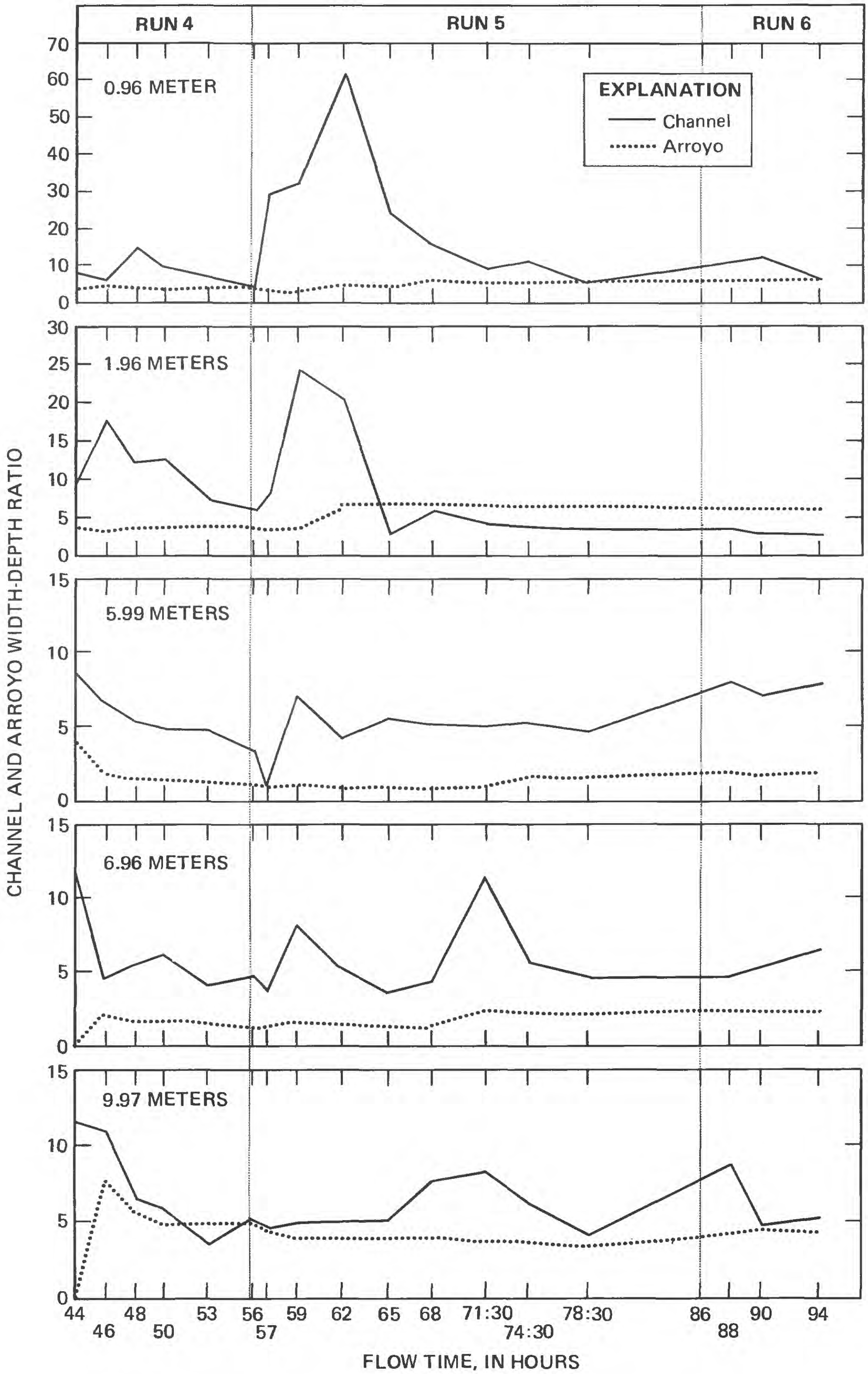


Figure 13. Changes in channel width-to-depth ratio (F_c) and arroyo width-to-depth ratio (F_a) with time at selected cross sections, runs 4 through 6 in Rainfall Erosion Facility. Vertical scale differs from plot to plot.

Incision was more gradual in upstream reaches than near the mouth, and the arroyo did not widen as rapidly as it did downstream. The channel above 5 m degraded slowly but steadily throughout runs 3 through 5. Downstream, where incision was localized at knickpoints and headcuts, rapid erosion overloaded the channel. The upstream channel was consistently scoured clean, and all material eroded by channel incision was transported to lower reaches.

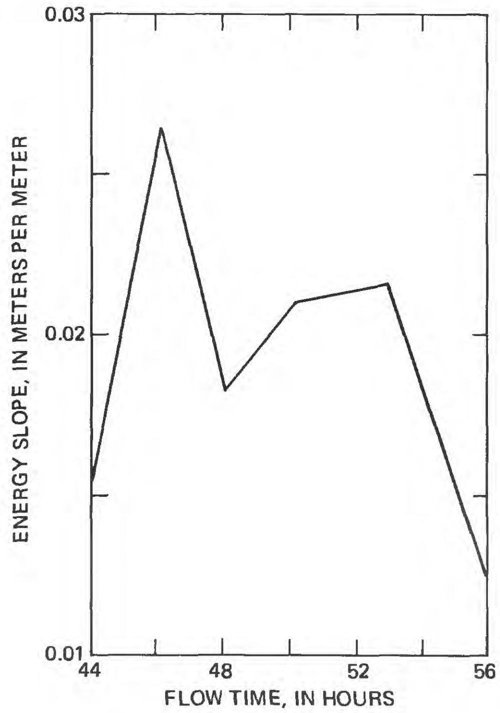


Figure 14. Fluctuation of slope of total energy head measured at 0.96 m, at specified times during run 4.

The cross section 5.99 m above the mouth degraded 14.4 cm during the 18 hours before flow time 62:00, but it was only 13 cm wide (fig. 15). During the next 6 hours, the arroyo was stable with this narrow, deeply incised geometry.

Upstream, entrenched meanders incised at the same slow rate as at 5.99 m. No sediment was stored along the slip-off slopes of these meanders. Cut banks of the entrenched meanders eventually failed, however, and sediment from the failed blocks of material overloaded the channel downstream, including the 5.99-m cross section, and it was stored in alternate bars (flow time 71:30, fig. 15). Lateral thalweg shifting then eroded and undercut banks opposite alternate bars along the channel downstream of the initial failure. Point-bar building and bank failures then reinforced each other as observed at the cross section at 0.96 m in run 4.

The width of the channel at 5.99 m increased during point-bar formation; it had been narrow before flow time 68:00 when the arroyo was stable (fig. 12). The width-to-depth ratio of the channel did not increase above 5.5 during point-bar building and arroyo widening as observed earlier (fig. 13). The width-to-depth ratio of the arroyo remained below 2.

Initiation of arroyo widening was apparently dependent in part on supply of sediment during the REF experiments. Knickpoint migration produced large amounts of sediment that overloaded the channel. Once the knickpoints stabilized, however, the point bars responsible for forcing flow against the arroyo walls were eroded. This effectively stopped arroyo widening. In order to study the effect of sediment delivered

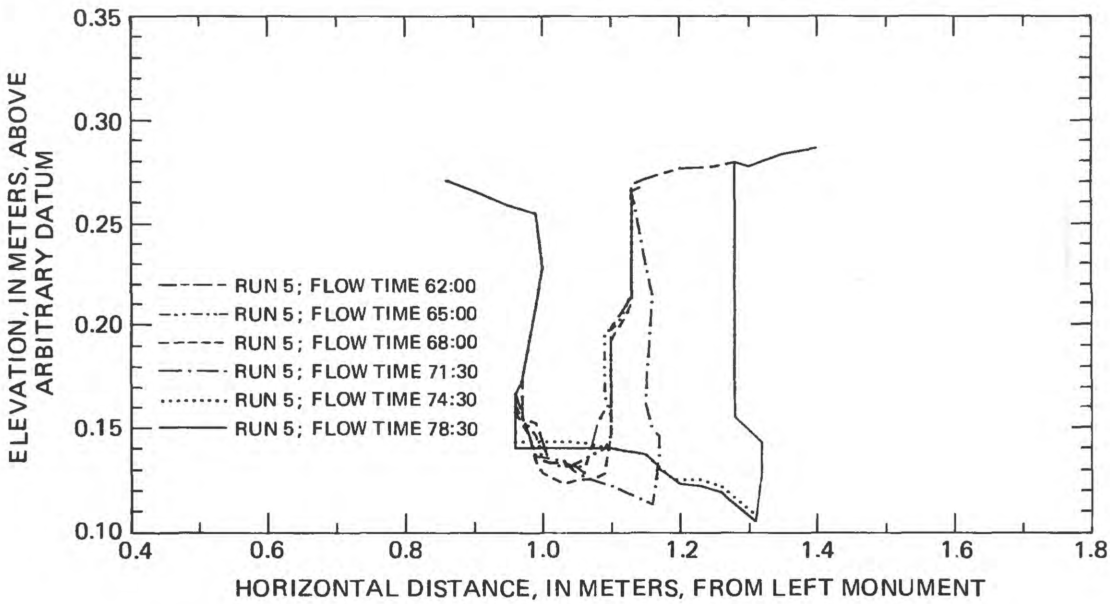


Figure 15. Development of arroyo at 5.99 m during run 5, flow time 62:00 through 78:30. Vertical exaggeration 3×.

to the channel independent of knickpoint migration, a sediment feeder was utilized during run 14.

The sand fed into the channel during run 14 was carried at first in the thalweg. Without bank failure, point-bar building was slow. An alternate bar had formed during runs 12 and 13 between 6 and 7 m, but it was unchanged during the last 7 hours of run 13. The cross section at 6.00 m (fig. 16) and photographs of the reach from 6 m to 7 m (fig. 17) show the slow building of this bar in response to the additional sediment transported during run 14. The bar directed the flow to the opposite bank which was undercut promoting arroyo widening.

The width of the channel increased while the alternate bar was building (fig. 18). The width-to-depth ratio of the channel also increased, although not steadily, during alternate-bar building (run 13, flow time 8:30 to run 14, flow time 4:00, fig. 19). Between flow time 4:00 and 11:30 of run 14, channel width and width-to-depth ratio fluctuated as the arroyo widened slightly and the channel degraded. The values of arroyo width that are less than channel width (fig. 18) are due to undercut banks.

These examples illustrate how bedload transport initiates lateral instability of laboratory channels when bedload is stored temporarily as alternate or point bars. Lateral channel migration induces bank failure, which reinforces point-bar building and thus lateral migration (fig. 20). This positive feedback at a section is unique to channels receiving massive bank failures or landslides, relative to their size, such as experimental channels. Bank failures rarely dam the channel in natural rivers.

In the experimental channels in which positive feedback was observed, about two-thirds of the total eroded sediment was eroded by lateral migration of the sinuous channel. The remaining one-third was eroded during initial channel incision.

Unstable Arroyos with Sinuous Channels—Field Examples

All actively eroding arroyos observed in southeastern Arizona contain coarse-grained point bars. Coarse-grained point bars occur in meandering channels, but they differ in form and particle size from point bars formed in finer grained sediments (McGowan and Garner, 1970). At the San Simon, San Pedro, and Santa Cruz Rivers, coarse-grained point bars occur at 10 of the 15 measured reaches. At four of the reaches, however, the point bars are heavily vegetated and mantled by fine-grained deposits, and channel banks are stable. In these four reaches where the banks coincide with arroyo walls, accumulations of failed material from the arroyo walls at the base of the bank are commonly vegetated.

Cross sections measured at reaches with active coarse-grained point bars (fig. 21) show that the channels meander across arroyo floors and are eroding the base of arroyo walls at the apex of the meanders. Arroyo walls are unvegetated and nearly vertical where the channel meanders against them (fig. 22). The failed bank material is eroded quickly. The physiographic features at station 9 are shown in figure 23, and are described using the terminology of McGowan and Garner (1970).

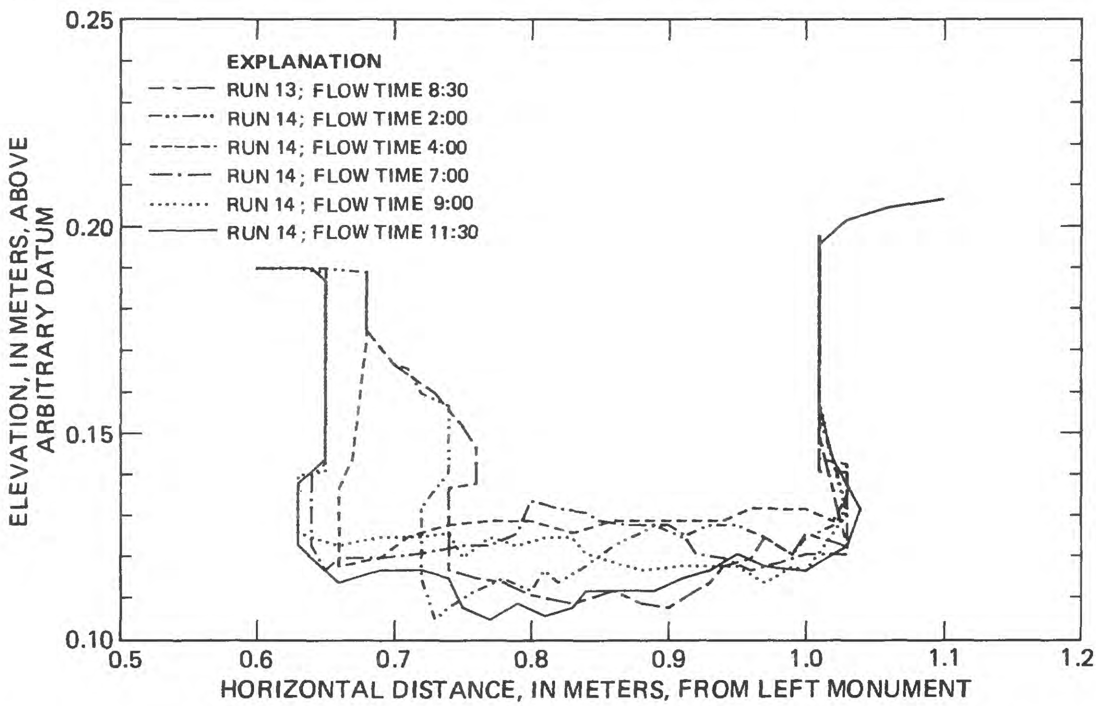


Figure 16. Development of arroyo at 6.00 m, during run 13, flow time 8:30, through run 14, flow time 11:30. Vertical exaggeration 3×.

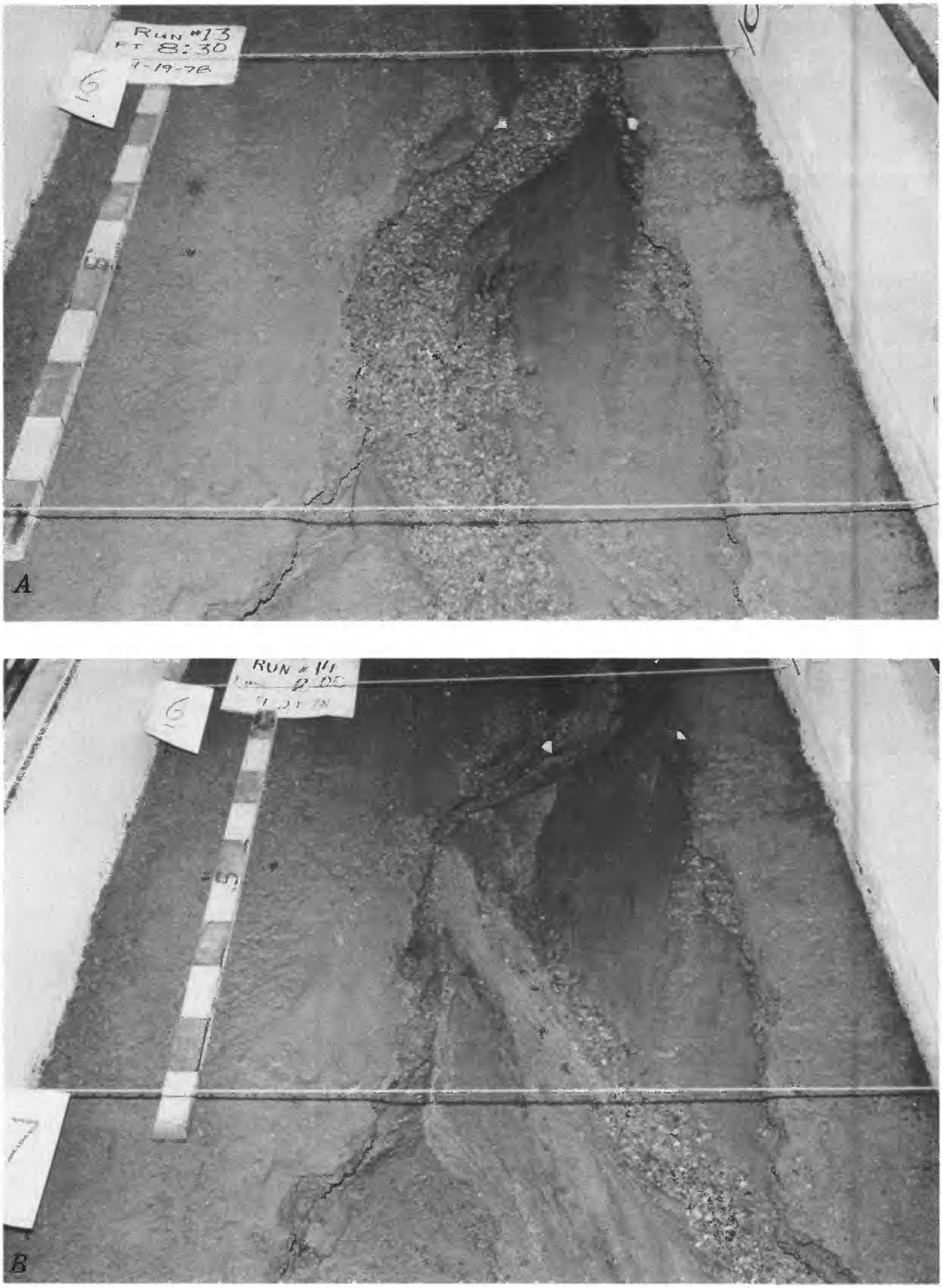


Figure 17. Reach between 6 and 7 m during run 13 at flow time 8:30 (*A*) and during run 14 at flow time 2:00, after sediment was fed into channel (*B*). Strings are 1 m apart. Flow is from bottom to top.

The coarse-grained point bars are composed primarily of poorly sorted gravel (table 3) with some sandy areas on the surface. Point-bar chute channels are common to all active coarse-grained point bars (figs. 21, 22, 23) and are present on some inactive bars. The bars are 90 to 210 m wide (table 4), although the wider bars are vegetated in places.

Unstable Arroyos with Braided Channels—Experimental Examples

Many widening arroyos contain braided channels, and in them both arroyo walls may erode. This was observed experimentally along one reach during one run in the REF. At flow time 56:00, base level was lowered 7.5 cm to initiate run 5. Bank failure began shortly after the headcut passed a given point, but it was of much larger proportions than during run 4 (fig. 24). The most dramatic bank attack was on the right bank below 1 m. However, downvalley migration of the cut bank between 2.5 m and 3.5 m soon caused the thalweg to shift away from the right bank (fig. 25). A retaining fence was placed on the left bank at flow time 64:00 to prevent any further arroyo widening as the channel was approaching the wall of the REF.

A bar that was built between 0.5 and 3.5 m was larger than any point bar observed in this study. When bank failures blocked the channel, flow spread across the entire bar, but the bar was extensive and deposition was not concentrated

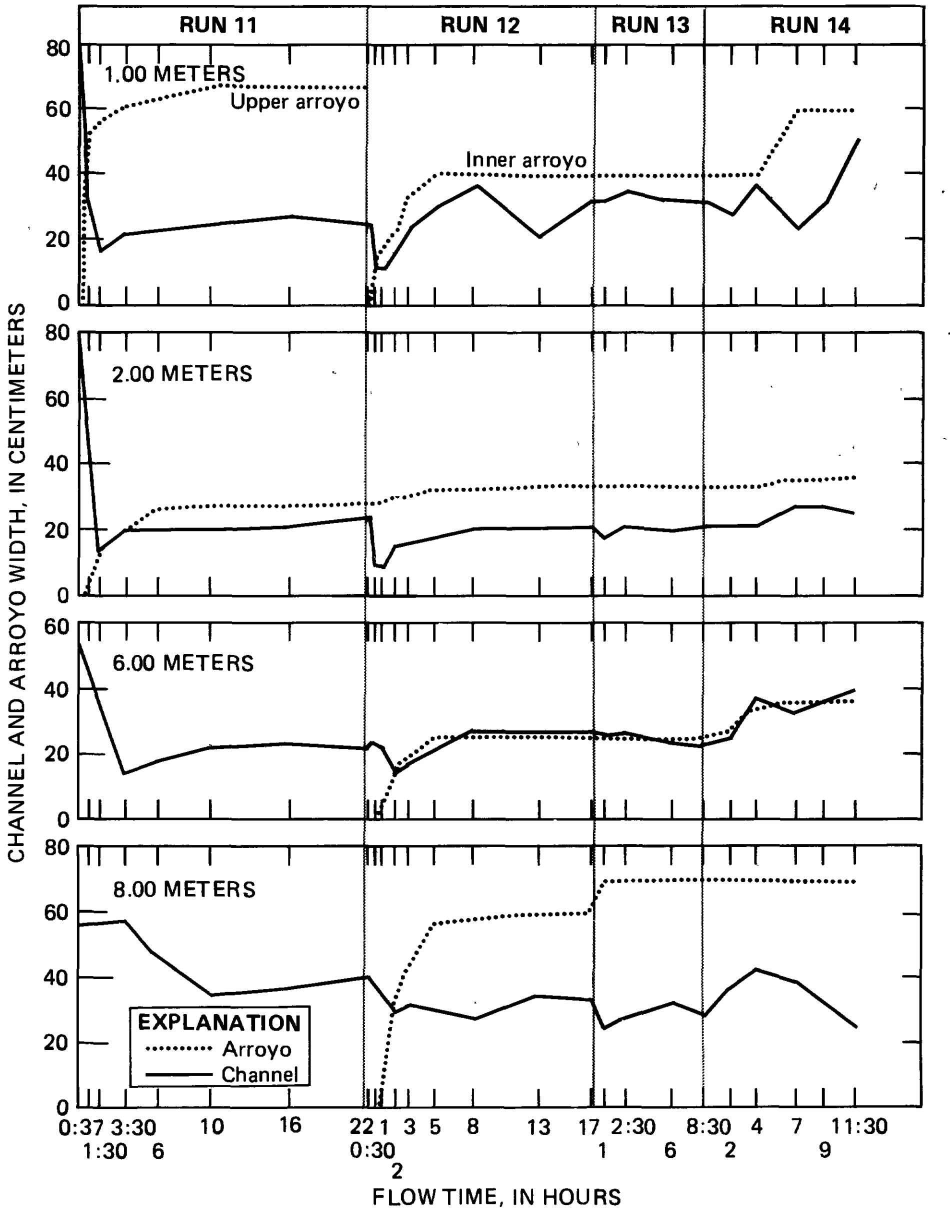


Figure 18. Changes in channel width (W_c) and arroyo width (W_a) with time at selected cross sections, runs 11 through 14 in flume.

