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DOWNSTREAM PATTERN OF RIVER-BED SCOUR AND FILL

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INTRODUCTION

Progress has been made in describing river-bed scour and fill at a given stream section. One needs only the data routinely collected at a stream-gaging station to observe scour and fill at that station. However, similar progress has not been made to determine whether or not the scour and fill observed at a given section extends over a relatively long reach of channel. Gaging stations are generally located too far apart to draw any conclusions as to scour processes between stations. It remains necessary then to establish a sufficient number of cross sections along a channel to describe the downstream pattern of river-bed scour.

The purpose of this paper is to present recent observations of channel scour and fill over relatively long reaches of three streams in the western United States. Separate sections have been devoted to those observations on an ephemeral channel and those on perennial streams.

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The authors acknowledge with thanks the work of Leon A. Wiard, Robert M. Myrick, and other colleagues of the U. S. Geological Survey for data important to the present discussion.

EPHEMERAL STREAMS

Geographic Setting and Basic Measurements

The Arroyo de los Frijoles is a sandy ephemeral channel located about 4 miles northwest of Santa Fe, New Mexico. Physiographic and hydraulic characteristics of channels in this locality have been previously studied. Only a summary of those characteristics pertinent to the present paper are presented here.

Normally, flows are the result of runoff from local thunderstorms during the summer months. The flash flood is typical. Peak flow occurs within several minutes after the initial flood wave. Throughout the study reach, the channel increases in size from a rill near the watershed divide to a width of about 100 feet downstream. The bed is composed of median sand and a moderate amount of gravel. This material extends downward many feet, far deeper than the scour that occurs. The median sand-grain diameter is about 0.5 mm.

Scour and fill data from the Arroyo de los Frijoles were collected by means of scour chains during the five years, 1958-1962. Determination of the amount of scour and fill using the chain method is a simple procedure. The chains are buried vertically in the stream bed with the top link at or slightly above the bed surface. After a flow, the elevation of the stream bed is resurveyed and the bed is dug until the chain is exposed. If a scour has occurred, a portion of the chain will be lying horizontally. The difference between the previous stream-bed elevation and the elevation of the horizontal chain is the depth of scour. The difference between the existing bed elevation and the horizontal chain is the depth of fill. If no scour has occurred, the depth of fill is the increase in bed elevation.

Scour chains, each four feet in length, were installed along a reach of nearly six miles. The location of the chains usually followed the low-water channel. Thus, a flow in any reach of the channel could be expected to pass over the chain location. Over most of the study reach, chains were placed on 1000-foot intervals. In one reach of 2000 feet, chains were placed on 100-foot intervals. This spacing was believed sufficient to determine any downstream trend in the scour pattern in this arroyo. At seven of the chain sections, additional chains were installed across the width of the channel and provided an indication of any lateral variation in scour.

Observations of Scour and Fill

On the average, there are about three flows down the arroyo each year. Scour and fill data are available for most flows in the five-year period. However, since some chains were installed before others, an equal length of record does not exist for each chain location. In addition, some chains, usually those in the uppermost or lowermost reaches, were not surveyed after each flow. These missing segments of data disallow a true accumulative value of scour and fill. However, the net change in bed elevation since the time of the initial survey may still be obtained.

By 1959, the majority of the chains had been installed along the arroyo. Scour and fill data for a sample flow, for the year 1962, and for the period 1959-1962 are shown on Figure 1. For each flow on this figure, the lower dashed line represents the depth of scour and is plotted against distance along the channel. The upper dashed line represents the depth of fill. The heavy solid line represents the net change in bed elevation after scour and fill. The upper portion of Figure 1 shows the drainage area studied and the general location of the chains by chain number.