near the channel; consequently, the channel braided. Originally (flow time 57:00 to 59:00), flow was confined by the arroyo after a bank failure, as with previously examined reaches. This corresponds to a period of point-bar building with a wide channel, low arroyo width-to-depth ratio, and increasing channel width-to-depth ratio. After flow times

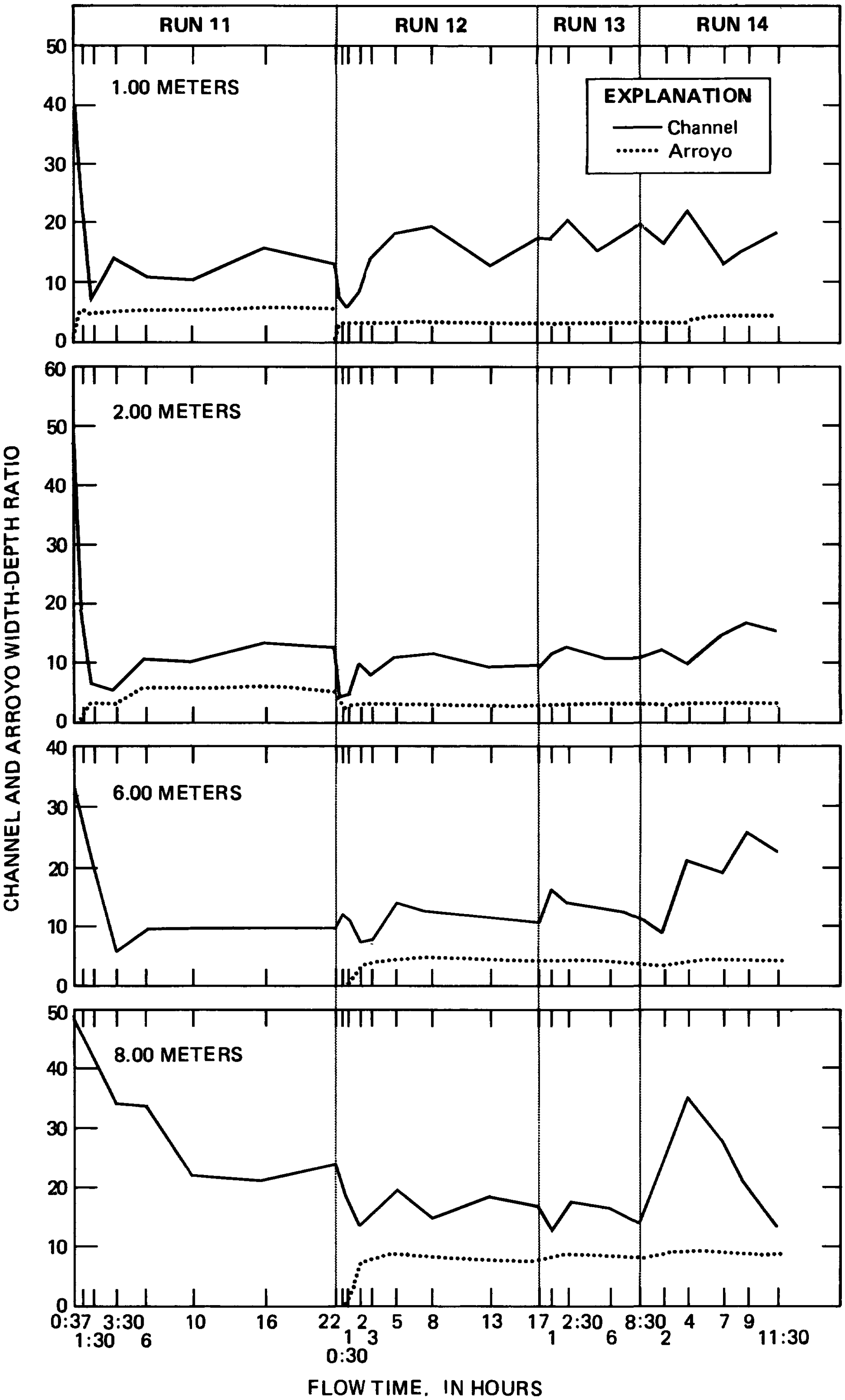


Figure 19. Changes in channel width-to-depth ratio (F_c) and arroyo width-to-depth ratio (F_a) with time at selected cross sections, runs 11 through 14 in flume.

59:00 at 1.96 m, and 62:00 at 0.96 m, the bar aggraded and degraded across its entire width (fig. 25). During this period, the width and width-to-depth ratio of the channel decreased while the arroyo widened. Deposition on the bar no longer forced the channel against the cut bank. Arroyo widening on the left bank was accomplished by downvalley migration of the meander. Bank failures occurred on the right bank when the main channel was blocked, and flow spread across the flat bar. In most other cross sections, the convex bank was protected by an outward-sloping point bar.

At the beginning of channel braiding, the arroyo was 60 cm wide and 22 cm deep. The arroyo increased in width to 144 cm by flow time 65:00 with no change in arroyo depth.

The channel between 3.85 and 4.50 m was straight at flow time 59:00, but it was oblique to the downvalley direction (fig. 26). This straight reach extended downvalley, widening the arroyo as it did. The apex of the meander moved from 3.85 m at flow time 57:00 in a straight, oblique line, until the apex was at 2.45 m, and the arroyo wall had to be stabilized at flow time 65:00.

The width of the measured channel did not include the broad bar, although flow did cover parts of this bar when the main channel was blocked by bank failures. With no lateral point-bar building during the flow time period 59:00 to 68:00, the channel width and width-to-depth ratio decreased, and the final stable channel was narrow. The width-to-depth ratio of the arroyo increased to 6.7 at 1.96 m and to 5.8 at 0.96 m during the period of braiding and rapid widening. As sediment transport decreased and arroyo widening ceased, the width-to-depth ratio of the arroyo stabilized.

Prior to the time the channel became braided, about two-thirds of the total amount of sediment eroded was from arroyo widening, as opposed to arroyo incision. An equal

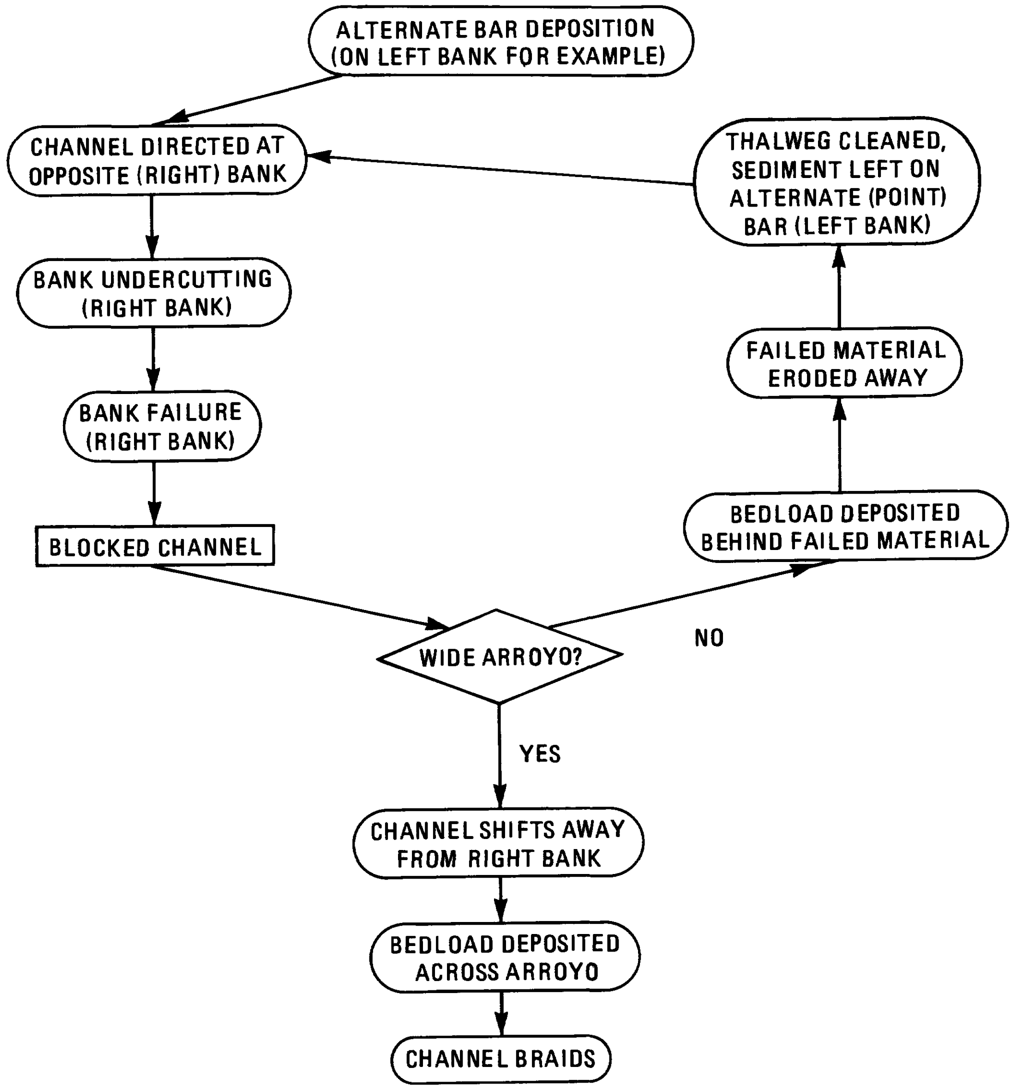


Figure 20. Model of feedback loop of bank failure and point-bar building. Oblongs indicate arroyo-modifying processes, box indicates condition of arroyo, and diamond indicates decision points in model.

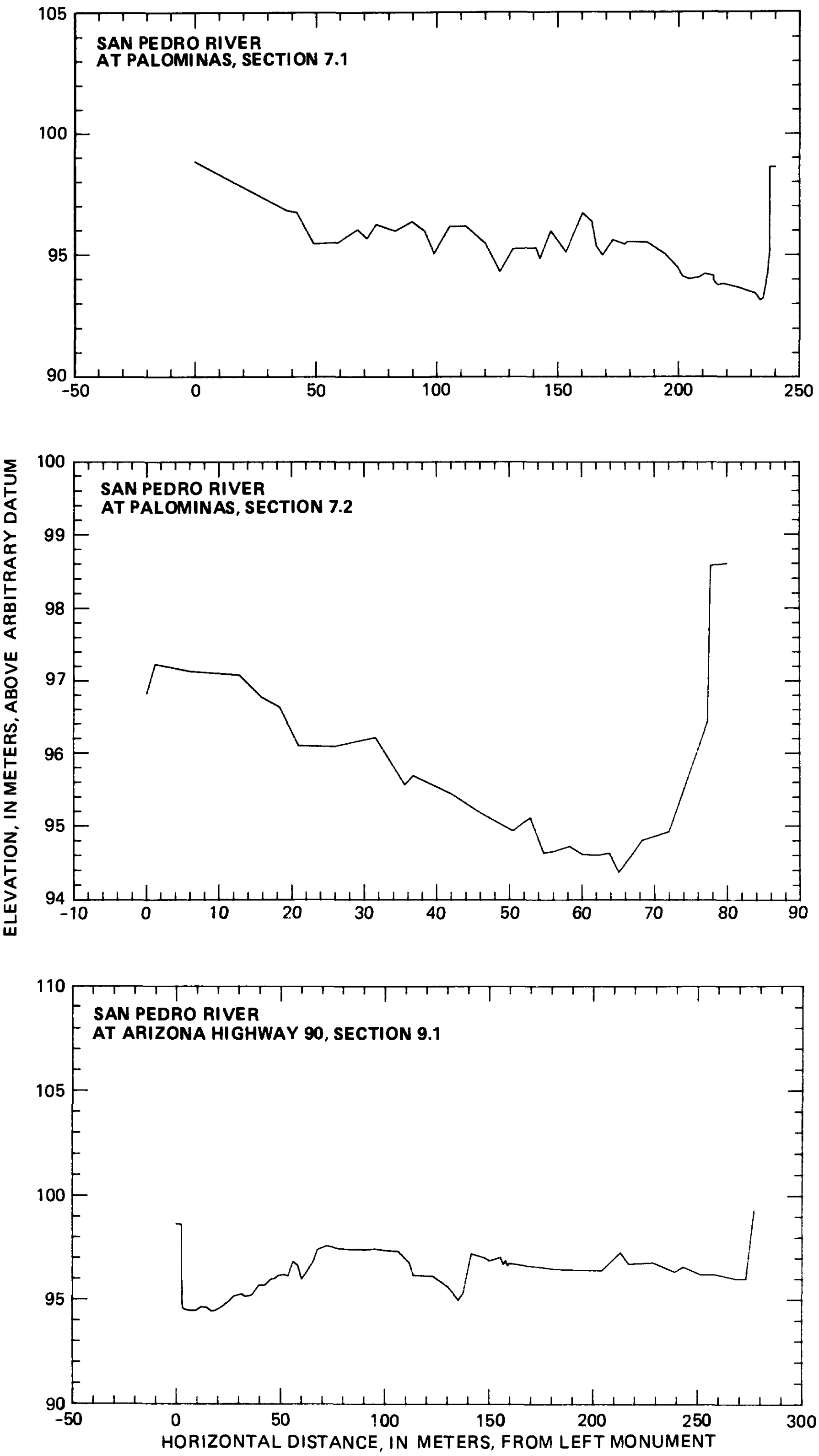
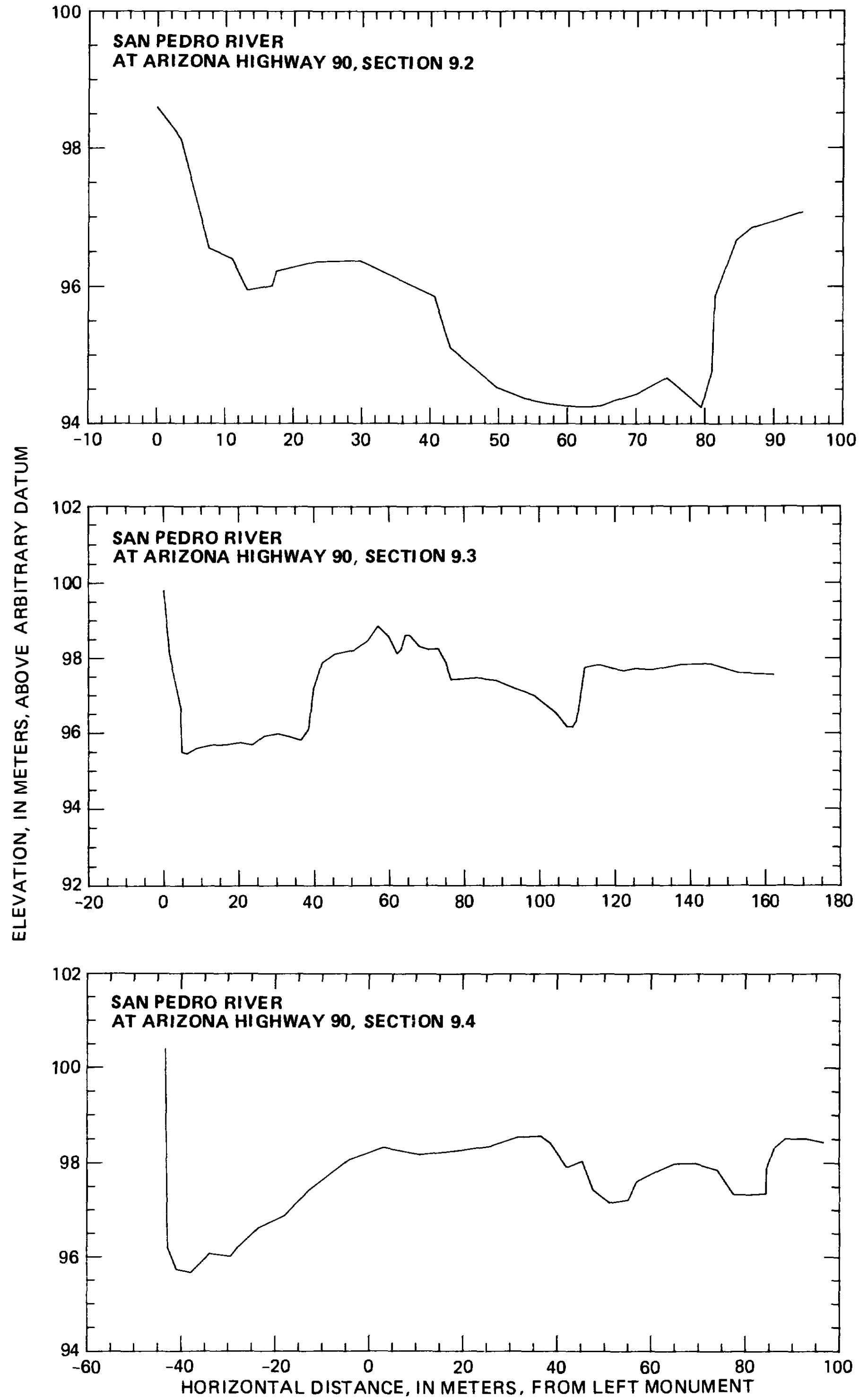


Figure 21. Cross sections of arroyos at meandering reaches experiencing cut-bank erosion. Cross sections 7.1, 9.1, 10.1, 12.1, 13.1, and 14.1 are at apex of meanders; cross sections 7.2, 9.2, and 10.2 are at crossings; cross sections 9.3 and 9.4 are across lower and upper point bar, respectively. Vertical exaggeration 10×.



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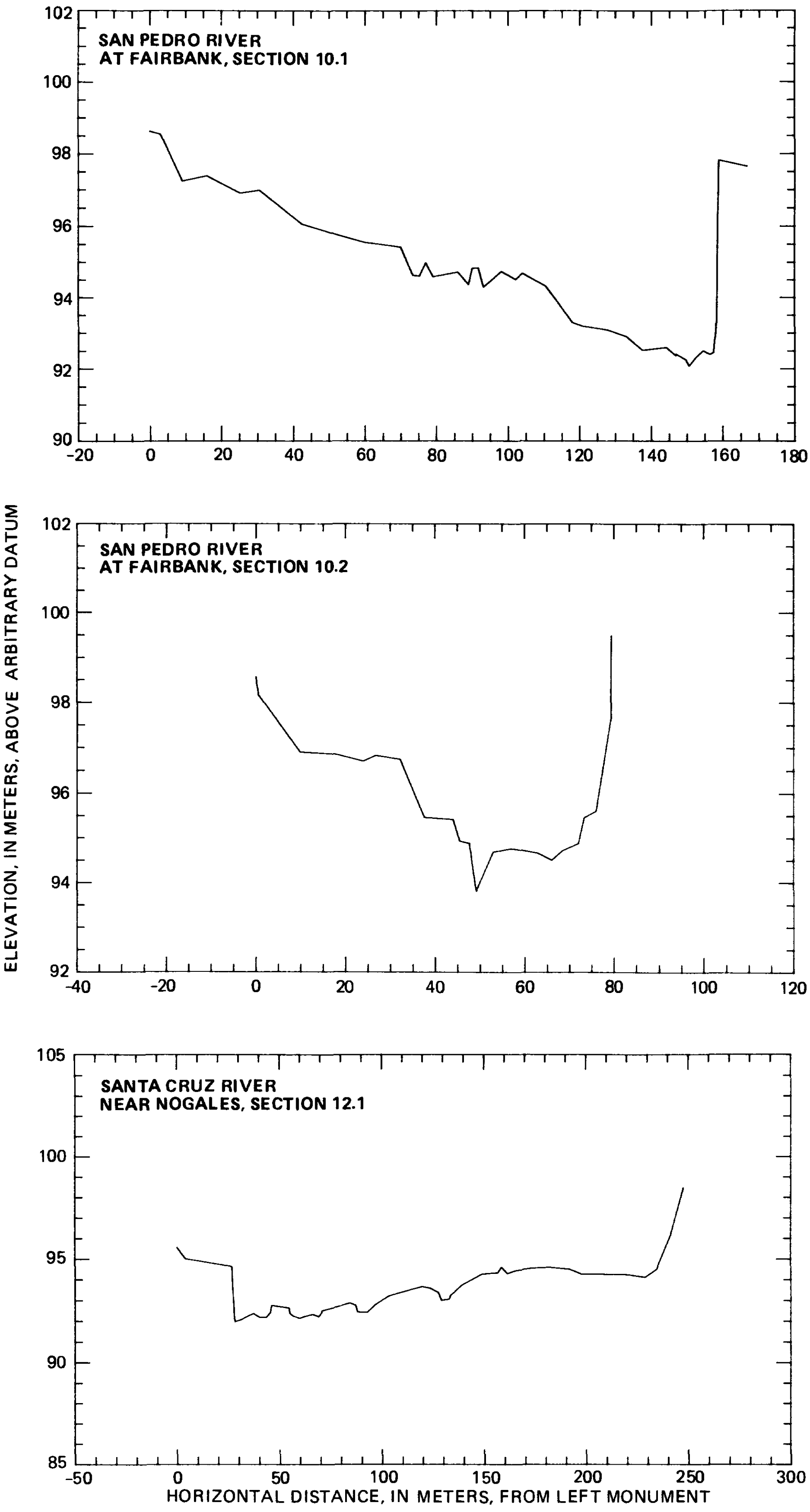

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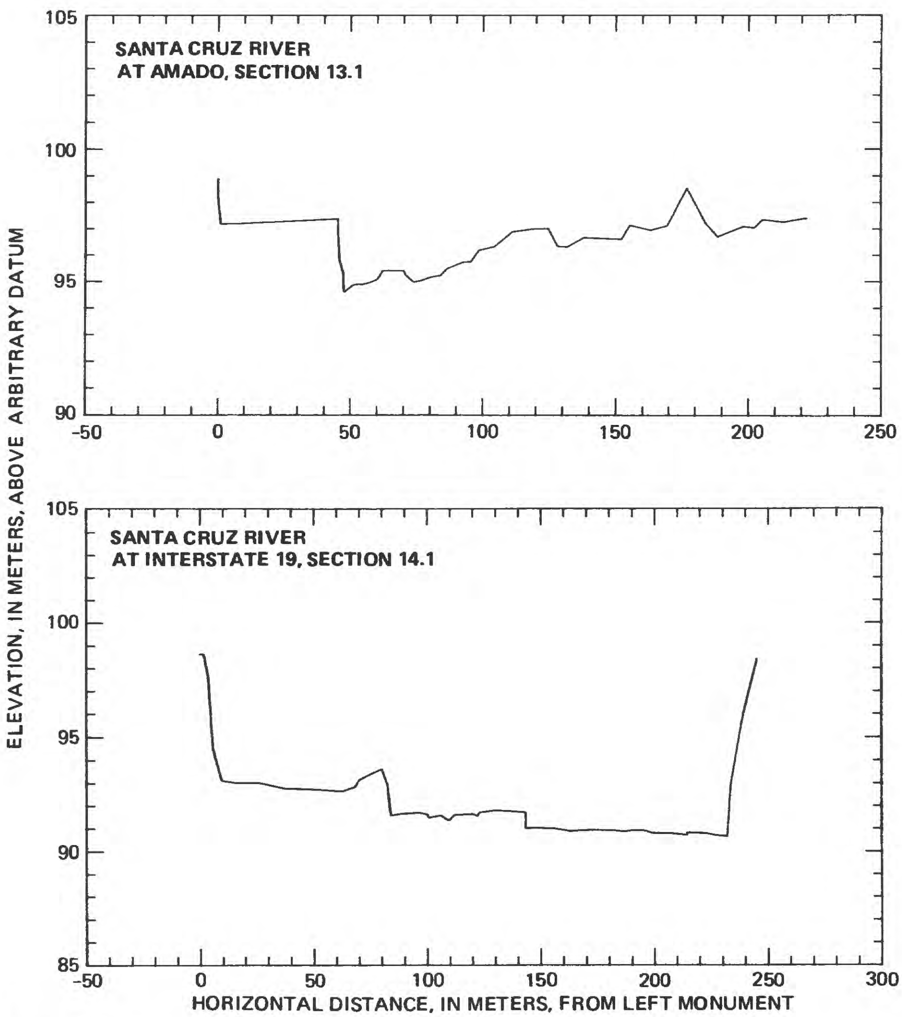

Figure 21. Continued.

amount of sediment was eroded while the channel was braided and before a retaining fence was placed along the left bank. About 20 percent of the sediment produced along this reach was produced by incision, about 40 percent by widening associated with point-bar growth and a sinuous channel, and about 40 percent by widening associated with a braided channel.

Unstable Arroyos with Braided Channels—Field Examples

No unstable arroyos observed in Arizona contained braided channels. Unstable arroyos observed by Elliott (1979) along the Rio Puerco, however, were characterized by wide, shallow, braided channels (fig. 27). Channels along the upper reaches of the Rio Puerco above Guadalupe, New Mexico, were braided (Elliott's stations 1 through 13, tables 9 and 10). The channels are wide and shallow and characterized by transverse bars. Vegetation is youthful and scarce. These arroyo reaches were referred to as "Type 1" reaches by Elliott (1979). Braided, unstable reaches are remarkably flat bottomed, and the active channel commonly extends from one side of the arroyo to the other. Commonly, both arroyo walls are vertical with minor accumulations of recently failed bank material at their base. Channel and bank sediments are dominantly composed of sand, sandy gravel, or sandy silt.

Stable Arroyos with Narrow, Sinuous, and Braided Channels—Experimental Examples

Narrow arroyos without channel bars, arroyos of moderate width with point bars, and wide arroyos containing braided channels were all stable for many hours in the experimental studies. The common characteristic among these stable arroyos was low sediment production upstream, and therefore low sediment transport through the stable reach.

The cross section at 5.99 m degraded steadily without widening throughout runs 4 and 5 until flow time 62:00. At 62:00, the arroyo was relatively straight ($P=1.01$), deep

Figure 22. San Pedro River at Arizona Highway 90, station 9 (see fig. 7). Features listed from left to right: *A*, concave bank (arroyo wall), channel, and lower point bar; *B*, lower point bar, chute bar with cottonwoods at left edge, chute, convex bank; and *C*, chute bar, chute, convex bank. Person standing on point bar is about 1.5 m tall. View is downstream.

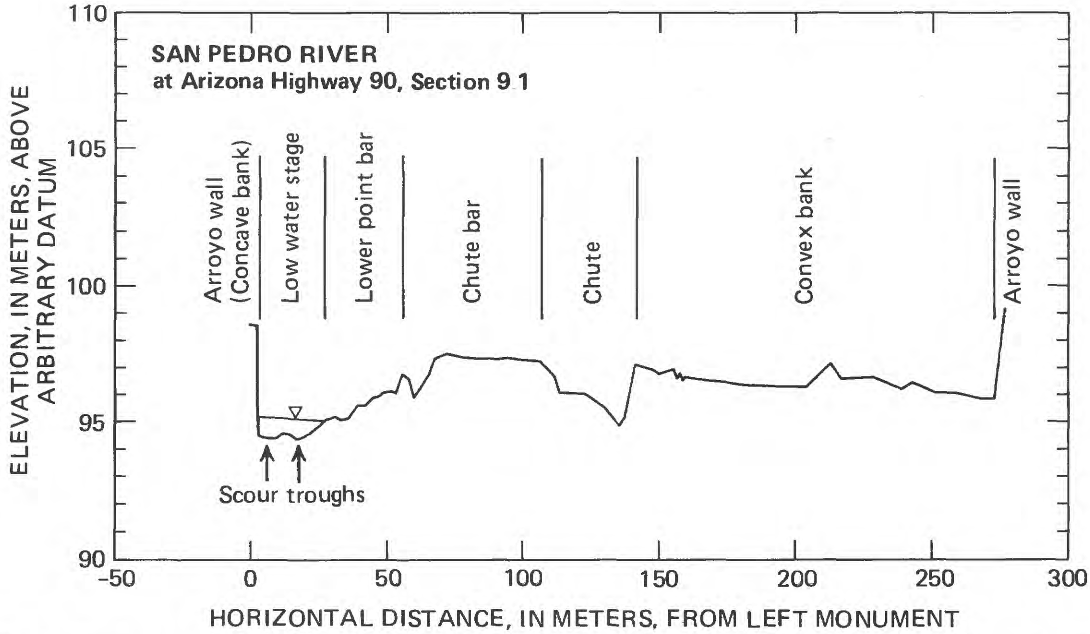

Figure 23. Cross section of coarse-grained point bar on San Pedro River at Arizona Highway 90, station 9 (see fig. 7), labeled after facies model of McGowan and Garner (1970). Vertical exaggeration 10×.

(D_a = 14.4 cm), and narrow (W_a = 13 cm). The cross section at 5.99 m did not change from flow time 62:00 to 68:00. Channel degradation initiated at the beginning of run 5 had virtually ceased by 62:00, and sediment production from the drainage basin portion of the REF was minimal. Arroyo widening began, however, when a bank failed upstream from 5.99 m, as described earlier.

Base level was lowered by 7.5 cm at the beginning of run 12 in the flume (base level had been lowered 7.2 cm at the start of run 11). Incision near the mouth of the flume was instantaneous as a headcut migrated upstream. Initially the arroyo developed as point-bar building and bank sloughing reinforced one another. As sediment production from upstream migration of the knickpoint declined, sediment was no longer added to the point bars. Without the continual addition of sediment to the point bars, opposite banks were no longer undercut, and they were stable from flow time 5:00, run 12, until flow time 4:00, run 14 (21.5 hours). During this period, the channel at 1.00 m above the mouth ranged from 21 cm to 37 cm in width, but the arroyo remained 40 cm wide and 12.1 cm deep (fig. 18). The channel was relatively sinuous (P = 1.18).

Once the wide, braided arroyo was formed during run 5, it was stable for the remainder of the experiments in the REF. This was in spite of relatively high rates of arroyo widening upstream, as at 5.99 m during run 5. Although portions of the left arroyo wall were artificially stabilized in this reach, neither the unprotected portions of the left wall nor the right wall were eroded for the 26 hours following flow time 68:00. This stable arroyo was 144 cm wide and 22 cm deep at 1.96 m above the mouth of the REF, and the channel was braided.

In all stable reaches, except the braided reach in the lower parts of the REF during run 5, channel instability and arroyo widening were later induced when additional sediment was introduced. The section at 5.99 m was discussed earlier; when upstream bank failures introduced additional sediment as bedload, point bars were built and the arroyo widened. In the flume cross section at 1.00 m when sediment was artificially fed into the channel, the additional sediment transport induced point-bar building, causing bank failure.

Two additional types of arroyo development were observed in the experimental studies, but channels were relatively stable immediately after incision. The first type was observed when a headcut migrated up a wide or indistinct channel. This produced badlands-like topography with flow concentrated in a central, narrow channel and was observed in runs 3.5, 11, and 12. The second was produced by relatively shallow entrenchment where banks were stable when undercut. Upstream migration of both types of knickpoints produced minor amounts of sediment, and thus arroyo widening was negligible.

Field Examples of Stable Arroyos—Arizona Arroyos

Three sampled reaches on the San Simon River and one reach on the San Pedro River were sinuous with coarse-grained point bars, but they were not actively eroding (fig. 28). At San Simon River at Tanque, station 6, dense vegetation, mostly salt cedar, was present on both banks (fig. 29). The vegetation extended to the arroyo wall from the right bank (concave bank) and was about 60 m from the channel

Table 3. Mean grain size (M_z) and other sedimentary characteristics of different alluvial deposits at sites on San Simon, San Pedro, and Santa Cruz Rivers, Arizona, and Rio Puerco, New Mexico

[Rio Puerco data are from Elliott (1979). - -, deposits not present]

Station	Channel M_z (mm)	Channel sediment type[1]	Point bar M_z (mm)	Bank M_z (mm)	Alluvium M_z (mm)	Flood plain M_z (mm)	M[2] (percent)
			San Simon River				
1	0.93	sG	1.6	0.09	0.80	--	11.4
2	.43	gmS	1.7	.11	.47	--	14.9
3	.36	gmS	--	.0625	--	--	18.5
5	.47	gS	--	.79	--	--	16.9
6	.33	gmS	.32	.17	--	--	17.0
			San Pedro River				
7	.53	gS	10.5	.076	.28	--	4.3
8	.37	gS	10.5	.082	--	--	9.7
9	2.0	msG	11.5	--	.15	.09	9.4
10	10.0	sG	--	--	--	.21	3.3
11	13.5	sG	--	.074	--	--	3.7
			Santa Cruz River				
12	2.8	sG	2.0	--	.11	--	4.8
13	5.1	msG	1.0	--	.071	--	6.4
14	.80	gmS	--	--	.14	--	9.1
15	7.2	msG	--	.083	.23	.0625	8.3
16	.16	gmS	--	--	.13	--	37.7
			Rio Puerco				
1	0.15	msG	--	0.093	--	--	36.6
2	.24	msG	--	.47	--	--	17.2
3	.25	gmS	--	.12	--	--	25.4
4	.19	gmS	--	.065	--	--	24.1
6	.36	msG	--	.11	--	--	11.2
7	.10	msG	--	.16	--	--	42.6
8	.15	msG	--	.082	--	--	30.6
9	.30	sG	--	.15	--	--	9.1
10	.35	sG	--	.26	--	--	8.5
11	.15	mS	--	.058	--	--	26.4
12	.17	msG	--	.15	--	--	13.5
13	.11	mS	--	.075	--	--	42.4
15	.11	mS	--	.090	--	--	41.0
16	.15	mS	--	.11	--	--	26.4
17	.12	mS	--	.11	--	--	37.1
18	.15	mS	--	.080	--	--	23.9
19	.13	mS	--	.11	--	--	35.2
20	.091	gsM	--	.081	--	--	58.1
21	.093	mS	--	.071	--	--	54.9
22	.082	sM	--	.099	--	--	59.1
23	.081	gsM	--	.073	--	--	62.6
24	.081	sM	--	.073	--	--	54.3
25	.093	mS	--	.11	--	--	40.8
26	.10	mS	--	.090	--	--	45.7
27	.10	mS	--	.086	--	--	44.0
28	.081	sM	--	.071	--	--	52.8
29	.13	mS	--	.084	--	--	38.2

[1] Folk's (1974) descriptive terms: G, gravel; g, gravelly; S, sand; s, sandy; M, mud or silt; m, muddy or silty; example: msG = muddy, sandy gravel.

[2] Percent silt-clay in the channel perimeter, after Schumm (1960).

Table 4. Morphometric data from sites on San Simon, San Pedro, and Santa Cruz Rivers, southeast Arizona, and Rio Puerco, New Mexico

[See figures 7 and 8 and appendix 2 for locations of stations. *P*, channel sinuosity; S_V, valley slope; S_C, map channel slope; S_L, local channel slope; W_C, channel width; W_a, width of arroyo; D_C, depth of channel; D_a, depth of arroyo; *R*, hydraulic radius of channel; F_C, width-to-depth ratio of channel; F_a, width-to-depth ratio of arroyo; m, meters; --, not applicable]

Station	*P*	S_V	S_C	S_L	W_C[1] (m)	W_a[2] (m)	D_C[1] (m)	D_a[2] (m)	R[2] (m)	F_C[1]	F_a[2]
					San Simon River						
1	1.14	0.00252	0.00222	0.00041	28.1	45.9	0.098	3.68	0.65	29	12
	--	--	--	--	15.6	--	.074	--	--	21	--
2	1.07	.00262	.00246	.00114	10.9	40.9	1.01	3.52	.69	11	12
	--	--	--	--	18.0	--	.052	--	--	35	--
3	1.13	.00099	.00088	.003[3]	41.7	99.9	.69	5.22	.30	60	19
5	1.61	.00289	.00179	.00258	11.7	31.3	1.53	6.87	.92	7.7	5
6	1.61	.00289	.00179	.00192	13.2	350	1.00	8.18	.93	13	43
					San Pedro River						
7	1.33	.00189	.00142	.00248	77.3	238	3.56	5.57	1.99	22	43
	--	--	--	--	61.6	--	2.40	--	--	26	--
8	1.31	.00210	.00161	.00089	31.0	122	1.38	4.47	.89	22	27
	--	--	--	--	31.8	--	1.71	--	--	19	--
9	1.22	.00250	.00205	.00424	63.1	277	2.41	4.53	1.40	26	61
	--	--	--	--	40.8	--	1.63	--	--	25	--
10	1.10	.00277	.00251	.00271	47.9	156	2.24	6.06	1.39	21	26
	--	--	--	--	53.3	--	3.03	--	--	18	--
11	1.22	.00356	.00317	.00233	106	133	2.17	5.31	1.36	49	25
					Santa Cruz River						
12	1.79	.00669	.00373	.00387	92.4	208	1.68	2.67	.98	55	78
13	1.15	.00363	.00316	.00440	65.5	--	2.28	0	1.36	29	--
14	1.35	.00414	.00308	.00372	151	245	2.27	7.86	1.71	67	31
15	1.10	.00301	.00274	.00430	87.4	--	2.73	0	1.75	32	--
16	1.17	.00208	.00178	.00250	285	--	2.21	0	.83	129	--
					Rio Puerco						
1	1.6	.0052	--	.0034	48.2	--	.5	--	--	96	--
2	1.3	.0033	--	.0036	23.7	--	.5	--	--	47	--
3	1.3	.0033	--	.0044	21.3	--	.6	--	--	36	--
4	1.1	.0030	--	.0045	58.9	--	.3	--	--	196	--
5	1.7	.0036	--	.0029	58.4	--	.6	--	--	97	--
6	1.7	.0036	--	.0034	26.5	--	.7	--	--	38	--
7	1.7	.0036	--	.0028	40.3	--	.6	--	--	67	--
8	2.0	.0021	--	.0056	27.6	--	.7	--	--	39	--
9	2.0	.0021	--	.0024	16.4	--	.6	--	--	27	--
10	2.0	.0021	--	.0033	23.1	--	.6	--	--	39	--
11	1.4	.0050	--	.0023	33.2	--	1.2	--	--	28	--
12	1.0	.0033	--	.0022	33.4	--	.3	--	--	111	--
13	1.8	.0030	--	.0014	68.4	--	.5	--	--	137	--
14	1.8	.0030	--	.0024	45.0	--	.5	--	--	90	--
15	1.5	.0020	--	.0013	23.6	--	1.6	--	--	15	--
16	1.4	.0022	--	.0017	24.3	--	1.8	--	--	14	--
17	1.5	.0036	--	.0012	29.7	--	1.8	--	--	17	--
18	1.7	.0024	--	.0022	22.5	--	1.7	--	--	13	--
19	1.7	.0019	--	.0008	21.0	--	1.8	--	--	12	--
20	1.1	.0018	--	.0006	19.3	--	1.9	--	--	10	--
21	1.4	.0014	--	.0010	25.0	--	2.1	--	--	12	--
22	1.2	.0014	--	.0009	21.4	--	1.9	--	--	11	--
23	1.2	.0014	--	.0012	25.3	--	1.7	--	--	15	--
24	1.4	.0014	--	.0010	16.3	--	1.6	--	--	10	--
25	1.2	.0014	--	.0022	16.7	--	1.6	--	--	10	--
26	1.7	.0014	--	.0018	18.7	--	1.7	--	--	11	--
27	2.2	.0022	--	.0012	20.0	--	1.9	--	--	11	--
28	1.7	.0022	--	.0030	13.9	--	1.0	--	--	14	--
29	2.2	.0022	--	.0012	19.7	--	2.4	--	--	8.2	--

[1] Where two values are listed, the top value was measured at the apex of the meander, the bottom value was measured at the crossing.

[2] Measured at the apex of the meander.

[3] Local slope was measured with a Brunton compass at station 3.

Figure 24. Large bank failure between about 0.3 and 1.5 m at flow time 56:14, run 5. Bank is about 10 cm high, and failed block is about 1 m x 10 cm. Strings are 1 m apart. Flow is from bottom to top.

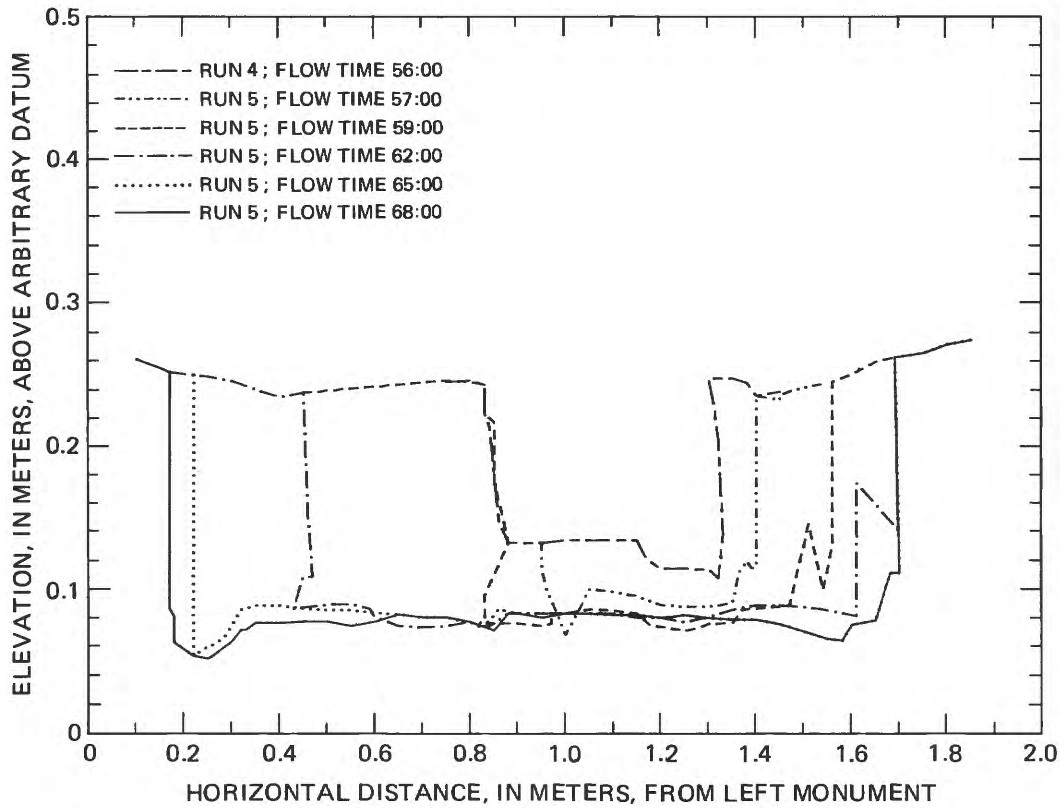

Figure 25. Development of arroyo at 1.96 m during run 4, flow time 56:00, through run 5, flow time 68:00. Vertical exaggeration 3×.

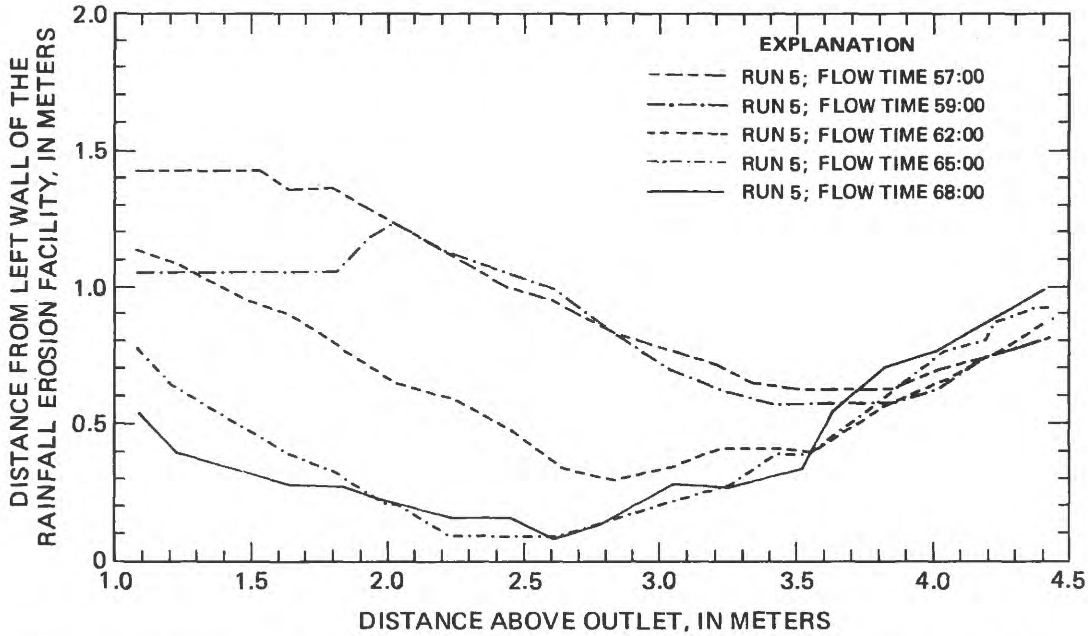

Figure 26. Lateral migration of thalweg in lower portion of Rainfall Erosion Facility during run 5, flow time 57:00 through 68:00.

Figure 27. Rio Puerco below Cuba, New Mexico, Elliott's (1979) station 7. Arroyo wall is about 8 m high. View is downstream.