The nature of the flash flow allows that the entire length of the arroyo need not be flooded with each storm. It may be that the flow-producing rain was so located that only lower reaches received runoff. Or, for a smaller storm near the headwaters, a portion or possibly the entire flow may be absorbed into the ground by percolation before it reaches a downstream section. A third possibility remains that a particular chain section may be left dry or has very little scour because it was not in the low-water path of flow. For a single storm then, it is likely that there may be a considerable variation in the recorded depth of scour from section to section. This is further exemplified in the reach centered around stationing 24,000 feet where the chains are placed on a 100-foot intervals. In spite of individual variations, a general consistency prevails among the data, that is, at most all sections along the channel, there is a scour and subsequent fill. All flows produce this same pattern with the magnitude of scour primarily dependent upon hydraulic factors of individual flows and these are related to the intensity and total amount of rainfall.

In the data for some flows, short reaches do not indicate a scour. An example is in the reach between stations 2000 to 3000 feet for the flow of July 5, 1962 (top profile, Figure 1). In these reaches, the combined action of previous aggradation and of the chain sagging in the vertical had left the top link of the chain some distance below the bed elevation. Thus, scour may and probably did occur, but not to the depth necessary to register on the chain. After the flow of July 5, 1962, extra length was added to the top of the chains to compensate for the channel aggradation. In addition, closer watch was maintained to check against the chains losing length by sagging.

Three reaches of the channel are the objects of special study and at these flow rates are measured by indirect means, that is from slope of the high water marks, estimated roughness, and measured cross-sectional areas of flow. These reaches are centered around stationing 2850 feet, 9700 feet, and 24,000 feet. It is also within these reaches that the chain sections are located to determine the cross-channel pattern of scour. The mean depth of scour at a section may be determined by averaging the values from the several chains at each of the sections. In a comprehensive report describing various hydraulic and geomorphic processes in the Arroyo Frijoles locale the authors have related these mean values of scour to discharge per unit width of channel. The results of this study are summarized on Figure 2. Despite considerable scatter among the data, the mean scour depth appears to be proportional to the square root of discharge per unit width of channel.

An increasing depth of scour is not observed in any single profile as in those shown in Figure 1 because during individual flows, discharge rarely increases downstream as drainage area increases. This follows from the local nature of most thunderstorm rains, and because of the importance of water loss by infiltration into the bed during flows of short duration.

Probably for similar reasons the depth of scour is apparently independent of the channel width. Channel widths average about 4 feet between stationing 0 to 1,000 feet, 20 feet between stationing 1000 to 9000 feet, 45 feet between stationing 9000 to 13000 feet, 75 feet between stationing 13,000 to 16,000 feet, 50 feet between stationing 16,000 to 21,000 feet, and 80-90 feet from stationing 21,000 feet throughout the remainder of the study reach. In addition to the increase of width downstream, local variations occur on the order of 3 to 5 fold. No systematic relationship could be established between local depth of scour and the corresponding channel width. Further, since slope decreases downstream as width increases, the magnitude of scour also appears to be independent of slope.

Seven sections provided data to study lateral variation in scour across the width of the channel. Three of these sections, chosen as representative of a particular reach, are illustrated on Figures 3 through 5.

Figure 3, illustrating a section at station 2500 feet, indicates a net aggradation for the five-year period. The whole width of channel scours during nearly every flow but the amount of scour and fill varies across the width.

Figure 4 illustrates a section near stationing 9700 feet. Again considerable variations exist among the yearly records. The five-year average indicates little net change across the width of the channel. Of particular interest is the lateral distribution in depth of scour. A four-fold decrease in depth of scour is noted across the 40-foot width of channel. This difference may be attributed to the higher stream-bed elevations near the right bank but even this portion of the width scours at times and then fills. The data indicate that some flows may have missed these chain locations entirely, and certainly, for all flows, the depths of flow were much shallower on the right side of the channel. The chains at higher elevations are thus expected to indicate less scour.

The scour chains provide an economical and simple way of recording net scour and fill for individual flows. It is important that elevations be determined from a reliable bench mark in the immediate vicinity of the chain cross-section. We use a four-foot length of iron reinforcing bar driven nearly flush at each end of the cross-section, and one of these is also used as local bench mark for elevation surveys. This iron pin is labeled by a brass tag on which elevation and section number are stamped.

The chain should have a wide or open link so that sand will pack in the chain link. The bottom of the chain is anchored to a rock or a metal head to keep it from pulling out.

The disadvantage of the method is that one does not know when during the flow the scour or fill occurred nor the relative simultaneity of scour or fill at different chains.

PERENNIAL STREAMS

Geographic Setting and Basic Measurements

The Rio Grande del Ranchos is a small perennial stream on the west slopes of the Sangre de Cristo Range about seven miles south of Taos, New Mexico. Peak discharges occur in the spring and are normally produced by snowmelt. The study reach consists of a straight reach of 250 feet followed by a curved reach of 700 feet as can be seen in Figure 5. The stream bed is predominantly gravel and quite uniform in size from section to section. Median particle size varies from 21 to 33 mm with the minimum median size found in the curved reach. The riffle or bar at station 1 + 00 is a predominant feature of the straight reach. A total of seven sequences of pool-riffle occur within the study reach. Channel width at bankfull stage varies from 17 to 36 feet.

Data were collected by Leon A. Wiard and his associates on the Rio Grande del Ranchos during and immediately after the 1961 snowmelt. A total of 32 measurement stations were established along the study reach. At each measurement station, channel cross sections were obtained by level and rod during the peak flow and at a low flow by depth measurements in conncection with velocity observations. Depth measurements were referenced to the earlier survey by known water-surface elevations. High-flow discharge was 130 cfs and low-flow discharge was 25 cfs. The data then consist of 32 cross-sections surveyed just during spring high flow (near bankfull stage) and again at low flow in the succeeding summer.

The Popo Agie River is a larger perennial stream in western Wyoming. The study reach is located about one mile northeast of Hudson, Wyoming, and consists of a curved reach of 2000 feet followed by a straight reach of 2100 feet, Figure 6. Peak flow is normally associated with the spring runoff from snowmelt. The stream bed is predominantly gravel, ranging in size from fine gravel to large cobbles. Seven sequences of pools-riffles were observed within the study reach. Channel widths at near bankfull stage vary from 86 to 160 feet.

Data were collected at 15 stations along the 4100-foot reach. Channel cross sections at these stations were obtained during the peak flow in the spring of 1961 and at a low flow later that summer. A second set of data was collected during the rising stage in the spring of 1962 and during a lower, but falling stage that summer. The high-flow observations were obtained by depth measurements referenced to known water-surface elevations. Low-flow cross sections were surveyed with rod and level. High-flow discharge in 1961 was 1400 cfs and low-flow discharge in 1962 was 310 cfs.

Figures 7 and 8 are typical of the cross-sectional measurements obtained, the former for the Rio Grande del Ranchos and the latter for the Popo Agie. For each a section is shown from the curved reach and another from the straight reach.

For both streams and for each measured cross section, the plotted cross sections at high and low flow were superposed and provided the basis for a scour-fill study. Areas were planimetered from these plots to show the difference in bed between high and low flows.

Low-flow measurements were taken after the high-flow measurements. It is believed, however, that the order in which the measurements were obtained is not of prime importance. Our studies indicate that the cross-sectional configuration of a stream before a high flow is reasonably similar to that sometime after the high flow.

The 1961 Popo Agie data and the Rio Grande del Ranchos data represent high-stage measurements obtained during peak flow and the low-stage measurements during the stable low flow. Under these conditions, the changes occurring in stream-bed elevation were similar in that the bed elevation was scoured during the high flow.

The 1962 Popo Agie data were collected during a different condition of flow. Here, high-stage data were collected during the rising stages of the peak flow and the low-flow data were collected before the stable low flow. In addition, the collection of these data was in the aftermath of an unusually large flood from an early spring thaw. Because of stream-bed conditions left by the flood, and because of the river stages at the times of this survey, these data are inconclusive in describing a scour pattern and are omitted from the present discussion.