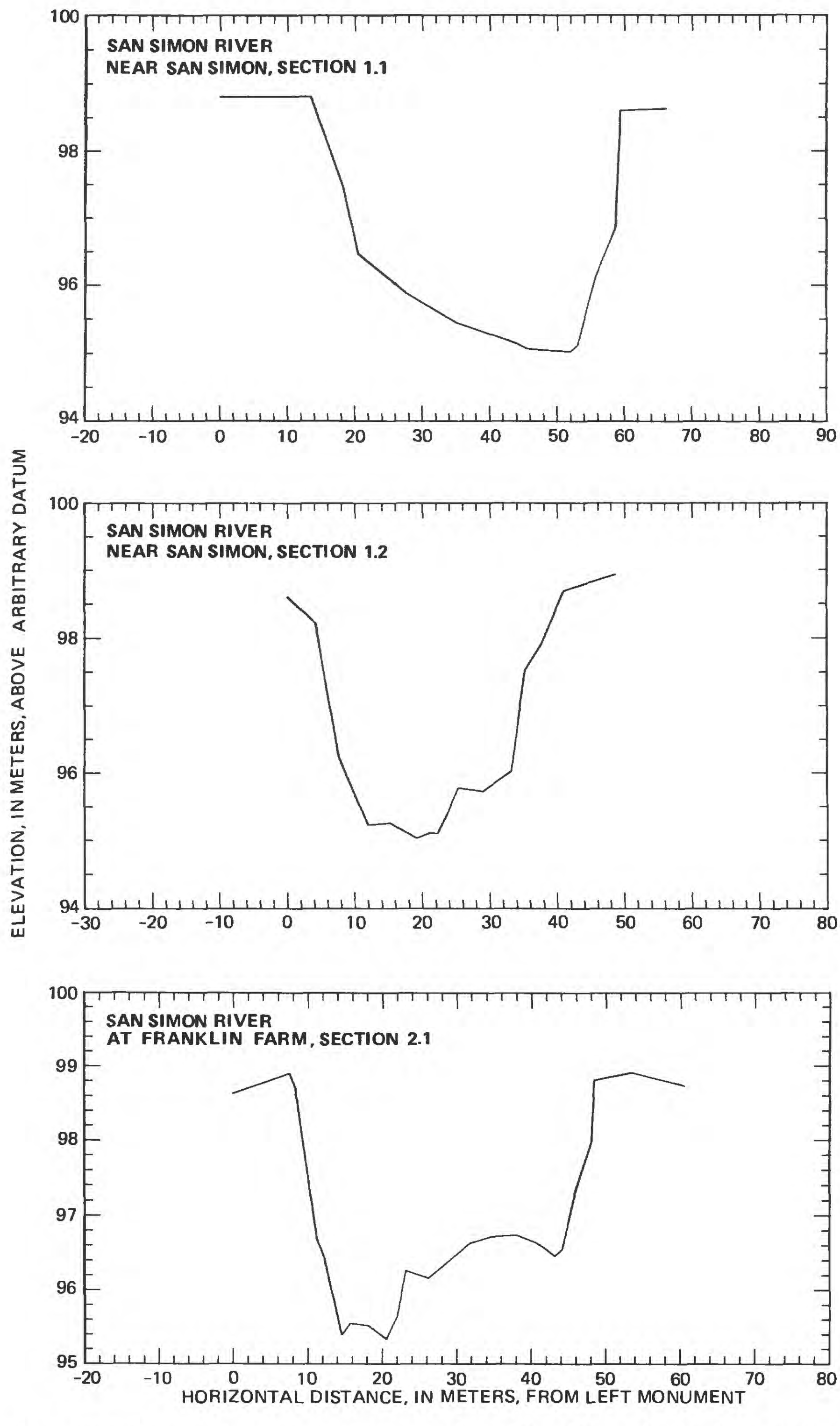

Figure 28. Cross sections at meandering reaches with stable cut banks. Cross sections 1.1, 2.1, 6.1, and 8.1 are at apex of meanders; cross sections 1.2, 2.2, and 8.2 are at crossings. Vertical exaggeration 10×.

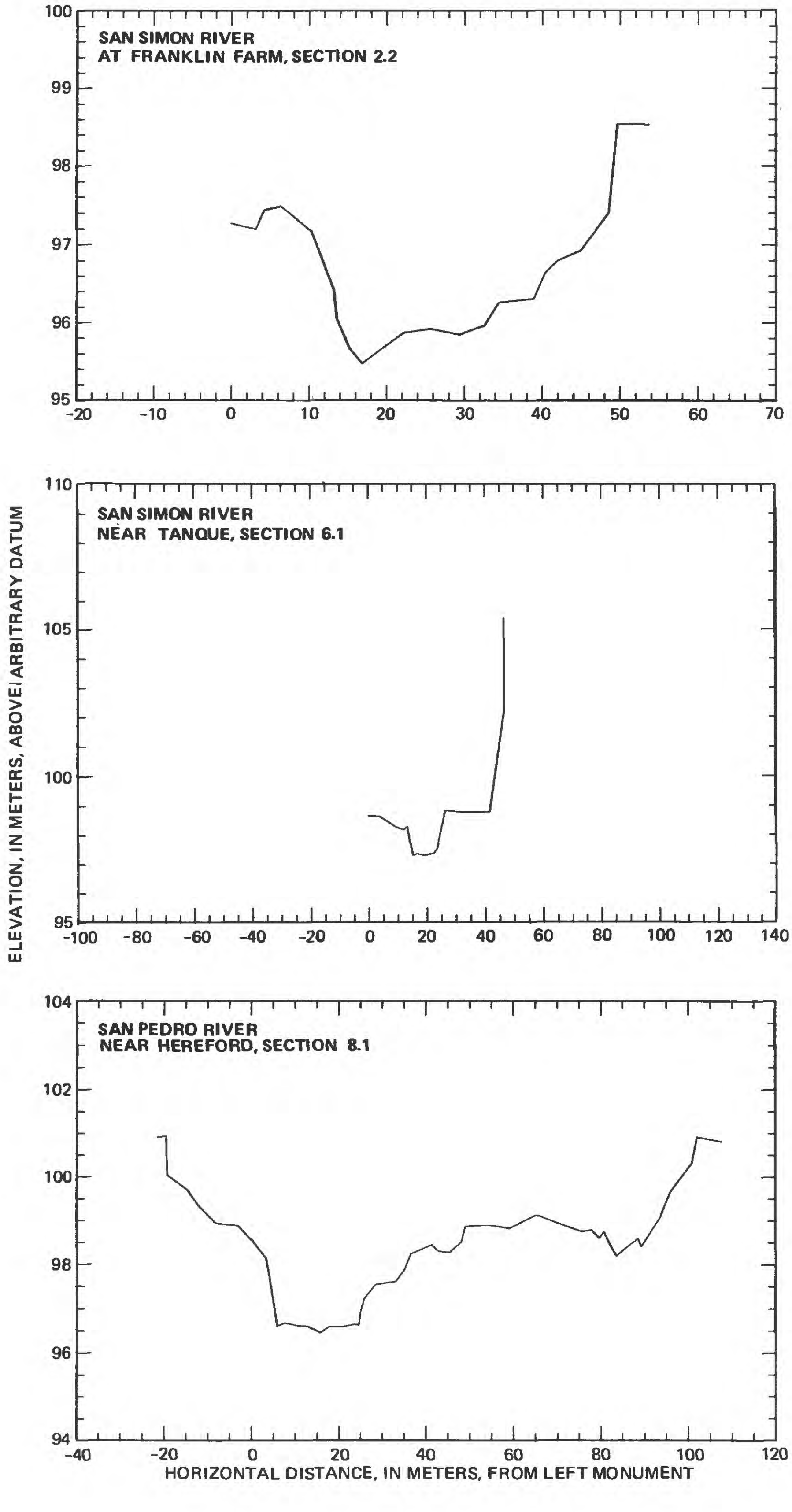

Figure 28. Continued.

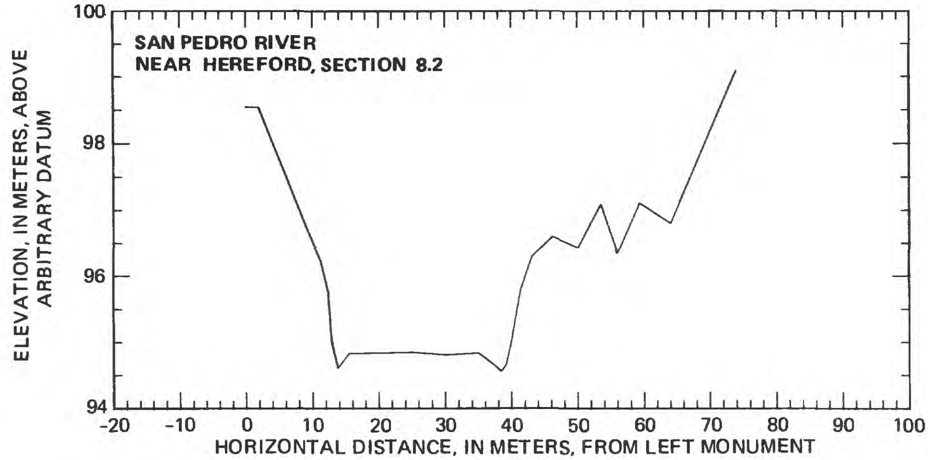

Figure 28. Continued.

Figure 29. Stable banks of San Simon River at Tanque, Arizona, station 6 (see fig. 7). Channel is about 17 m wide, between vegetation. View is downstream.

on the left bank (point bar). The arroyo reached a maximum width of about 350 m at the apex of this meander, although the dense vegetation made it impossible to survey the entire arroyo cross section (fig. 28). At 250 m upstream from station 6, the arroyo was about 30 m wide.

The point bar at station 6 is fairly flat, but it does contain a few ridges and swales. The ridges are about 0.6 m higher than the swales. Two chutes cross the point bar, one at the edge of the vegetation about 60 m from the channel, and one in the midst of the salt cedar growth about 35 m from the channel. These chutes are both about 4 m wide and 1 m deep. The sediment on the bed of the chutes ranges in size from coarse sand to boulders, in contrast to the medium-fine sand covering most of the point bar (table 3). Boulders were not observed in any other area within this reach or the adjacent reach at station 5, except on the riffles, where boulders were present in minor amounts.

Other reaches with stable arroyos and sinuous channels on the San Simon and San Pedro Rivers differ from station 6 mainly in scale. The point-bar sediment of stations 1, 2, and 8 are coarser than those at station 6, and channel sediment at station 1 is coarser than at station 6 (table 3).

Two sampled reaches on the San Simon River, one sampled reach on the San Pedro River, and two sampled reaches on the Santa Cruz River are straight and are not actively eroding (fig. 30). Station 3 on the San Simon River

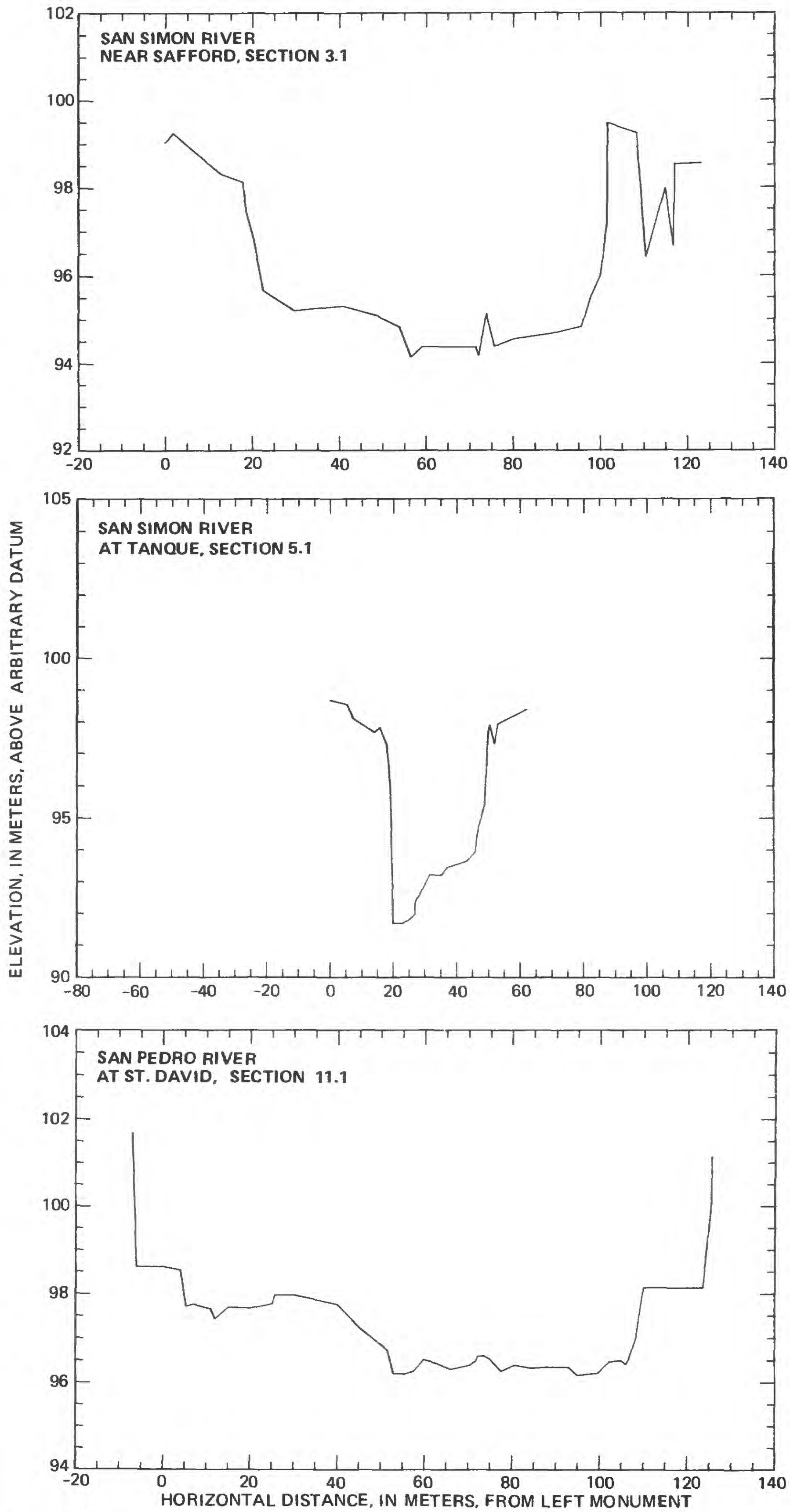

Figure 30. Cross sections at straight reaches. Vertical exaggeration 10×.

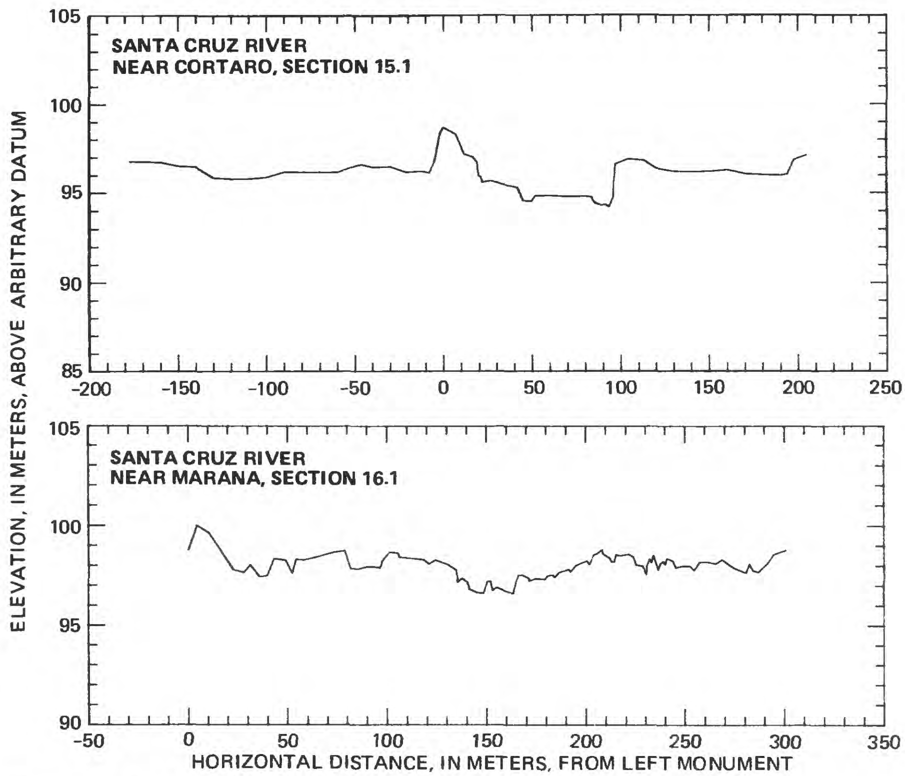

Figure 30. Continued.

and station 16 on the Santa Cruz River are braided. At the remaining reaches, single, low-water channels shift periodically within the arroyos (fig. 31).

Braided channels appear in the downstream reaches of San Simon, San Pedro, and Santa Cruz arroyos, although the lower San Pedro River was not sampled or surveyed. At the San Simon River at Safford (figs. 30, 32), the channel and arroyo are straight, and the arroyo walls are vegetated and gently sloping. At this site, the channel is wider (W_a = 100 m) and the channel sediments are finer (M_z = 0.36 mm) than at any other reach along the San Simon River except station 6 at Tanque. The lower reaches of San Pedro arroyo are deeply entrenched, but the arroyo is commonly more than 500 m wide (fig. 33). The channel occupies most of the arroyo bottom and is braided with occasional vegetated islands. The banks of the channel are low and unstable, but they rarely coincide with the arroyo walls. The remainder of the arroyo bottom is vegetated. The furthest downstream station sampled on the Santa Cruz River (station 16, fig. 30) does not flow in an arroyo; instead, sediment is being deposited in the Santa Cruz Flats as the flow of the Santa Cruz is lost to infiltration and evaporation.

Field Examples of Stable Arroyos—Arroyo of Rio Puerco

The upper reaches of the Rio Puerco examined by Elliott (1979) are braided and unstable, and their arroyos widen during floods. The lower reaches of the Rio Puerco (extending from about 50 km north of the town of Rio Puerco to its mouth, fig. 8) contain narrow, sinuous channels flowing across a vegetated flood plain (table 4, fig. 34). The arroyo is wide, and the meandering channel rarely encounters the arroyo walls. These arroyos are stable laterally although the banks and flood plains aggrade (Elliott, 1979). Channel and bank sediments are sandy silt or silty sand (table 3). These reaches are referred to as "Type 2" reaches by Elliott (1979) and include stations 15 through 29.

Sediment Transport, Channel Geometry, and Arroyo Widening

Observations discussed earlier distinguish qualitatively between processes that create unstable arroyos and those that do not affect arroyo stability, and between the form and sedimentology of unstable and stable arroyos transporting coarse and fine bed material. In the experiments and in San Simon, San Pedro, and Santa Cruz arroyos, the arroyos are unstable when point bars are active. Active point bars are being reworked during high flow or following bank failures and are commonly the site of deposition of bed material. In the experiments when sediment from either upstream erosion or from a sediment feeder was transported as bed load, the arroyos were unstable and widened. In the Rio Puerco arroyo and in one run of the experiments, braided channels widen arroyos. In the experiments when there was no supply

Figure 31. San Pedro River at St. David, Arizona, station 11 (see fig. 7). Prior to flood during October 1977, low water channel occupied right half of arroyo. Person standing on right bank is about 1.5 m tall. View is downstream.

Figure 32. San Simon River at Safford, Arizona, station 3 (see fig. 7). Person standing in channel is about 1.5 m tall.

of sediment or when the arroyos were very wide, the arroyos were stable. Stable arroyos in the San Simon, San Pedro, and Santa Cruz Rivers contain vegetated, inactive point bars, or they are straight or braided. The arroyo of the Rio Puerco is stable where the channel is sinuous. The analyses that follow refine these observations and relate morphologic and sedimentologic characteristics of the arroyos observed in the field to processes and patterns of arroyo development observed in the experiments.

Experimental Relations

The relation between sediment transport and arroyo widening was observed qualitatively by comparing W_c and W_a (figs. 12, 18). Except when the channel was braided, increases in the width of the channel caused by increased sediment transport rates, preceded or accompanied increases in arroyo width. Increased sediment transport rates were caused by either (1) upstream channel incision, (2) upstream bank failures, or (3) input from a sediment feeder. Multiple regression and correlation analyses of transport-sensitive parameters also support the thesis that sediment transport rate controls arroyo widening rate.

Arroyo cross-sectional area as excavated from the beginning of each run, was computed for runs 3.5, 4, 5, 6, 11, and 12. The change in arroyo cross-sectional area (fig. 6) from the preceding measurement, divided by the flow time since the preceding measurement, equals the rate of erosion at a given cross section. The results of these computations, as well as other variables used in this analysis, are listed in appendix 1. Correlation coefficients were calculated and a

Figure 33. San Pedro River at Casabel, Arizona. Channel is about 400 m wide and occupies most of arroyo bottom. Flow is from left to right.

Student's *t* test applied to test the null hypothesis that the true correlation coefficient was equal to zero (Nie and others, 1975). Correlation coefficients were significant when the probability of rejecting the null hypothesis, when it was true, was less than 0.01. Significant correlation coefficients exist for relations between the rate of arroyo area change (ΔA) and the following variables measured from the channel: average unit discharge (discharge divided by channel width, *UQ*), average energy slope (*S*), wetted perimeter (*WP*), hydraulic radius (*R*), width-to-maximum depth ratio of the channel (F_c), and distance from the mouth (*Y*). The average unit discharge and average energy slopes were computed from the values measured at the start and end of the period in which the change in arroyo area took place. Correlation coefficients between ΔA and *S*, F_c, and *WP* are positive while those between ΔA and *UQ*, *R*, and *Y* are negative.

The correlations between ΔA and *WP*, F_c, and *R* confirm observations of an increase in channel width while point bars are building, causing arroyo widening, and a decrease in channel width while point bars are stable or eroding. The negative correlation between ΔA and *UQ* also is related to the process responsible for the relation between point-bar building, arroyo widening, and channel width, in that, with constant discharge, unit discharge will vary inversely with the width of the channel. Small values of *UQ* correspond to large values of width and thus to periods of arroyo widening.

The correlation coefficient between ΔA and F_c was statistically significant, but was nevertheless small when the entire data set was analyzed. When the REF experiments were separated from flume experiments, the correlation between ΔA and F_c was larger for the REF experiments, and it was nonsignificant and small for the flume experiments. The relation between point-bar building, arroyo widening,

Figure 34. Rio Puerco at Elliott's (1979) cross section 29. Small flash flow is in progress. Channel is about 20 m wide. View is downstream.

and sediment transport is complicated in the flume experiments by point-bar erosion and channel armoring. Stable channels in the REF scoured their beds through alluvial fill and often into bedrock as sediment delivery from upstream decreased. This caused a decrease in the width-to-depth ratio of the channel. Downward scour by the channel in the flume was limited by armor, so the channel eroded the finer material on the point bars. During point-bar erosion, sinuosity of the channel decreased. Point-bar erosion also caused channel widening with little change in maximum channel depth, and thus the channel width-to-depth ratio increased or remained constant.

The use of data measured during periods of incision and headcut migration introduced a bias in the analysis, as slopes were steeper during downcutting than at any other time, regardless of whatever else was occurring. In addition, degradation increased the arroyo area independent of arroyo widening. During runs 13 and 14, sediment transport and arroyo widening were initiated without downcutting. This removed the source of the bias, and change of arroyo width (ΔW) was substituted for arroyo-area change. Change in arroyo width was correlated positively with the average energy slope.

With an unlimited supply of sediment, and all other factors being equal (which is admittedly rare), large values of slope usually indicate a greater rate of sediment transport, indicating that the positive correlation between ΔA and S for runs 4, 5, 6, 11, and 12 and between ΔW and S for runs 13 and 14 are related to high sediment-transport rates, and the processes described earlier involving point-bar building.

Using standard regression techniques (Draper and Smith, 1966; Nie and others, 1975), simple and multiple least-squares linear equations were computed relating ΔA to S, and ΔA to S and UQ as follows:

$$\Delta A=(-64.5)+5009(S) \qquad R^2=0.34,\ s=1.68$$

$$\Delta A=(-42.4)+5115(S)-0.533(UQ) \qquad R^2=0.40,\ s=1.60$$

where R^2 is the squared multiple correlation coefficient representing the amount of variation in ΔA explained by the equation, and s is the standard error of estimate. Neither equation is accurate enough to be used for predictive purposes. Each cross section examined was unique, and many different factors that are not included in the equations played important roles in arroyo development. Among the most important of these factors were the height of the arroyo wall, the width of the arroyo (whether or not the flow was confined when the banks failed), and the sinuosity of the reach. The equations do, however, support the qualitative observations outlined earlier: that an increase in sediment transport, as indicated by an increase in energy slope and (or) a decrease in unit discharge, induces arroyo widening.

Bank cohesion affected arroyo dimensions in the experimental data, but the above-mentioned differences between arroyo development processes may bias such a comparison. Material used to fill the REF was about 50 percent silt-clay by weight, compared to about 25 percent silt-clay by weight in the flume material. This indicates that banks cut in REF materials should be more cohesive and more resistant to failure than those cut in flume sediments, and thus, under identical conditions, arroyo width-to-depth ratios in the REF should be less than in the flume. Comparison of stable arroyo width-to-depth ratios in the REF and flume, excluding the braided reach in runs 5 and 6, show such a trend. Mean arroyo width-to-depth ratios for the lower 7 m in the REF (excluding braided reaches) was 2.3, compared to 3.4 for the lower 7 m in the flume (Student's t test indicates the difference is highly significant). The amount of base-level lowering and amounts of sediment delivered from upstream, unfortunately, were not the same in the two sets of experiments which may account for some of the above-mentioned difference in arroyo width-to-depth ratios.

Three different arroyo development phases were stable during the experiments, and they can be characterized on the basis of the arroyo width-to-depth ratio. Deeply incised channels formed without point-bar formation and, consequently, without significant widening or massive bank failures in the upper reaches of the channels where sediment-transport rates were never high. Arroyos of this type formed between 3.5 m and 7.5 m above the mouth in runs 4, 5, and 6 had final width-to-depth ratios between 1.5 and 3.1, averaging 2.0. Nonbraided arroyos that received sediment at high rates for only a limited period of time, either from channel erosion upstream or artificially, were intermediate in width. Stable arroyo width-to-depth ratios in the lower 3.5 m in run 4 and the lower 7 m in runs 12, 13, and 14 ranged from 2.5 to 4.8, and averaged 3.5. Arroyos that received continuous sediment at high rates from both failure of high banks and channel incision upstream became braided and wider than any others observed in the experimental study. This type of arroyo occurred in the lower 3.5 m during runs 5 and 6. Stable arroyo width-to-depth ratios of these reaches ranged from 4.9 to 6.1 and averaged 5.6, although arroyo widths were limited by the walls of the REF.

Field Relations

Five groups of arroyos in the field were differentiated on the basis of form and grain-size parameters that illustrate the effect of bedload transport: (1) sinuous stable arroyos having coarse-grained bed material; (2) sinuous unstable arroyos; (3) straight stable and braided stable arroyos; (4) braided unstable arroyos; and (5) sinuous stable arroyos having fine-grained bed material. Because observations along the San Simon, San Pedro, and Santa Cruz Rivers, and the Rio Puerco were made during a short period, rates of arroyo widening were not measured.

Local slope and percent silt/clay in the channel perimeter vary among the five types of arroyos (fig. 35). The differentiation between the three groups of Arizona arroyos (coarse-grained sinuous stable, sinuous unstable, and straight stable and braided stable) is good. Values of large slope and small silt/clay content indicate large bedload transport (Schumm, 1977, table 5-4). Sinuous unstable reaches display relatively steep slopes and small silt/clay ratios. Coarse-grained sinuous stable reaches display equally steep slopes that may be inherited from the time when the coarse-grained point bars were active. Large silt/clay ratios indicate that bedload transport is relatively small in these reaches. Straight stable and braided stable reaches exhibit relatively gentle slopes and larger silt/clay ratios than unstable reaches.

Braided unstable and fine-grained sinuous stable reaches exhibit a similar relation. Braided unstable reaches have steeper slopes and less silt/clay than do fine-grained sinuous stable reaches indicating more bedload transport in the braided unstable reaches.

Although mean values of local slope and percent silt/clay in the channel perimeter differ among the five groups, there is considerable overlap among the groups, especially between sinuous unstable and coarse-grained sinuous stable reaches, between coarse-grained sinuous stable and braided unstable reaches, and between braided unstable and fine-grained sinuous stable reaches. When values of mean grain size of the channel sediments are compared, however, the overlapping groups are distinct (table 3, fig. 36). Specifically, sinuous unstable reaches are statistically different from coarse-grained sinuous stable reaches, and braided unstable reaches are statistically different from fine-grained sinuous stable reaches. Straight stable and braided stable reaches cannot be differentiated from either sinuous group because there is a wide range of mean grain sizes sampled from straight stable and braided stable reaches. However, this group is distinct from the other groups on the basis of local slope and percent silt/clay in the channel perimeter. Braided unstable and fine-grained sinuous stable reaches are statistically different from each other, and the reaches of the Arizona arroyos are statistically different from the reaches of the Rio Puerco, based on mean grain size of the channel sediments.

These differences (figs. 35, 36) again indicate that bedload transport is an important control that causes differences in stability and arroyo form. Reaches along the San Simon, San Pedro, and Santa Cruz Rivers that carry coarse-grained bedload (gravel) at high rates, indicated by steep slopes and coarse-grained bed material, are sinuous and unstable. Many reaches along the same rivers that show morphology similar to those that are unstable (including coarse-grained point bars and steep slopes) but carry little coarse-grained bedload, indicated by fine-grained bed material, are stable. Along the Rio Puerco, reaches that carry sand-size bedload are braided and unstable, but reaches that carry finer sediment are sinuous and stable.

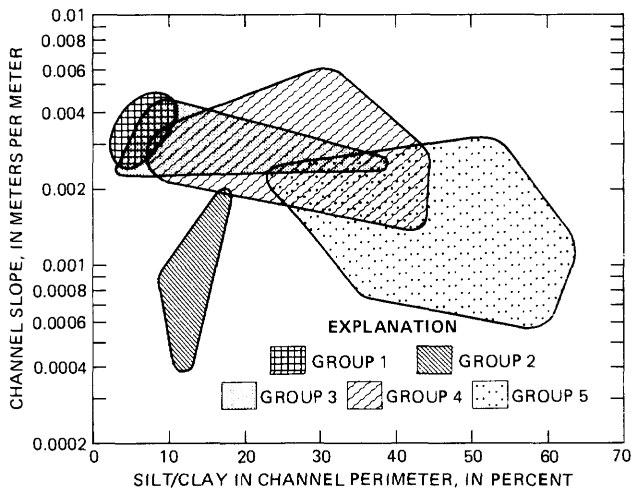

Figure 35. Relation between local slope and percent silt/clay in channel perimeter for sinuous coarse-grained channels in unstable arroyo reaches (group 1), straight and braided coarse-grained channels in stable arroyo reaches (group 2), sinuous coarse-grained channels in stable arroyo reaches (group 3), braided fine-grained channels in unstable arroyo reaches (group 4), and sinuous fine-grained channels in stable arroyo reaches (group 5), San Simon, San Pedro, and Santa Cruz Rivers, southeast Arizona, and Rio Puerco, New Mexico.

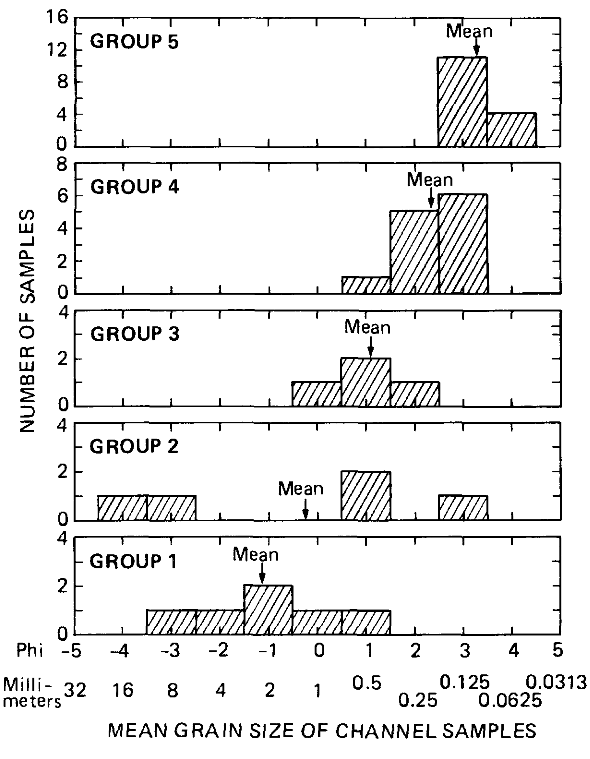

Figure 36. Mean grain size of sinuous coarse-grained channels in unstable arroyo reaches (group 1), straight and braided coarse-grained channels in stable arroyo reaches (group 2), sinuous coarse-grained channels in stable arroyo reaches (group 3), braided fine-grained channels in unstable arroyo reaches (group 4), and sinuous fine-grained channels in stable arroyo reaches (group 5), San Simon, San Pedro, and Santa Cruz Rivers, southeast Arizona, and Rio Puerco, New Mexico. Above histograms are means of each group.

MODEL OF ARROYO DEVELOPMENT

Experiments and field observations were used to develop a conceptual model to determine the influence of sediment load and grain size on the development and stability of arroyos (fig. 37). The model does not consider preincision characteristics of the channel or the cause of incision, but assumes that the resulting arroyo is initially narrow.

The sediment load of the arroyo is dependent on the particle-size distribution of the alluvium in which it is entrenched because the dominant source of sediment is initially upstream knickpoint migration. When alluvium delivered to the channel is gravel or coarser, alternate bars form and arroyo widening is asymmetric (fig. 37). Examples are reaches of San Simon, San Pedro, and Santa Cruz arroyos containing coarse-grained point bars.

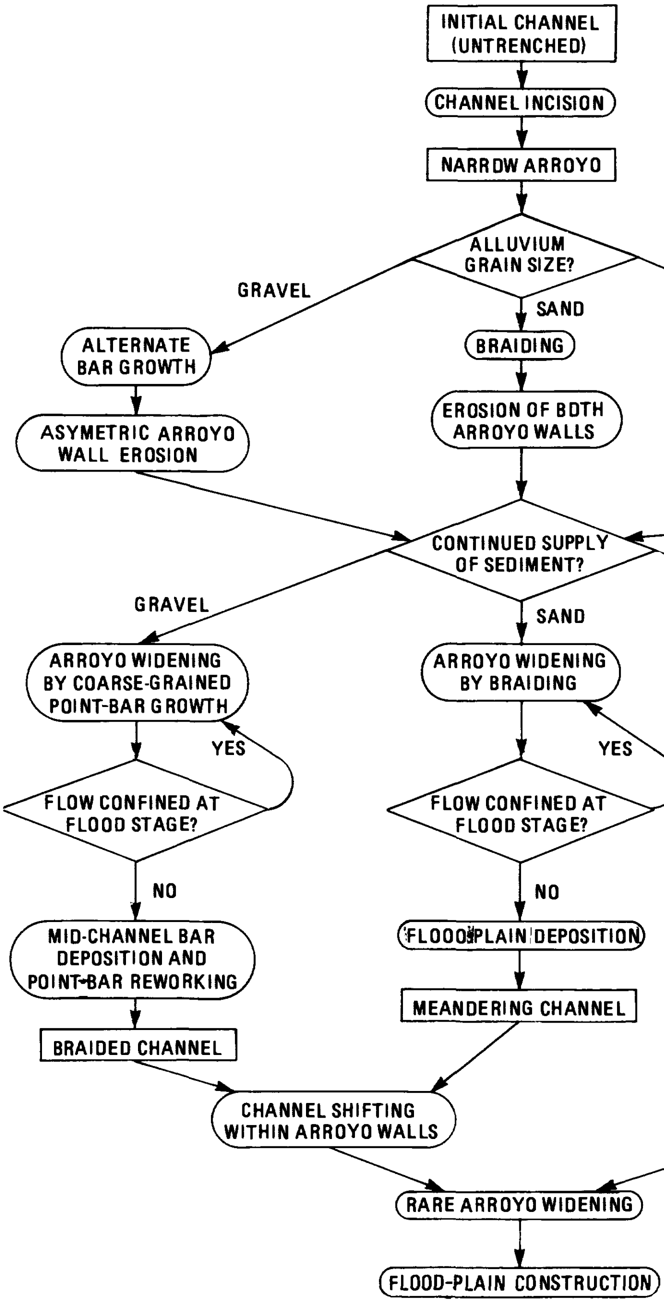

Figure 37. Model of arroyo development. Boxes indicate arroyo conditions, oblongs indicate arroyo-modifying processes, diamonds indicate decision points in model. Confined and unconfined channels refer to channel during floods; if floods fill arroyo bottom, channel is confined; if floods do not fill arroyo bottom, channel is unconfined.

If the coarsest alluvium is sand sized, alternate bars that may form during floods are reworked during recessional flows when most bank erosion takes place, channels braid, and both arroyo walls erode (fig. 37). Examples are the braided unstable reaches of the Rio Puerco.

When the alluvium is dominantly silt and clay sized, arroyo widening is primarily the result of bank-stability factors. The arroyo bottom is commonly no wider than prior to entrenchment, lateral migration is rare, and a straight trench results. Arroyos developed in fine-grained materials were not considered here, but examples of small gullies and artificially channelized streams in the Midwest and East are well documented (Ireland and others, 1939; Thornthwaite and others, 1942; Daniels, 1960; Daniels and Jordan, 1966; Emerson, 1971; Yearke, 1971; Hay and Stall, 1974; Barnard, 1977; Piest and others, 1977; Harvey and others, 1985; Simon and Hupp, 1986).

After entrenchment of an arroyo reach, further bedload transport is required to continue the development of the arroyo. The grain size of the alluvium in the arroyo walls remains important, as lateral migration of the channel upstream remains an important source of sediment, but tributaries also deliver a component of the sediment supply.

Arroyos that carry coarse-grained bedload (M_Z greater than 1 mm) at high rates exhibit geometries that suggest that they initially widen in a manner similar to the experimental arroyos (fig. 37). Confined channels naturally form alternate bars whenever they carry bedload (Leopold and others, 1964, p. 282). With a continued supply of coarse sand and gravel, alternate bars take the form of coarse-grained point bars (McGowan and Garner, 1970; Lewin, 1976). When arroyos widen, active coarse-grained point bars form and grow during floods. However, recessional and low flows are not sufficient to rework coarse-grained sediment. During flood recessions, the channels are forced against banks opposite coarse-grained point bars. Most channel widening and bank failures reflect this process. Thus, arroyo widening is asymmetric. Unconfined channels with erodible banks that carry gravel loads (fig. 37) do not exhibit alternate bars, but braid by depositing gravel as midchannel bars causing erosion of both banks. Thus, when a flood discharge is not confined by arroyo walls because the arroyo is already wide, a gravel-bed braided channel forms within the arroyo.

The major difference between arroyos with gravelly bed material and arroyos with sandy bed material is the ability of recessional and low flows to rework sandy alternate and midchannel bars. Arroyos with sandy bed material and frequent bedload movement initially braid and widen both arroyo walls. If alternate bars form during floods, they are composed of fine sediments. These sands and fine gravels ($M_Z \leqslant 1$ mm) are easily reworked during recessional and low flows, and thus flows are not directed consistently against one bank, and channels become braided during low flow. As this type of arroyo becomes sufficiently wide, fine-grained sediments are deposited in low-velocity areas, stabilizing the flood plain, and causing a sinuous channel to form.

Arroyos appear stable when bedload transport is infrequent or when they have previously widened to the point that even flood discharges are confined within the flood plain and do not erode the arroyo walls.

If an arroyo entrenched into coarse-grained alluvium continues to receive coarse-grained sediment at a relatively high rate, alternate bars grow to become coarse-grained point bars, and the arroyo walls opposite these bars erode. However, when the arroyo widens sufficiently that flood discharges no longer fill the arroyo, coarse-grained sediment is stored in midchannel bars instead of alternate bars, and the coarse-grained point bars are reworked. The channel within the arroyo braids, but arroyo widening occurs at a slower rate simply because the arroyo is already wide enough to accommodate most floods.

If an arroyo entrenched into fine-grained alluvium continues to receive sand-sized sediment at a relatively high rate, the channel continues to braid until the arroyo is wide enough that floods no longer fill the arroyo from wall to wall. At this stage, parts of the flood plain that experience low-velocity flow become sites of fine-grained deposition. Fine-grained sediments stabilize the channel and initiate a sinuous channel pattern.

Entrenched channels that continue to receive fine-grained sediment enter a process of healing (Ireland and others, 1939; Thornthwaite and others, 1942; Harvey and others, 1985; Simon and Hupp, 1986). The walls of the trench erode to progressively gentler slopes, channels and banks aggrade, and vegetation becomes established within the channel. Changes in channel pattern may occur as steeper channels become sinuous (Schumm and Khan, 1972; Edgar, 1973; Barnard, 1977).

If tributaries or entrenchment of upstream reaches deliver sediment of a different grain size than was delivered to a reach initially, the arroyos alter their pattern of development only when the grain size is larger than the initial sediment delivered to the reach. Along San Simon, San Pedro, and Santa Cruz arroyos, many sand channels meandered around coarse-grained point bars inherited from periods when the arroyos received coarse-grained sediment. The experiments demonstrated, however, that alternate-bar formation was initiated in different types of channels when coarse sediment was artificially fed into a stable channel as long as the arroyo was narrow enough to restrict channel width when banks failed.

Where arroyos are sufficiently wide that flood-channel width is no longer restricted by arroyo walls, arroyo widening rates decrease. Channel migration and avulsion continue, but channels rarely impinge on the wide arroyo walls. Flood-plain construction becomes the dominant process through dominantly lateral accretion in the sinuous channels receiving sand-size sediment or dominantly vertical accretion in braided channels receiving gravel-size sediment.

CHANNEL PATTERN

Postincision arroyo development is primarily the result of lateral channel migration and channel widening. In San Simon, San Pedro, Santa Cruz, and Rio Puerco arroyos and in physical models, especially rapid rates of arroyo widening result from development of meanders or widening of braided channels. The dominant process by which arroyos widen is related to bed material grain size, channel slope, and discharge.

The San Simon, San Pedro, and Santa Cruz Rivers have flashy discharges and carry coarse bedload, conditions commonly associated with braided channels (Leopold and Wolman, 1957; Carson, 1984). These rivers were braided along much of their courses before they became entrenched, and braiding has been observed along other widening arroyos (Elliott, 1979). Only two reaches sampled along the Arizona arroyos are braided, however, and the rest are sinuous or straight. Widening reaches of these arroyos contain well-developed, active coarse-grained point bars.

Channel Pattern, Dominant Discharge, and Channel Slope

River-channel patterns appear to be controlled by a combination of channel slope and dominant discharge (Lane, 1957; Leopold and Wolman, 1957). Even in perennial streams, opinions differ as to how to define dominant discharge. Lane (1957) used mean annual discharge (fig. 38), while Leopold and Wolman (1957) used bankfull discharge (fig. 39). In streams with relatively little variability in streamflow, either index is probably as good as the other as long as it is used consistently. However, it is difficult to define an index of dominant flow for streams in semiarid and arid climates because of the episodic character of streamflow. Furthermore, the magnitude of the channel-forming flow may, in fact, be dependent on the channel pattern (Mosley, 1981; Carson, 1984).

Most of the reaches sampled have slope-discharge combinations similar to the braided streams of Leopold and Wolman (fig. 39; tables 2, 4); however, only channels at stations 3 and 6 are braided. Some reaches falling on the braided side of the discriminating line in figure 39 have sinuosities higher than 1.5 which is Leopold and Wolman's lower limit for meandering streams (table 4). Reaches with low sinuosities but not exhibiting braiding, plotted on either side of the line in Leopold and Wolman's investigation. All of the stations plotted within or near Lane's (1957) limits for intermediate streams (fig. 38). Many of the channels confined in arroyos cannot fully adjust their width or their channel pattern to their discharge-slope characteristics, and, if they were not confined by the arroyos, these channels would be braided.

Stream-channel pattern is actually a continuum in that most channels show some tendency toward meandering (Leopold and Wolman, 1957). Braided channels are commonly defined as having midchannel bars or islands regardless of their sinuosity. Classifying the sampled reaches as intermediate is more valid than classifying them as either braided or meandering because of low sinuosity, yet well-developed point bars and lack of midchannel bars.

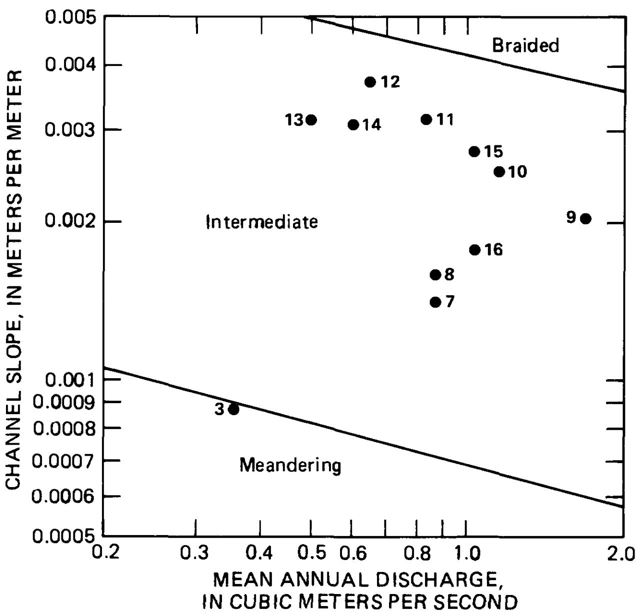

Figure 38. Relation among channel pattern, channel gradient, and mean discharge (from Lane, 1957), with channel slope and mean discharge of stations on San Simon, San Pedro, and Santa Cruz Rivers, Arizona (see fig. 7).