Observations of Scour and Fill

On Figures 9 and 10, profiles of the stream bed and water surfaces are plotted against distance along the channel. Below these profiles is a plot of the net changes in cross-sectional areas of the bed, and separately the cross-sectional area of flow. Values are considered scour if the bed elevations at high flow are lower than those at low flow. Thus, a negative area within this curve represents the total volume of material per foot of length scoured from the stream bed. A positive area represents the total volume of material brought in from upstream and temporarily deposited as a fill.

It is apparent that at the time of the high-stage measurements, a scour generally extended over the entire reach. No marked difference in the magnitude of scour occurs between pool and riffle. Likewise, it appears to make no difference as to whether the measurements were observed in the straight or curved reach. The few sections where fill did occur could not be related to their location within the reach.

It might be expected that scour should be greatest at sections of smallest flow area which, for constant discharge, have the highest mean velocity. To test this hypothesis, flow areas at both high and low stages are plotted at the bottom of Figures 9 and 10. No systematic correlation between the flow area and magnitude of scour is apparent. Since discharge is constant at a given stage, this plot may also be considered the mirror image of a comparison of velocity to magnitude of scour.

The absolute magnitude of flow area may not provide an ideal comparison for the influence of area. Some cross-sectional areas at low flow are larger than others at high flow. The relative increase in flow area from a low stage to a high stage would more accurately describe the changes which a particular section experienced. Superposed as a dashed line on the flow area plot is the relative increase in cross-sectional flow area. Efforts to relate this relative increase to the magnitude of scour were also unsuccessful.

Similar comparisons were made for other of the physical dimensions of the stream. Data for channel widths and depths were given the same analysis as for flow areas. No meaningful correlation could be established between these channel properties and the magnitude of scour.

Discussion

At some time during a period of high flow, the channel bottom of fine gravel or sand streams may scour. At present it is not possible to list the characteristics of channels in which this occurs. One tends to think that the scouring action is limited to streams in semi-arid areas but the experience of the U. S. Geological Survey at stream gaging stations shows that scour occurs during high flow in some rivers in all physiographic and climatic regions.

The extent of the scouring action appears to encompass the entire reach without regard to any of the physical dimensions of the stream, and applies to pool as well as riffle and to curved as well as straight reach.

Values of scour indicate a large volume of sediment being lifted from the stream bed. The data collected might lead one to imagine that this volume of sediment would appear as a block of material being picked up as a unit off the stream bed, being carried downstream at a velocity approximating that of the water near the bed. But the interaction or interference between grains tends to reduce the mean speed of the particles which then move at a mean velocity very small relative to the velocity of the flow. This conclusion is not only suggested by the theory of queues but has been verified experimentally by Langbein. 1/

1/ W. B. Langbein, unpublished data.

There is an apparent disparity between the observed magnitude of scour and rates of accumulation of sediment in reservoirs. Lane and Borland (1954) showed that the volume of sediment computed by multiplying observed mean scour depth at a few cross sections by average channel width by channel length is much larger than the observed accumulation of sediment in a downstream reservoir. They agreed that the observed scour was non-representative of the whole reach and at unmeasured points fill was simultaneous. Particularly, they said, scour occurs only at the narrow sections of rivers where observations are usually made, whereas at wide sections, if observations were available they would show simultaneous filling.

The present data dispute that argument. We measured, albeit in reaches of modest length, scour in narrow as well as wide sections, in riffles as well as pools, and in curves as well as straight reaches. The observations are deficient, as pointed out earlier, in not showing what was happening in the reach at any one instant of time. Nevertheless, if scour followed by fill in a narrow section were contemporaneous with fill followed by scour in wide sections, the latter should show no scour or much less than that occurring elsewhere. Rather, the magnitude of scour was of the same order in all types of sections.

We interpret the process, then, quite differently from Lane and Borland. Scour is associated with dilation of the grain bed through the scour depth, but individual particles may move intermittently, and at a speed much less than that of the water. The volume of material scoured and moved may be large but because of its low mean speed downstream, that whole volume does not move entirely out of a long reach but, in effect, is shifted downstream only a limited distance.