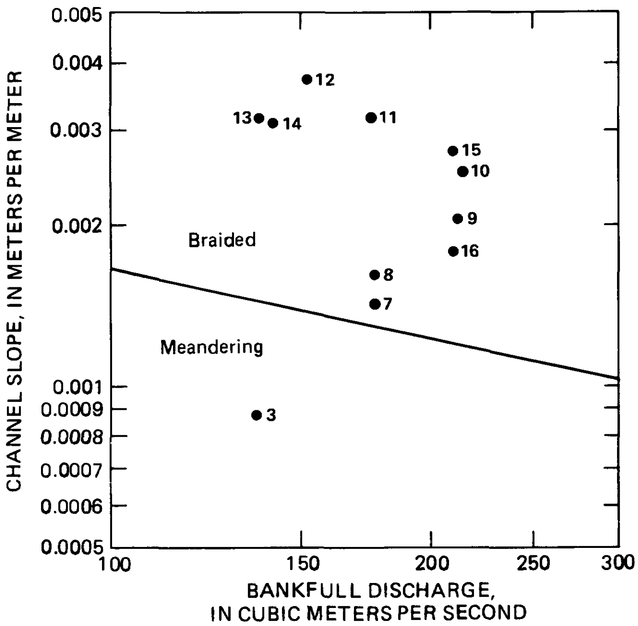

Figure 39. Relation among channel pattern, channel gradient, and bankfull discharge (from Leopold and Wolman, 1957), with channel slope and bankfull discharge of stations on San Simon, San Pedro, and Santa Cruz Rivers, Arizona (see fig. 7).

Channel Pattern and Channel Competence

In any river, bed-material size and its relation to stream competence (the size of the largest particle that can be moved by a flow) is an important factor in channel pattern. Carson (1984) suggested that differences observed between channel pattern are more closely related to the effects of grain size than to dominant discharge and slope, and that channels transporting coarse-grained sediments are more likely to braid than those transporting fine-grained sediments. In wide channels, when bed material is coarse, the coarsest particles are deposited as midchannel bars (Leopold and Wolman, 1957; Fahnestock, 1963). Further deposition, channel widening, and bank failure cause braiding.

Competence can be determined by calculating the shear stress at the river bed (τ) and comparing that number to the critical shear stress (τ_c) for a given grain size. Schulits and Hill (1968) related critical shear stress (τ_c) (in kg/m^2) to representative grain size (D_s) that can be transported for different ranges of D_s as follows:

$D_s = 2.28\ \tau_c$	for $0.091 \leqslant D_s \leqslant 0.27$ mm
$D_s = 1.74 * 10^{-2}\ \tau_c$	for $0.27 \leqslant D_s \leqslant 0.55$ mm
$D_s = 8.93 * 10^{-6}\ \tau_c$	for $0.55 \leqslant D_s \leqslant 6.7$ mm
$D_s = 1.09 * 10^{-4}\ \tau_c$	for $D_s \geqslant 6.7$ mm

assuming specific weight of water is 1.0 g/cm^3, specific weight of sediment is 2.64 g/cm^3, and kinematic viscosity of the water-sediment mixture is 9.66×10^{-7} m^2/s (the original equations are presented in U.S. Customary units and are converted here to metric).

Shear stress or tractive force (τ) was computed from the Du Boys equation for shear stress

$$\tau = \gamma R S$$

(Du Boys, 1879), where γ is the specific weight of water, R is hydraulic radius, and S is slope. The competence of the channel (D_z) was then calculated from the above equations and listed for each station in table 5. Values of hydraulic radius and slope are listed in table 4. A value of 1.01 g/cm^3 is assumed for the specific weight of the suspended sediment-water mixture. This specific weight was calculated for a suspended-sediment concentration of 10,000 parts per million as measured during the December 18, 1978 flood on the Santa Cruz River at Nogales, Arizona (Sam Jones, U.S. Geological Survey, written commun., 1979) by the formula

$$\gamma_m = \frac{\gamma\ \gamma_s}{\gamma_s - C_s(\gamma_s - \gamma)}$$

(Simons and Senturk, 1977, p. 248), where γ_m is the specific weight of the water-sediment mixture, γ is the specific weight of water, γ_s is the specific weight of the sediment grains, and C_s is the concentration of the suspended sediment expressed as a percentage.

Estimates of the competence of the San Simon, San Pedro, and Santa Cruz channels show that midchannel bar deposition is unlikely in many reaches where arroyo walls restrict channel width. The "representative grain size that can be transported" based on computations of critical shear stress are generally within an order of magnitude of the grain size found in the stream sediments (table 5). The agreement between the competence and the sediment present depends, in part, on which statistic of grain size is used. This is a problem that is resolved differently by different authors. It should be noted that the hydraulic radius was computed for bankfull conditions and would be considerably larger for flood discharges, and thus the competence would be proportionally larger. For example, concrete blocks up to 3 m long were moved by the December 1978 flood on the Santa Cruz River at Amado (station 12).

Shear stress, roughness value, and slope, associated with a given discharge, decrease as channels widen. For a given discharge, wider channels will have shallower depths and (or) slower velocities. Either change decreases the forces acting to transport sediment. Progressive widening of arroyos with sinuous, coarse-grained channels results in a loss of competence and deposition of coarse grains (boulders and cobbles, in the case of San Simon, San Pedro, and Santa Cruz arroyos). A threshold width should exist for a given discharge at which the flow is incompetent to move a given grain size, but given the episodic character of streamflow in both time and space, this threshold width is difficult to predict.

During initial stages of arroyo widening when arroyos are narrow, coarse sediment is deposited in alternate and point bars during high flows. Midchannel bars that may form as competence declines during recession divert low, incompetent flows toward the coarse-grained bars. However, midchannel bar formation occurs during progressively higher flows as the channel becomes progressively wider because competence becomes progressively smaller. The currents that are diverted toward the alternate and point bars during higher flows are competent to rework all but the coarsest sediment in these bars.

At constant discharge, progressive widening of an arroyo containing a coarse-grained point bar eventually results in a braided channel. Channel width of a larger discharge, however, is still restricted by the arroyo width, and alternate bars form at the higher discharge. With incremental widening during each high flow, the discharge needed to fill the arroyo becomes progressively larger, and thus less frequent. The tendency for braiding, therefore, increases with time.

Bank Height and Erodibility

Channel-bank erodibility is commonly cited as a prerequisite for braiding (Fahnestock, 1963), and high arroyo walls are relatively difficult to erode. For a given amount of energy expended in lateral erosion, more sediment is

Table 5. Shear stress (τ), competence (D_s), and representative grain sizes of channels and point bars (D_{75}, D_{84}, D_{90}) for sites on San Simon, San Pedro, and Santa Cruz Rivers, Arizona

[Competence was determined by equating shear stress of flow with critical shear stress for D_s. Representative grain size is listed in terms of a percentile of grain size distribution. - -, insufficient sample to compute]

Station	τ (kg/m2)[1]	D_s (mm)	D_{75} (mm)	D_{84} (mm)	D_{90} (mm)
1	1.46	14.7	16.0	24.3	36.8
2	1.71	17.3	1.19	3.25	12.1
3	.269	3.3	.93	1.62	2.83
5	1.66	16.8	.83	1.37	2.07
6	1.68	17.0	.81	1.15	1.52
7	2.86	28.8	64.0	73.5	78.8
8	1.45	14.6	97.0	128.0	--
9	2.90	29.3	45.3	90.5	--
10	3.53	35.6	111.4	--	--
11	4.36	44.0	90.5	--	--
12	3.69	37.3	45.3	84.4	107.6
13	4.34	43.8	64.0	--	--
14	5.32	53.7	1.23	9.85	64.0
15	4.84	48.9	84.4	119.4	128.0
16	1.49	15.1	.29	.81	48.5

[1] The use of the units kg/m^2 for shear stress is not dimensionally correct, but follows Vanoni (1975, p. 99).

delivered to the channel when banks are high than when they are low. Subsequently, energy must be expended to remove the sediment produced by bank failures when banks are high. When banks are low, this energy can be directed toward further bank erosion, and banks erode more quickly. Although the alluvium forming the arroyo walls along the San Simon, San Pedro, and Santa Cruz Rivers is relatively easy to erode, much more energy is required to transport the large amount of material delivered to the channel by a bank recession of high arroyo walls than for a stream that is not entrenched.

Field and laboratory data show that high banks erode more slowly than low banks. Along South Coldwater Creek, Washington, channel widening was induced by an artificial increase in discharge. During periods of active bank erosion, 1-m banks eroded much more rapidly than 5-m banks of the same material. About half of the time between high-bank failures was spent removing material that accumulated at the base of the high banks. Experimental channels in the REF braided only when the arroyo was wide and the channel unconfined; that is, the channel banks were low and not coincident with the high arroyo walls.

When bed-material grain size, channel slope, and stream discharge favor formation of a braided channel, but channel width is restricted, coarse-grained point bars form. McGowan and Garner (1970) ascribed the formation of coarse-grained meanders to dense vegetation that stabilizes the banks, thus inhibiting braiding. Similarly, the high arroyo walls along the San Simon, San Pedro, and Santa Cruz Rivers help stabilize the channel and inhibit braiding by slowing the process of channel widening.

The analyses of channel slope, dominant discharge, and channel pattern suggest that the channels observed would braid if they were not confined within deep, relatively narrow arroyos. Yet, in order to braid, midchannel bar deposition must be initiated, and the analysis of stream competence shows that the rivers can transport the largest material present at flood stages. Because the maximum width of the channel is constrained by arroyo walls, the depth of the channel is greater than that of an unconfined channel with the same water and sediment discharge. This causes the competence of the channel to be larger. If midchannel bar formation is initiated, irregularities in the channel that tend to favor one side over another can transform the midchannel bar into a point bar (Lewin, 1976).

Prominent Exceptions

Bank erosion processes observed along the San Simon, San Pedro, and Santa Cruz Rivers reflect the flashy run off regime, stable bed elevations, stream competence relative to bed material size, and the resistance to erosion caused by high arroyo walls of these rivers, as well as channel slope and dominant discharge. Processes responsible for rapid bank erosion are somewhat different when one or more of these factors change.

When stream competence consistently exceeds the size of the available bed-material particles, transverse bars can form during high flow. Dissection of these bars during recession causes a braided channel. Although such conditions do not occur along the coarse-grained San Simon, San Pedro, and Santa Cruz Rivers, they do occur in widening arroyos along the Rio Puerco (Elliott, 1979) and in the lower Platte River in Nebraska (Smith, 1970; Blodgett and Stanley, 1980). Transverse bars (referred to as linguoidal bars by Blodgett and Stanley) form and move during high flows. They are large-scale bedforms with widths about 50 percent or more of the channel width and have relatively flat tops and steep-avalanche faces at their downstream margins. At high flows, the lower Platte River and the braided unstable reaches of the Rio Puerco are single channels. The channels dissect and braid around these high-flow bedforms on recession as sand and fine gravel are easily transported.

The contrast in braiding processes between coarse sediments (boulders) hypothesized for wide arroyos along the San Simon, San Pedro, and Santa Cruz Rivers, and sand and gravel hypothesized for the Rio Puerco has been observed between upper and lower reaches of the South Platte and Platte Rivers in Colorado and Nebraska (Smith, 1970). Grain size decreases, sorting increases, and the proportion of midchannel bars (referred to as longitudinal bars by Smith) to transverse bars decreases in a downstream direction. Historic decreases in peak flows and increases in low flows have resulted in a more stable, narrower, less braided channel (Eschner and others, 1981; Nadler and Schumm, 1981).

In the Toutle River, Washington, lateral channel instability caused erosion of 1.5×10^5 Mg of bank material per kilometer of channel during water year 1982, and 2.1×10^5 Mg/km during water year 1983. This was the result of high sediment production from erosion of the North Fork Toutle debris avalanche deposit resulting from the 1980 eruption of Mount St. Helens (Meyer and Janda, 1986). Bed material is coarse ($M_z = 0.2$ to 68 mm), and alternate bars commonly form along narrow reaches where banks are composed of bedrock. Although the response of the Toutle River to storms is flashier than prior to the 1980 eruptions of Mount St. Helens (Orwig and Mathison, 1981), the river is not as flashy as desert streams. Recessional flows occurring over days or weeks rework all but the coarsest bed material. Bed material is deposited in midchannel bars, and the channel shifts laterally, even during low flows. On the 1980 debris avalanche deposit, where flashy storm discharges may resemble desert streams, the North Fork Toutle River aggrades and degrades by as much as 5 m during single storms (Meyer and others, 1985). If coarse-grained point bars form during high flow, they are either buried during recessional aggradation or entrenched during recessional degradation, and the channel remains braided.

SUMMARY

After initial incision, channels widen their trenches. When the channels experience flashy discharge, and sediment delivered to the channel is sand size or coarser, as is the case with most arroyos in the southwestern United States, lateral instability of the channel is responsible for arroyo widening. For a given bank material, the rate of arroyo widening is dependent on the amount of bedload transported through a reach, while the pattern of arroyo widening is dependent on the grain size of bedload transported through a reach. In laboratory experiments, arroyo widening caused by meandering and braiding produced five times the amount of sediment produced by initial incision. Initial erosion rates caused by arroyo widening were as high as during incision, but as widening continued, arroyo walls were eroded at a decreased rate.

Where bedload transport is significant and bed material is predominantly gravel, channels initially widen their arroyos by meandering; in later stages, the channels become braided. The initially narrow trenches constrain channel width, and alternate bars form during high flows. These bars are persistent features under the flashy hydrologic regime common in the Southwest, as they are too coarse to be reworked by recessional and low flows. Flow is thus directed against the opposite bank, and only one arroyo wall erodes. As the arroyo widens, the alternate bars grow and develop into coarse-grained point bars. Flow concentration within the arroyo inhibits deposition of midchannel bars. After further widening, however, the arroyo no longer constrains flood-channel width. At this point, coarse material is deposited as midchannel bars, alternate bars are reworked during high flows, and the channel becomes braided. Arroyos along the San Simon, San Pedro, and Santa Cruz Rivers widen in this manner.

Where bedload transport is significant and the bed material is predominantly sand, channels initially widen their arroyos by braiding, but in later stages the channels become sinuous. If alternate bars form during high flows, they are eroded and easily reworked during recession. Low flows are not restricted by arroyo walls, transverse bars are dissected, and the channel braids. Fine-grained material (silt and clay) cannot be deposited during high flows because velocities are too high within the relatively narrow arroyos. However, as the arroyo widens progressively, fine-grained materials can be deposited as low-velocity areas become more abundant. Deposition of the fine sediment promotes formation of a sinuous channel and a flood plain. The arroyo of the Rio Puerco widens in this manner (Elliott, 1979).

Where bedload is insignificant, channels widen by collapse of arroyo walls without significant change in active channel width or in channel pattern. Many gullies and channelized streams widen in this manner.

As arroyos widen progressively, channels can shift freely within the arroyos only rarely impinging upon arroyo walls. The rate of arroyo wall erosion decreases with time, and flood-plain construction becomes the dominant process.

Unstable arroyos differ from stable arroyos in ways that imply that bedload transport is the process that distinguishes between them. Channels contained within three different groups of arroyos exhibit different channel geometry when the arroyos are unstable than when arroyos are stable. The three types of arroyos are: (1) experimental arroyos; (2) the arroyos of the San Simon, San Pedro, and Santa Cruz Rivers; and (3) the arroyo of the Rio Puerco. Channels contained within unstable arroyos have larger width-to-depth ratios (types 1 and 3), steeper slopes (types 1, 2, and 3), coarser bed material (types 2 and 3), and less silt/clay in the channel perimeter (types 2 and 3) than do channels contained within stable arroyos.

Some arroyo reaches have widened to the point that channel instability does not necessarily imply arroyo instability. These arroyos are stable in that former flood plains are now terraces, and arroyo floors are now flood plains. When channels are transporting sand-size or finer material, they are sinuous. When the channels are transporting sand and gravel, they are braided.

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APPENDIXES 1 AND 2

Appendix 1. Morphologic and hydrologic characteristics measured during experiments in Rainfall Erosion Facility (runs 3.5 to 6) and flume (runs 11 to 14)

Run	Flow time (h)	Distance from mouth (m)	Discharge (mL/s)	Channel area (cm^2)	Wetted perimeter (cm)	Hydraulic radius (cm)	Channel width (cm)	Hydraulic depth (cm)	Total head (cm)	Average bed above mouth (m)	Rate of arroyo area change (cm^2/h)	Average unit discharge (mL/s/cm)	Average energy slope (m/m)	Width/depth ratio	
														Arroyo	Channel
3.5	44:00	13	716.0	16.5	19.40	0.851	15.83	1.04	21.220	0.190	17.8	42.4	0.0097	--	5.19
		12	716.0	20.5	17.27	1.187	16.80	1.22	19.852	.179	11.3	39.7	.0105	--	7.60
		11	716.0	26.8	29.43	.911	28.10	.95	18.404	.171	15.9	21.4	.0116	--	13.19
		10	716.0	18.4	17.55	1.048	16.81	1.09	17.212	.152	15.0	33.0	.0073	--	11.59
		9	716.0	25.8	26.51	.973	25.97	.99	16.423	.150	14.4	25.1	.0097	--	19.98
		8	716.0	35.5	39.39	.901	38.95	.91	15.187	.141	29.3	15.1	.0151	--	31.93
		7	716.0	31.2	29.44	1.060	29.00	1.08	13.758	.121	23.8	20.2	.0144	--	12.29
		6	716.0	22.0	17.58	1.251	15.98	1.38	12.180	.102	15.7	38.0	.0129	--	8.73
		5	716.0	22.8	20.26	1.125	18.79	1.21	10.363	.089	34.2	33.0	.0143	6.8	11.18
		4	716.0	17.4	16.78	1.037	15.98	1.09	8.723	.068	48.6	36.3	.0160	--	9.13
		3	716.0	25.5	18.58	1.372	16.99	1.50	7.492	.055	38.7	30.2	.0127	9.4	9.71
		2	716.0	19.2	17.78	1.080	16.99	1.13	5.839	.037	44.3	32.4	.0141	3.5	9.28
		1	716.0	15.9	18.19	.874	16.10	.99	4.154	.019	48.7	33.9	.0130	3.7	7.93
4	46:00	13	743.0	23.6	21.18	1.231	19.18	1.23	27.227	.254	-11.5	42.0	.0137	--	6.29
		12	743.0	27.4	30.28	.922	29.71	.92	25.533	.242	2.3	33.8	.0127	--	13.93
		11	743.0	19.4	21.11	.969	20.00	.97	24.488	.226	-.8	31.3	.0141	--	10.09
		10	743.0	41.0	29.56	1.443	28.44	1.44	22.228	.205	22.1	34.4	.0145	7.7	10.98
		9	743.0	28.2	27.73	1.044	27.00	1.04	20.485	.189	36.3	27.5	.0128	8.8	14.76
		8	743.0	17.9	19.63	.959	18.63	.96	19.043	.170	26.4	29.1	.0159	6.7	11.64
		7	743.0	28.0	16.17	2.157	13.00	2.16	16.728	.141	27.2	40.9	.0178	3.2	4.49
		6	743.0	20.4	14.74	1.702	12.00	1.70	14.966	.127	19.4	53.4	.0173	2.4	6.56
		5	743.0	22.6	18.04	1.407	16.05	1.41	13.218	.112	25.9	42.2	.0178	3.1	9.57
		4	743.0	23.7	25.12	1.034	22.89	1.03	11.092	.096	40.4	38.6	.0167	4.0	12.51
		3	743.0	25.7	26.12	1.008	25.50	1.01	9.401	.080	64.3	35.6	.0165	4.3	17.61
		2	743.0	19.7	24.08	.861	22.89	.86	7.214	.057	78.4	37.3	.0199	3.1	17.67
		1	743.0	19.5	18.97	1.124	17.36	1.12	4.529	.025	90.2	43.6	.0211	4.4	6.16
4	48:00	13	743.0	29.5	32.31	1.020	28.96	1.02	25.445	.241	21.4	32.2	.0142	--	10.86
		12	743.0	26.6	16.50	1.846	14.40	1.85	24.032	.215	30.6	38.3	.0133	2.4	4.50
		11	743.0	36.5	23.74	1.671	21.86	1.67	22.122	.201	46.8	35.6	.0159	4.6	6.83
		10	743.0	23.1	15.61	1.660	13.93	1.66	20.149	.179	26.7	39.7	.0173	5.6	6.53
		9	743.0	16.8	16.77	1.053	16.00	1.05	18.914	.168	17.3	37.0	.0145	5.8	12.35
		8	743.0	33.4	17.17	2.271	14.71	2.27	17.423	.147	19.7	45.2	.0180	4.1	5.08
		7	743.0	17.0	16.18	1.138	14.93	1.14	15.365	.129	10.5	53.5	.0197	2.5	5.44
		6	743.0	29.0	17.81	1.991	14.55	1.99	13.560	.113	15.4	56.5	.0178	1.8	5.30
		5	743.0	24.7	14.86	1.938	12.77	1.94	11.755	.092	1.0	52.2	.0186	2.3	5.24
		4	743.0	20.7	17.55	1.295	16.00	1.30	9.721	.079	25.9	39.4	.0164	3.5	8.75
		3	743.0	15.6	18.25	.870	17.93	.87	8.761	.065	8.2	35.3	.0166	3.8	13.84
		2	743.0	29.3	27.45	1.229	23.88	1.23	6.740	.051	72.0	31.8	.0213	3.5	12.05
		1	743.0	45.0	33.81	1.425	31.57	1.43	4.920	.034	65.1	33.2	.0224	4.0	14.80

Appendix 1. Morphologic and hydrologic characteristics measured during experiments in Rainfall Erosion Facility (runs 3.5 to 6) and flume (runs 11 to 14)—Continued

Run	Flow time (h)	Distance from mouth (m)	Discharge (mL/s)	Channel area (cm^2)	Wetted perimeter (cm)	Hydraulic radius (cm)	Channel width (cm)	Hydraulic depth (cm)	Total head (cm)	Average bed above mouth (m)	Rate of arroyo area change (cm^2/h)	Average unit discharge (mL/s/cm)	Average energy slope (m/m)	Width/depth ratio	
														Arroyo	Channel
4	50:00	2	751.0	29.1	27.04	1.186	24.51	1.19	6.297	0.046	29.8	30.9	0.0181	3.6	12.37
		3	751.0	22.2	17.15	1.363	16.28	1.36	7.809	.058	11.8	43.8	.0148	3.2	7.12
		4	751.0	18.1	15.90	1.204	15.00	1.20	9.490	.072	4.4	48.3	.0150	2.9	8.20
		5	751.0	25.8	17.00	1.767	14.59	1.77	11.118	.089	12.2	54.8	.0170	2.2	6.84
		6	751.0	24.4	14.94	2.045	11.94	2.04	12.793	.101	4.0	57.0	.0176	1.7	4.90
		7	751.0	18.6	14.24	1.459	12.77	1.46	14.608	.124	3.4	54.3	.0181	2.5	5.98
		8	751.0	21.7	13.30	1.849	11.71	1.85	16.259	.135	7.3	57.3	.0203	3.6	5.49
		9	751.0	9.8	15.78	.629	15.52	.63	19.340	.157	16.9	47.4	.0131	5.2	16.98
		10	751.0	20.7	15.88	1.475	14.00	1.48	18.849	.166	0.0	53.5	.0110	4.7	5.57
		11	751.0	29.8	22.43	1.398	21.30	1.40	20.787	.188	14.9	34.6	.0163	3.9	6.50
		12	751.0	26.9	17.05	1.744	15.43	1.74	22.811	.204	20.8	50.1	.0148	2.4	5.96
		13	751.0	28.8	15.44	1.994	11.94	1.99	24.410	.217	8.0	44.3	.0146	--	4.02
4	53:00	1	727.0	25.9	21.49	1.328	19.50	1.33	4.802	.025	160.2	30.4	.0199	4.2	6.92
		2	727.0	16.8	16.39	1.067	15.72	1.07	7.295	.051	-8.0	38.4	.0151	3.6	7.11
		3	727.0	21.7	16.57	1.419	15.33	1.42	7.718	.054	-3.2	46.8	.0122	3.1	5.75
		4	727.0	25.1	17.02	1.690	14.83	1.69	9.496	.071	-2.0	49.5	.0157	2.6	4.42
		5	727.0	23.6	15.38	1.653	14.31	1.65	11.316	.089	-.4	51.1	.0147	2.1	5.52
		6	727.0	27.5	15.85	2.128	12.94	2.13	12.361	.097	-.7	59.5	.0181	1.6	4.72
		7	727.0	11.6	8.86	1.646	7.07	1.65	15.083	.116	.6	80.8	.0173	2.4	4.03
		8	727.0	27.1	15.07	2.128	12.75	2.13	15.860	.132	.6	60.6	.0165	3.2	4.65
		9	727.0	25.9	19.28	1.448	17.91	1.45	17.103	.147	4.4	44.5	.0119	4.1	5.73
		10	727.0	22.5	17.52	2.256	9.96	2.26	18.175	.161	10.5	63.3	.0117	4.8	3.44
		11	727.0	43.6	19.71	2.541	17.15	2.54	20.681	.174	-.4	38.8	.0164	3.5	4.17
		12	727.0	25.0	17.22	1.629	15.33	1.63	22.161	.200	1.9	48.0	.0139	2.5	6.09
		13	727.0	24.6	15.83	2.244	10.95	2.24	23.587	.202	4.0	64.6	.0148	--	2.71
4	56:00	1	751.0	22.7	14.52	1.889	12.00	1.89	5.188	.024	1.0	49.9	.0170	4.4	4.38
		2	751.0	32.0	18.92	1.947	16.41	1.95	6.466	.040	38.5	46.0	.0117	3.5	5.82
		3	751.0	23.0	18.47	1.548	14.86	1.55	7.464	.056	3.6	49.0	.0104	3.1	6.50
		4	751.0	29.1	22.55	1.390	20.97	1.39	8.947	.071	14.8	42.4	.0150	3.1	9.17
		5	751.0	25.3	15.85	1.984	12.75	1.98	10.538	.078	8.1	54.9	.0131	1.8	4.20
		6	751.0	18.7	11.84	2.083	8.96	2.08	11.613	.085	2.9	70.0	.0162	1.5	3.46
		7	751.0	24.8	14.80	1.987	12.50	1.99	13.255	.106	6.4	81.5	.0166	2.1	4.69
		8	751.0	18.5	12.50	1.718	10.79	1.72	14.807	.122	5.7	63.3	.0126	2.8	4.72
		9	751.0	22.0	15.55	1.694	13.00	1.69	16.381	.142	.4	49.2	.0135	3.8	4.61
		10	751.0	16.6	12.45	1.552	10.67	1.55	18.080	.151	0.0	71.7	.0159	4.8	5.00
		11	751.0	46.5	28.69	1.859	25.00	1.86	19.758	.172	19.9	36.2	.0155	3.5	5.47
		12	751.0	28.8	16.83	2.032	14.16	2.03	21.695	.191	5.1	50.2	.0136	2.5	5.16
		13	751.0	23.0	13.52	2.324	9.89	2.32	23.228	.198	3.0	71.2	.0145	--	2.54

Appendix 1. Morphologic and hydrologic characteristics measured during experiments in Rainfall Erosion Facility (runs 3.5 to 6) and flume (runs 11 to 14)—Continued

Run	Flow time (h)	Distance from mouth (m)	Discharge (mL/s)	Channel area (cm^2)	Wetted perimeter (cm)	Hydraulic radius (cm)	Channel width (cm)	Hydraulic depth (cm)	Total head (cm)	Average bed above mouth (m)	Rate of arroyo area change (cm^2/h)	Average unit discharge (mL/s/cm)	Average energy slope (m/m)	Width/depth ratio Arroyo	Width/depth ratio Channel
5	57:00	1	711.0	46.7	51.09	0.953	49.00	0.95	6.606	0.054	302.3	14.5	0.0491	3.1	29.23
		2	711.0	92.3	43.01	2.366	39.00	2.37	11.656	.095	173.5	18.2	.0333	3.2	8.25
		3	711.0	28.7	18.88	1.600	17.93	1.60	13.741	.115	131.7	39.7	.0196	3.8	7.59
		4	711.0	33.4	18.02	2.210	15.10	2.21	15.881	.134	9.6	47.1	.0165	2.9	4.50
		5	711.0	26.0	14.18	2.466	10.54	2.47	17.270	.140	10.9	67.5	.0164	1.6	2.51
		6	711.0	20.8	15.88	3.467	5.99	3.47	19.339	.146	-13.2	118.7	.0183	1.0	1.31
		7	711.0	27.6	15.09	2.286	12.07	2.29	20.930	.182	1.0	58.9	.0148	1.2	3.68
		8	711.0	26.4	14.96	2.223	11.87	2.22	22.296	.194	-1.4	59.9	.0135	--	3.71
		9	711.0	22.7	16.94	1.627	13.95	1.63	23.710	.212	.2	51.0	.0143	--	4.58
		10	711.0	22.7	14.31	1.899	11.97	1.90	25.258	.227	2.2	59.4	.0168	4.3	4.49
		11	711.0	53.4	26.71	2.366	22.55	2.37	27.442	.244	.9	31.5	.0156	--	4.85
		12	711.0	25.7	16.64	1.705	15.10	1.70	29.159	.267	-5.4	47.1	.0138	--	5.08
		13	711.0	19.6	12.98	2.091	8.90	2.09	30.697	.275	-1.7	79.9	.0150	--	2.78
5	59:00	1	762.0	39.3	60.46	.674	58.35	.67	5.917	.050	121.1	13.8	.0404	2.7	31.90
		2	762.0	60.2	51.10	1.246	48.30	1.25	9.269	.079	170.7	17.0	.0308	3.6	24.38
		3	762.0	30.0	44.95	.677	44.24	.68	12.157	.112	38.1	28.4	.0210	5.7	24.19
		4	762.0	26.5	21.63	1.257	21.07	1.26	14.166	.124	59.4	41.6	.0175	2.9	13.17
		5	762.0	17.2	14.74	1.323	13.00	1.32	16.137	.137	22.9	63.0	.0167	1.8	6.56
		6	762.0	20.2	14.39	1.571	12.86	1.57	17.791	.153	17.2	89.0	.0163	1.1	7.03
		7	762.0	30.3	19.97	1.624	18.63	1.62	19.010	.168	30.7	49.9	.0157	1.6	8.15
		8	762.0	23.0	14.91	1.748	13.14	1.75	21.115	.184	13.3	58.9	.0156	--	4.79
		9	762.0	20.8	16.10	1.494	13.93	1.49	22.673	.201	14.4	52.8	.0145	--	4.35
		10	762.0	25.9	15.60	1.993	12.97	1.99	24.135	.217	8.6	59.1	.0159	3.8	4.86
		11	762.0	43.7	19.96	2.435	17.96	2.44	25.906	.229	19.4	37.0	.0168	--	4.36
		12	762.0	21.2	14.52	2.071	10.21	2.07	28.513	.254	2.6	60.9	.0158	--	2.35
		13	762.0	22.8	12.85	2.848	7.99	2.85	29.991	.265	2.4	87.6	.0147	--	2.33
5	62:00	1	732.0	19.9	47.18	.422	47.07	.42	6.417	.053	68.6	14.3	.0280	4.4	61.77
		2	732.0	22.7	25.19	.914	24.87	.91	9.106	.076	102.1	22.6	.0256	6.3	20.40
		3	732.0	21.1	14.84	1.653	12.75	1.65	11.452	.090	92.7	37.3	.0200	5.2	5.77
		4	732.0	18.0	14.92	1.410	12.77	1.41	12.911	.106	5.4	46.7	.0179	2.2	6.70
		5	732.0	24.4	15.51	1.791	13.64	1.79	15.212	.126	4.3	56.1	.0167	1.6	4.84
		6	732.0	18.9	14.20	1.575	12.00	1.57	16.382	.138	3.7	60.1	.0148	0.9	4.26
		7	732.0	29.0	18.71	1.712	16.32	1.71	18.250	.161	3.3	42.1	.0173	1.4	5.05
		8	732.0	30.7	17.58	2.005	15.33	2.01	20.005	.175	4.6	52.9	.0165	--	4.28
		9	732.0	18.7	13.97	1.559	12.02	1.56	21.397	.187	10.9	57.8	.0143	--	3.94
		10	732.0	23.9	17.56	1.600	14.93	1.60	22.875	.203	20.2	53.9	.0167	3.8	4.90
		11	732.0	25.6	15.17	1.867	13.72	1.87	25.710	.230	-6.3	47.9	.0180	--	4.09
		12	732.0	29.3	16.91	2.489	11.77	2.49	27.564	.251	6.5	68.4	.0176	--	2.45
		13	732.0	17.7	11.69	2.525	6.99	2.53	29.763	.262	2.1	100.0	.0180	--	2.29

Appendix 1. Morphologic and hydrologic characteristics measured during experiments in Rainfall Erosion Facility (runs 3.5 to 6) and flume (runs 11 to 14)—Continued

Run	Flow time (h)	Distance from mouth (m)	Discharge (mL/s)	Channel area (cm²)	Wetted perimeter (cm)	Hydraulic radius (cm)	Channel width (cm)	Hydraulic depth (cm)	Total head (cm)	Average bed above mouth (m)	Rate of arroyo area change (cm²/h)	Average unit discharge (mL/s/cm)	Average energy slope (m/m)	Width/depth ratio	
														Arroyo	Channel
5	65:00	1	745.0	49.9	50.98	1.005	49.69	1.00	6.373	0.052	19.4	15.3	0.0298	4.4	24.15
		2	745.0	12.6	24.50	1.365	9.24	1.36	10.740	.066	136.3	55.0	.0226	6.7	2.58
		3	745.0	20.6	15.52	1.557	13.21	1.56	11.429	.093	48.9	56.9	.0134	5.8	6.67
		4	745.0	23.2	19.00	1.351	17.18	1.35	12.746	.106	5.1	50.3	.0167	2.2	8.35
		5	754.0	19.5	12.67	2.015	9.70	2.02	15.008	.121	.9	65.2	.0160	1.6	3.90
		6	745.0	22.0	14.86	1.694	12.97	1.69	16.051	.138	4.2	59.2	.0149	1.0	5.49
		7	745.0	27.3	16.02	2.192	12.45	2.19	17.924	.151	1.9	51.6	.0173	1.3	3.48
		8	745.0	26.5	16.31	1.783	14.83	1.78	19.358	.170	2.9	49.0	.0156	--	5.26
		9	745.0	22.8	15.30	1.624	14.02	1.62	21.165	.188	10.5	57.0	.0145	--	5.75
		10	745.0	25.1	17.28	1.791	14.00	1.79	22.466	.201	1.1	51.1	.0175	3.8	4.97
		11	745.0	38.1	22.53	1.851	20.59	1.85	25.032	.228	10.3	44.8	.0187	--	6.43
		12	745.0	23.8	13.44	2.473	9.64	2.47	27.515	.241	1.1	69.7	.0171	--	2.11
		13	745.0	18.7	11.68	2.678	6.99	2.68	28.932	.253	1.6	105.7	.0177	--	2.09
5	68:00	1	754.0	13.4	17.31	.782	17.10	.78	6.357	.039	207.8	29.5	.0258	5.9	14.96
		2	754.0	24.7	15.74	1.818	13.58	1.82	8.139	.057	13.5	68.1	.0209	6.7	5.57
		3	754.0	33.9	18.17	2.372	14.31	2.37	10.479	.076	5.5	54.5	.0118	5.3	4.58
		4	754.0	27.0	27.79	1.023	26.43	1.02	11.321	.098	25.9	35.9	.0143	2.1	13.34
		5	754.0	27.8	19.81	1.549	17.91	1.55	13.302	.110	42.3	59.5	.0171	2.2	6.72
		6	754.0	21.8	13.83	1.822	11.94	1.82	15.239	.127	6.4	60.3	.0171	0.9	5.22
		7	754.0	29.2	18.36	2.292	12.75	2.29	17.274	.149	5.9	59.5	.0180	1.3	4.29
		8	754.0	30.6	21.13	1.621	18.86	1.62	19.263	.171	3.8	45.1	.0158	--	6.04
		9	754.0	20.7	13.93	1.655	12.52	1.65	20.608	.183	.2	56.7	.0145	--	4.98
		10	754.0	36.2	22.20	1.833	19.78	1.83	22.162	.199	16.0	45.7	.0168	3.8	7.63
		11	754.0	39.1	20.89	2.042	19.16	2.04	24.569	.221	4.4	37.8	.0192	--	5.24
		12	754.0	25.0	16.33	2.210	11.33	2.21	27.175	.240	2.3	71.9	.0167	--	2.48
		13	754.0	17.2	11.56	2.870	5.99	2.87	28.494	.244	.2	116.2	.0134	--	1.79
5	71:30	1	743.0	20.2	21.22	1.056	19.15	1.06	5.042	.034	13.8	41.4	.0187	5.5	8.98
		2	743.0	21.8	14.11	1.822	11.99	1.82	7.262	.048	.2	58.7	.0203	6.3	4.03
		3	743.0	19.1	15.33	1.519	12.58	1.52	9.398	.070	11.3	55.9	.0161	5.0	4.58
		4	743.0	28.7	21.99	1.425	20.15	1.42	11.190	.095	-.4	32.7	.0140	2.0	8.01
		5	743.0	26.6	16.91	1.773	14.98	1.77	12.868	.107	1.0	45.8	.0184	1.8	5.96
		6	743.0	40.6	22.82	2.303	17.65	2.30	14.950	.129	14.7	52.6	.0184	1.0	5.04
		7	743.0	27.1	27.64	1.047	25.86	1.05	16.480	.149	12.2	43.9	.0169	2.4	11.31
		8	743.0	20.5	16.73	1.491	13.72	1.49	18.102	.163	29.8	47.1	.0153	--	7.20
		9	743.0	17.5	13.64	1.454	12.07	1.45	19.702	.169	7.4	60.9	.0144	--	4.95
		10	743.0	28.1	18.36	1.654	16.98	1.65	21.153	.191	4.7	40.9	.0168	3.6	8.25
		11	743.0	37.3	18.35	2.290	16.28	2.29	23.591	.209	4.5	42.5	.0197	--	4.19
		12	743.0	17.2	12.53	2.493	6.90	2.49	26.519	.229	-6.1	87.1	.0191	--	1.71
		13	743.0	19.5	11.33	2.656	6.97	2.66	28.566	.246	-.7	116.2	.0165	--	2.03

Appendix 1. Morphologic and hydrologic characteristics measured during experiments in Rainfall Erosion Facility (runs 3.5 to 6) and flume (runs 11 to 14)—Continued

Run	Flow time (h)	Distance from mouth (m)	Discharge (mL/s)	Channel area (cm^2)	Wetted perimeter (cm)	Hydraulic radius (cm)	Channel width (cm)	Hydraulic depth (cm)	Total head (cm)	Average bed above mouth (m)	Rate of arroyo area change (cm^2/h)	Average unit discharge (mL/s/cm)	Average energy slope (m/m)	Width/depth ratio	
														Arroyo	Channel
5	74:30	1	745.0	24.1	20.38	1.242	19.40	1.24	5.070	0.034	7.9	38.6	0.0196	5.7	11.07
		2	745.0	30.2	14.95	2.521	11.99	2.52	6.983	.038	6.8	62.1	.0199	6.1	3.50
		3	745.0	23.2	15.59	1.763	13.14	1.76	9.002	.066	2.4	57.9	.0174	5.0	5.07
		4	745.0	25.4	17.99	1.555	16.35	1.56	10.829	.089	7.0	41.2	.0158	2.0	6.92
		5	745.0	27.6	20.11	1.460	18.91	1.46	12.611	.107	3.7	44.5	.0173	1.8	9.54
		6	745.0	27.6	18.78	1.724	16.00	1.72	14.237	.122	32.6	44.3	.0168	1.7	5.25
		7	745.0	29.3	17.75	1.867	15.69	1.87	16.197	.139	-.2	38.1	.0152	2.2	5.56
		8	745.0	22.2	15.95	1.520	14.58	1.52	17.777	.155	3.5	52.6	.0145	--	5.63
		9	745.0	37.9	36.64	2.803	13.53	2.80	19.216	.153	-3.1	58.3	.0157	--	1.05
		10	745.0	32.8	18.77	2.052	15.98	2.05	21.237	.190	2.6	45.2	.0172	3.6	6.05
		11	745.0	38.0	19.72	2.259	16.81	2.26	23.433	.209	1.0	45.0	.0190	--	4.50
		12	745.0	24.2	13.73	2.811	8.62	2.81	25.899	.224	8.1	97.1	.0201	--	2.51
		13	745.0	18.7	11.47	2.667	7.00	2.67	27.793	.239	1.8	106.5	.0193	--	2.14
5	78:30	1	732.0	38.2	21.21	2.102	18.20	2.10	5.303	.029	-3.9	39.3	.0160	5.4	5.43
		2	732.0	26.1	14.51	2.376	11.00	2.38	6.768	.038	-5.3	64.3	.0185	6.1	3.21
		3	732.0	19.3	14.05	1.698	11.39	1.70	9.128	.065	-14.3	60.5	.0168	4.9	4.27
		4	732.0	24.4	15.69	1.753	13.93	1.75	10.469	.082	-5.5	49.1	.0150	1.9	5.38
		5	732.0	27.2	20.23	1.432	19.00	1.43	12.304	.105	1.5	39.0	.0164	1.8	8.91
		6	732.0	16.9	17.05	1.128	15.00	1.13	13.981	.119	2.2	47.7	.0168	1.6	5.97
		7	732.0	27.3	16.77	1.869	14.60	1.87	16.005	.139	.4	48.8	.0163	2.1	4.56
		8	732.0	18.8	13.52	1.559	12.07	1.56	17.667	.148	-1.9	55.9	.0151	--	4.66
		9	732.0	26.9	15.61	2.216	12.13	2.22	19.473	.168	-1.4	57.7	.0162	--	4.42
		10	732.0	23.0	16.15	1.776	12.94	1.78	20.933	.185	-1.0	51.6	.0177	3.3	4.04
		11	732.0	42.4	19.40	2.446	17.33	2.45	23.693	.210	2.3	43.3	.0187	--	4.64
		12	732.0	24.6	16.86	3.258	7.55	3.26	26.097	.234	.1	91.7	.0177	--	2.48
		13	732.0	17.4	10.94	2.493	6.99	2.49	27.500	.237	1.0	105.6	.0161	--	2.29
6	86:00	1	745.0	19.0	18.50	1.059	17.93	1.06	5.367	.034	3.5	40.9	.0141	5.9	12.39
		2	745.0	26.4	14.73	2.404	10.99	2.40	6.850	.042	-.3	67.2	.0175	6.0	3.00
		3	745.0	25.9	15.75	2.017	12.86	2.02	8.819	.062	.5	61.1	.0170	5.0	5.12
		4	745.0	18.7	15.94	1.219	15.33	1.22	10.668	.081	-.2	50.6	.0151	2.0	7.18
		5	745.0	26.3	19.36	1.477	17.80	1.48	12.420	.103	-1.5	40.2	.0166	1.8	7.54
		6	745.0	18.9	16.64	1.248	15.18	1.25	14.196	.121	3.5	48.9	.0170	1.9	5.53
		7	745.0	27.6	17.30	2.030	13.58	2.03	16.087	.137	.4	52.5	.0166	2.3	4.57
		8	745.0	27.3	15.62	1.981	13.77	1.98	17.809	.153	1.4	57.4	.0156	--	4.41
		9	745.0	27.3	16.05	1.949	14.00	1.95	19.323	.168	.9	56.8	.0147	--	5.10
		10	745.0	22.2	16.10	1.589	13.98	1.59	20.683	.184	11.8	54.9	.0178	4.1	5.73
		11	745.0	26.1	14.13	2.049	12.73	2.05	23.576	.210	-1.6	50.4	.0190	--	3.80
		12	745.0	32.5	16.76	3.041	10.67	3.04	25.990	.227	.4	83.4	.0166	--	3.42
		13	745.0	19.0	12.03	2.721	6.99	2.72	27.382	.236	0.0	105.7	.0137	--	2.09

Appendix 1. Morphologic and hydrologic characteristics measured during experiments in Rainfall Erosion Facility (runs 3.5 to 6) and flume (runs 11 to 14)—Continued

Run	Flow time (h)	Distance from mouth (m)	Discharge (mL/s)	Channel area (cm^2)	Wetted perimeter (cm)	Hydraulic radius (cm)	Channel width (cm)	Hydraulic depth (cm)	Total head (cm)	Average bed above mouth (m)	Rate of arroyo area change (cm^2/h)	Average unit discharge (mL/s/cm)	Average energy slope (m/m)	Width/depth ratio	
														Arroyo	Channel
11	0:00	1	750.0	90.6	76.16	1.192	76.03	1.19	1.951	0.007	0.0	9.9	-0.0009	--	45.35
		2	750.0	61.1	78.21	.783	78.01	.78	1.850	.009	0.0	9.6	.0021	--	53.85
		3	750.0	31.2	63.95	.491	63.68	.49	2.382	.015	0.0	11.8	.0064	--	59,71
		4	750.0	52.6	78.34	.674	78.09	.67	3.139	.023	0.0	9.6	.0082	--	56.88
		6	750.0	28.7	55.01	.526	54.61	.53	4.873	.040	0.0	13.7	.0102	--	32.59
		8	750.0	24.5	56.07	.441	55.60	.44	7.279	.063	0.0	13.5	.0099	--	48.62
		10	750.0	37.6	53.05	.712	52.83	.71	8.935	.080	0.0	14.2	.0080	--	43.32
		12	750.0	33.6	53.68	.631	53.32	.63	10.587	.097	0.0	14.1	.0095	--	43.68
		14	750.0	36.5	61.87	.591	61.78	.59	12.827	.120	0.0	12.1	.0105	--	73.69
		16	750.0	33.8	56.11	.604	56.00	.60	14.879	.140	0.0	13.4	.0110	--	52.49
		18	750.0	66.5	61.14	1.101	60.41	1.10	17.353	.161	0.0	12.4	.0110	--	33.05
		20	750.0	64.3	54.71	1.191	54.00	1.19	19.381	.181	0.0	13.9	.0101	--	37.29
11	0:37	1	765.0	25.7	34.75	0.740	33.00	.78	4.692	.033	287.0	16.5	.0120	5.3	24.09
		2	765.0	43.9	57.10	.769	54.89	.80	8.255	.071	82.9	11.8	.0209	--	18.00
11	1:30	1	748.0	23.0	17.40	1.438	15.98	1.44	3.980	.019	67.0	35.0	.0206	4.3	6.99
		2	748.0	24.1	16.16	1.742	13.85	1.74	5.465	.031	61.7	34.0	.0282	3.2	6.27
		3	748.0	22.5	15.28	1.633	13.77	1.63	7.376	.048	73.8	33.2	.0149	--	5.32
		4	748.0	48.4	83.41	.583	83.00	.58	10.321	.095	-4.1	9.3	.0178	--	60.45
11	3:30	1	740.0	23.7	22.94	1.033	22.00	1.08	3.857	.022	0.0	40.2	.0135	5.1	13.75
		2	740.0	26.0	24.65	1.055	20.97	1.24	5.163	.034	6.6	44.6	.0149	3.2	5.30
		3	740.0	28.0	21.67	1.292	21.00	1.33	6.556	.048	38.7	44.8	.0209	2.7	11.48
		4	740.0	39.4	44.16	.892	42.68	.92	8.930	.078	52.9	13.2	.0207	--	21.56
		6	740.0	25.3	16.79	1.507	14.37	1.76	10.826	.086	11.5	32.6	.0123	--	5.73
		8	740.0	36.5	57.65	.633	57.00	.64	14.399	.135	-.8	13.2	.0102	--	33.93
11	6:00	1	754.0	29.8	24.62	1.210	22.97	1.30	3.766	.022	8.7	33.2	.0123	5.1	10.78
		2	754.0	30.4	22.41	1.357	20.97	1.45	5.064	.032	11.3	35.6	.0128	6.0	10.59
		3	754.0	29.9	24.90	1.201	24.00	1.25	6.374	.048	.3	33.3	.0171	7.0	12.12
		4	754.0	23.9	17.56	1.361	15.69	1.52	8.267	.062	.4	32.7	.0138	4.4	7.37
		6	754.0	26.3	19.82	1.327	17.98	1.46	10.509	.086	2.2	46.7	.0145	5.3	9.46
		8	754.0	35.2	47.07	.748	46.00	.77	14.199	.131	4.5	14.7	.0122	--	33.58
		10	754.0	37.2	54.59	.681	54.00	.69	16.179	.152	-2.2	14.1	.0089	--	41.54
11	10:00	1	745.0	32.3	26.71	1.209	24.72	1.31	3.711	.019	3.7	31.5	.0114	5.1	10.13
		2	745.0	30.4	21.97	1.384	20.97	1.45	4.826	.030	1.0	35.7	.0124	5.8	10.18
		3	745.0	33.0	29.06	1.136	27.97	1.18	6.240	.047	1.7	29.0	.0160	6.6	12.66
		4	745.0	35.1	22.23	1.579	20.97	1.67	8.140	.061	2.7	41.8	.0138	4.7	9.85
		6	745.0	35.6	23.57	1.510	21.76	1.64	10.463	.088	2.9	38.1	.0141	5.5	9.85
		8	745.0	33.8	36.60	.923	34.83	.97	13.678	.125	5.4	18.9	.0139	--	21.77
		10	745.0	36.9	51.99	.710	51.72	.71	16.098	.151	1.8	14.2	.0098	--	37.75
		12	745.0	33.5	54.50	.615	54.00	.62	17.752	.168	-.4	13.9	.0067	--	35.29

Appendix 1. Morphologic and hydrologic characteristics measured during experiments in Rainfall Erosion Facility (runs 3.5 to 6) and flume (runs 11 to 14)—Continued

Run	Flow time (h)	Distance from mouth (m)	Discharge (mL/s)	Channel area (cm^2)	Wetted perimeter (cm)	Hydraulic radius (cm)	Channel width (cm)	Hydraulic depth (cm)	Total head (cm)	Average bed above mouth (m)	Rate of arroyo area change (cm^2/h)	Average unit discharge (mL/s/cm)	Average energy slope (m/m)	Width/depth ratio	
														Arroyo	Channel
11	16:00	1	748.0	27.0	27.27	0.990	26.87	1.00	3.601	0.020	0.5	29.0	.0107	5.5	15.35
		2	748.0	30.1	23.21	1.297	21.89	1.38	4.755	.031	0.0	34.8	.0125	6.2	13.03
		3	748.0	31.5	29.66	1.062	29.00	1.09	6.267	.048	-.5	26.2	.0156	7.0	15.18
		4	748.0	29.1	21.64	1.345	20.77	1.40	7.797	.061	.9	35.8	.0141	8.1	10.49
		6	748.0	35.4	23.90	1.481	23.00	1.54	10.618	.089	-.3	33.4	.0141	6.1	9.75
		8	748.0	40.5	38.91	1.043	37.00	1.10	13.798	.125	-.2	20.8	.0137	--	21.14
		10	748.0	30.5	53.38	.571	53.00	.58	16.197	.152	-1.5	14.3	.0107	--	38.69
11	22:00	1	751.0	33.3	25.27	1.318	24.51	1.36	3.469	.019	1.5	29.2	.0112	5.3	12.83
		2	751.0	35.3	24.59	1.436	23.28	1.52	4.671	.030	2.2	33.2	.0129	6.0	11.76
		3	751.0	39.0	30.41	1.282	29.85	1.31	6.169	.048	.8	25.5	.0150	6.7	14.49
		4	751.0	34.4	23.31	1.476	22.55	1.53	7.773	.061	1.0	34.7	.0143	8.1	10.95
		6	751.0	33.4	23.30	1.433	21.97	1.52	10.498	.086	.1	33.4	.0146	6.1	9.94
		8	751.0	39.3	43.59	.902	39.95	.98	13.731	.126	.8	19.5	.0138	--	23.78
		10	751.0	39.8	54.55	.730	53.73	.74	16.151	.152	1.4	14.0	.0110	--	37.06
		12	751.0	43.7	55.21	.792	54.00	.81	17.871	.169	-.2	13.9	.0082	--	28.27
12	0:30	1	762.0	15.2	13.02	1.295	11.77	1.30	5.781	.031	125.0	64.7	.0354	3.1	7.02
		2	762.0	16.6	11.70	1.684	9.84	1.68	9.557	.065	119.6	77.4	.0373	3.2	4.45
		3	762.0	33.0	29.05	1.151	28.68	1.15	13.562	.121	-6.8	26.6	.0280	7.1	15.05
		4	762.0	31.2	23.10	1.382	22.55	1.38	15.228	.133	-2.6	33.8	.0145	7.7	10.57
		6	762.0	29.8	24.68	1.241	24.00	1.24	17.967	.163	-56.2	31.8	.0135	6.1	12.11
12	1:00	1	743.0	16.5	13.25	1.509	10.97	1.51	5.586	.030	75.2	66.2	.0274	2.9	5.54
		2	743.0	16.9	12.04	1.697	9.93	1.70	7.641	.048	7.2	76.1	.0278	2.7	4.83
		3	743.0	20.3	14.79	1.727	11.77	1.73	9.400	.070	115.6	44.8	.0226	2.7	5.72
		4	743.0	18.9	13.77	1.645	11.49	1.64	11.215	.088	104.0	49.2	.0211	3.7	4.57
		6	743.0	28.9	23.69	1.256	23.00	1.26	17.894	.165	-4.2	32.0	.0233	5.8	11.18
12	2:00	1	740.0	28.9	18.10	1.320	17.10	1.40	5.449	.035	46.8	55.5	.0191	3.2	8.64
		2	740.0	22.4	17.56	1.276	15.52	1.44	7.516	.055	18.4	61.3	.0181	3.1	9.70
		3	740.0	28.7	25.19	1.139	22.97	1.25	9.359	.077	33.6	47.7	.0173	2.8	11.15
		4	740.0	21.8	18.35	1.188	16.92	1.29	11.167	.092	12.2	54.2	.0231	4.1	9.67
		6	740.0	16.0	15.89	1.007	13.93	1.15	14.990	.126	51.2	42.7	.0256	3.1	7.33
		10	740.0	33.3	53.04	.628	51.97	.64	23.612	.226	-2.4	14.1	.0134	--	37.93
		12	740.0	33.2	54.59	.608	53.73	.62	25.293	.244	-6.6	13.9	.0091	--	37.06
12	3:00	1	741.0	28.0	24.89	1.170	23.95	1.17	5.245	.036	44.5	37.1	.0205	3.2	13.66
		2	741.0	27.0	18.94	1.613	16.71	1.61	7.493	.054	-.3	46.0	.0194	3.0	8.12
		3	741.0	26.9	26.98	1.037	25.97	1.04	9.561	.080	2.1	30.4	.0178	2.9	14.81
		4	741.0	25.2	20.84	1.336	18.91	1.34	11.324	.094	4.8	41.5	.0184	4.0	8.55
		6	741.0	27.8	20.20	1.641	16.92	1.64	15.178	.131	14.2	48.5	.0179	3.8	7.66
		10	741.0	20.6	20.80	1.044	19.72	1.04	21.280	.195	86.6	25.9	.0148	--	10.79

Appendix 1. Morphologic and hydrologic characteristics measured during experiments in Rainfall Erosion Facility (runs 3.5 to 6) and flume (runs 11 to 14)—Continued

Run	Flow time (h)	Distance from mouth (m)	Discharge (mL/s)	Channel area (cm²)	Wetted perimeter (cm)	Hydraulic radius (cm)	Channel width (cm)	Hydraulic depth (cm)	Total head (cm)	Average bed above mouth (m)	Rate of arroyo area change (cm²/h)	Average unit discharge (mL/s/cm)	Average energy slope (m/m)	Width/depth ratio	
														Arroyo	Channel
12	5:00	1	751.0	25.6	30.83	0.830	30.18	0.85	4.949	0.037	39.0	27.9	0.019	3.3	17.96
		2	751.0	23.7	19.44	1.219	18.43	1.29	6.932	.051	24.2	42.5	.0194	3.1	10.97
		3	751.0	21.3	22.37	.952	22.00	.97	8.824	.071	10.2	31.3	.0185	2.7	14.47
		4	751.0	19.4	21.03	.922	19.78	.98	10.814	.088	3.7	38.6	.0184	3.7	9.99
		6	751.0	17.7	21.82	.811	20.48	.86	14.518	.128	30.5	40.2	.0170	4.1	14.12
		8	751.0	28.3	30.88	.916	29.85	.95	17.749	.164	13.9	24.3	.0146	8.6	19.64
		10	751.0	23.1	20.63	1.120	19.98	1.16	20.699	.190	6.7	37.6	.0140	7.0	11.89
		12	751.0	29.3	30.00	.977	27.97	1.05	24.345	.227	24.0	20.4	.0144	--	10.21
12	8:00	1	748.0	43.6	38.36	1.131	36.87	1.18	4.730	.034	5.4	22.6	.0180	3.3	19.41
		2	748.0	26.7	22.09	1.209	21.34	1.25	6.820	.050	1.5	37.9	.0178	3.1	11.66
		3	748.0	25.1	24.80	1.012	24.00	1.05	8.563	.069	1.7	32.7	.0177	2.5	11.65
		4	748.0	25.6	22.00	1.182	21.34	1.22	10.242	.085	6.6	36.5	.0168	3.7	12.19
		6	748.0	30.1	27.75	1.085	26.70	1.13	13.225	.118	9.7	32.3	.0170	4.7	12.54
		8	748.0	26.2	27.39	.957	27.03	.97	17.655	.161	5.3	26.4	.0160	8.1	14.77
		10	748.0	28.1	20.45	1.374	19.61	1.43	20.671	.188	1.0	37.9	.0148	6.3	8.56
		12	748.0	29.0	21.86	1.327	19.98	1.45	23.169	.214	1.5	32.1	.0163	--	9.38
12	13:00	1	748.0	25.6	21.62	1.184	20.51	1.25	4.565	.029	-3.2	28.4	.0171	3.2	12.82
		2	748.0	31.2	22.21	1.405	21.00	1.49	6.333	.044	2.1	35.3	.0170	2.9	9.50
		3	748.0	31.8	24.91	1.277	23.97	1.33	8.082	.063	3.4	31.2	.0168	2.5	11.64
		4	748.0	29.3	21.10	1.389	19.90	1.47	9.842	.078	2.5	36.3	.0156	3.4	9.00
		6	748.0	28.2	27.91	1.010	26.87	1.05	12.959	.114	1.5	27.9	.0176	4.3	11.73
		8	748.0	39.4	35.01	1.125	34.48	1.14	17.354	.160	5.7	24.7	.0171	7.7	18.15
		10	748.0	28.2	19.75	1.428	18.79	1.50	20.219	.185	5.8	39.0	.0135	5.6	7.70
		12	748.0	33.2	25.49	1.302	23.73	1.40	22.939	.213	17.4	34.5	.0136	--	9.73
		14	748.0	37.0	42.75	.865	37.58	.98	25.813	.246	3.4	22.9	.0180	--	17.00
		16	748.0	34.9	55.65	.627	53.80	.65	29.794	.288	1.7	13.5	.0118	--	29.40
13	1:00	1	759.0	35.7	32.40	1.102	31.73	1.13	4.590	.033	--	23.9	.0201	3.2	17.34
		2	759.0	17.9	18.93	.946	18.45	.97	6.806	.048	--	41.1	.0167	3.1	11.53
		3	759.0	21.1	23.46	.899	22.65	.93	8.240	.066	--	33.5	.0141	2.5	14.90
		4	759.0	23.4	23.36	1.002	22.31	1.05	9.816	.082	--	34.0	.0164	3.5	13.28
		6	759.0	18.4	27.72	.644	25.86	.71	13.397	.117	--	29.4	.0174	4.0	16.16
		8	759.0	26.6	25.33	1.050	24.14	1.10	17.125	.156	--	31.4	.0165	8.4	12.64
		10	759.0	22.3	19.74	1.130	19.16	1.16	20.220	.184	--	39.6	.0126	6.2	10.03
13	2:30	1	754.0	24.3	35.52	.684	34.38	.71	4.691	.034	--	21.9	.0199	3.2	20.46
		2	754.0	25.6	23.19	1.104	21.57	1.19	6.862	.052	--	35.0	.0172	3.2	12.84
		4	754.0	22.6	23.17	.975	22.55	1.00	10.157	.085	--	33.4	.0158	3.7	14.84
		6	754.0	34.5	27.90	1.237	26.43	1.31	13.533	.120	--	28.5	.0161	4.2	13.84
		8	754.0	26.7	29.67	.900	27.85	.96	17.116	.157	--	27.1	.0152	8.7	17.41
		10	754.0	25.0	20.11	1.243	18.79	1.33	20.014	.181	--	40.1	.0128	6.0	9.49

Appendix 1. Morphologic and hydrologic characteristics measured during experiments in Rainfall Erosion Facility (runs 3.5 to 6) and flume (runs 11 to 14)—Continued

Run	Flow time (h)	Distance from mouth (m)	Discharge (mL/s)	Channel area (cm^2)	Wetted perimeter (cm)	Hydraulic radius (cm)	Channel width (cm)	Hydraulic depth (cm)	Total head (cm)	Average bed above mouth (m)	Rate of arroyo area change (cm^2/h)	Average unit discharge (mL/s/cm)	Average energy slope (m/m)	Width/depth ratio	
														Arroyo	Channel
13	6:00	1	751.0	33.9	33.18	1.022	32.09	1.06	4.450	0.032	--	23.4	0.0207	3.1	15.07
		2	751.0	28.4	21.82	1.302	21.07	1.35	6.706	.049	--	35.6	.0176	3.1	11.03
		4	751.0	31.8	24.13	1.318	21.35	1.49	10.024	.082	--	35.2	.0155	3.4	9.32
		6	751.0	29.2	24.25	1.204	23.48	1.24	13.247	.116	--	32.0	.0160	4.0	12.83
		8	751.0	34.4	33.94	1.014	32.50	1.06	16.873	.155	--	23.1	.0160	8.3	16.41
		10	751.0	31.1	19.79	1.572	17.93	1.73	20.007	.181	--	41.9	.0129	5.7	7.35
13	8:30	1	745.0	33.2	33.13	1.002	31.84	1.04	4.387	.031	--	23.4	.0201	3.2	19.90
		2	745.0	29.4	23.26	1.264	22.03	1.33	6.597	.048	--	33.8	.0173	3.1	11.13
		3	745.0	32.3	23.22	1.391	21.89	1.48	8.071	.064	--	34.0	.0151	2.5	10.63
		4	745.0	31.2	23.45	1.330	22.03	1.42	9.731	.079	--	33.8	.0160	3.3	9.62
		6	745.0	27.4	23.74	1.154	22.65	1.21	13.137	.116	--	32.9	.0160	3.5	11.44
		8	745.0	31.1	29.53	1.053	28.78	1.08	16.692	.153	--	25.9	.0157	7.9	13.97
		10	745.0	26.8	19.84	1.351	18.24	1.47	19.874	.180	--	40.8	.0129	6.0	9.55
14	2:00	1	751.0	28.4	28.62	1.033	27.44	1.03	4.560	.032	--	27.4	.0192	3.2	16.37
		2	751.0	27.3	22.58	1.259	21.71	1.26	6.730	.050	--	34.6	.0167	3.2	12.39
		3	751.0	25.8	24.37	1.089	23.73	1.09	8.235	.066	--	31.6	.0157	2.5	13.54
		4	751.0	30.6	23.80	1.335	22.89	1.34	10.050	.083	--	32.8	.0166	3.5	11.55
		6	751.0	28.3	26.41	1.170	24.21	1.17	13.572	.120	--	31.0	.0161	3.4	8.82
		8	751.0	33.6	37.23	.922	36.40	.92	17.116	.159	--	20.6	.0147	9.1	25.14
		10	751.0	27.7	22.77	1.317	21.00	1.32	19.852	.181	--	35.8	.0136	5.8	10.20
14	4:00	1	753.0	30.5	37.70	.829	36.80	.83	4.665	.035	--	20.5	.0223	3.3	21.95
		2	753.0	26.0	23.07	1.179	22.03	1.18	7.078	.054	--	34.2	.0221	3.1	9.97
		3	753.0	23.5	22.47	1.102	21.03	1.10	9.396	.078	--	35.4	.0174	2.8	11.18
		4	753.0	27.7	28.54	.996	27.78	1.00	10.805	.094	--	27.1	.0142	4.7	15.85
		6	753.0	29.6	39.15	.801	37.00	.80	13.924	.128	--	20.4	.0154	4.1	21.10
		8	753.0	24.4	43.02	.571	42.69	.57	17.270	.162	--	17.6	.0148	9.3	35.00
		10	753.0	26.8	22.98	1.243	21.57	1.24	20.031	.184	--	34.9	.0132	6.2	11.32
14	7:00	1	757.0	19.8	23.50	.843	22.75	.87	5.175	.036	--	33.3	.0193	4.4	13.00
		2	757.0	27.5	29.60	.929	28.32	.97	7.186	.056	--	26.7	.0191	3.4	14.91
		3	757.0	23.7	27.77	.853	26.43	.90	9.160	.077	--	28.6	.0170	2.9	19.29
		4	757.0	25.7	28.89	.890	28.13	.91	10.722	.094	--	26.9	.0142	4.8	19.40
		6	757.0	31.2	34.25	.911	31.96	.98	13.515	.122	--	23.7	.0154	4.2	19.02
		8	757.0	26.1	40.00	.653	39.22	.67	16.989	.160	--	19.3	.0157	8.7	27.05
		10	757.0	26.7	24.86	1.074	23.73	1.13	19.890	.183	--	31.9	.0131	6.2	13.56

Appendix 2. Locations of arroyo cross sections and sampling sites along San Simon, San Pedro, and Santa Cruz Rivers, Arizona

Station	Location
1	S1/2, sec. 29, T. 13 S., R. 31 E., about 275 m downstream from railroad bridge about 1.6 km east of San Simon, Arizona.
2	SW1/4, sec. 10, T. 14 S., R. 31 E., about 140 m upstream from Portal Road bridge, Elmer Franklin Farm, south of San Simon, Arizona.
3	NW1/4 NW1/4, sec. 32, T. 7 S., R. 27 E., about 10 km southeast of Safford, Arizona.
5	SW1/4 NE1/4, sec. 36, T. 9 .S, R. 27 E., at Tanque, Arizona.
6	NE1/4 NE1/4, sec. 36, T. 9 S., R. 27 E., about 0.6 km northeast of Tanque, Arizona.
7	NW1/4 NE1/4, sec. 4, T. 24 S., R. 22 E., about 0.8 km south of AZ 92 bridge, at Palominas, Arizona.
8	NE1/4 NE1/4, sec. 16, T. 23 S., R. 22 E., about 300 m south of Hereford road bridge, 0.8 km west of Hereford, Arizona.
9	About 700 m upstream from AZ 90 bridge, about 16 km southwest of Tombstone, Arizona.
10	About 180 m downstream from AZ 82 bridge at Fairbank, Arizona.
11	NW1/4 NW1/4, sec. 6, T. 18 S., R. 21 E., about 200 m upstream from US 80 bridge at St. David, Arizona.
12	SW1/4 SE1/4, sec. 36, T. 23 S., R. 14 E., about 1 km upstream from AZ 82 bridge, about 6.5 km northeast of Nogales, Arizona.
13	NW1/4 NW1/4, sec. 7, T. 20 S., R. 13 E., about 250 m downstream from Amado Road ford, at Amado, Arizona.
14	NW1/4 NW1/4, sec. 26, T. 15 S., R. 13 E., 200 m east of I-19 bridge, about 2 km south of Tucson, Arizona.
15	NW1/4 NW1/4, sec. 35, T. 12 S., R. 13 E., about 75 m upstream from Cortaro Road bridge, about 0.9 km southeast of Cortaro, Arizona.
16	SW1/4 SE1/4, sec. 9, T. 11 S., R. 10 E., about 50 m downstream from Hardin Road ford, about 2.9 km south of Marana Air Park, about 11 km northwest of Marana, Arizona

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