References

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

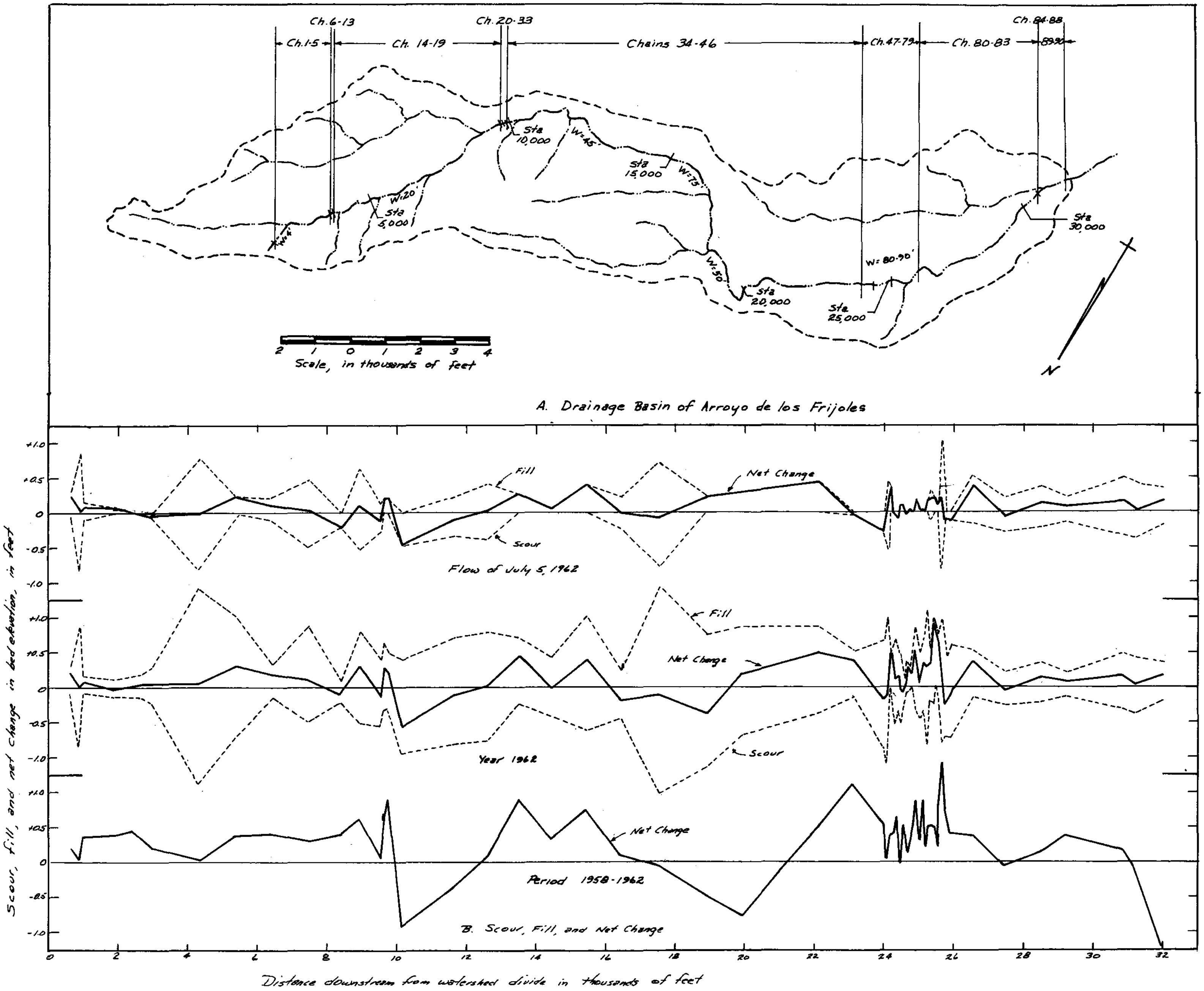

Figure 1. Arroyo de los Frijoles near Santa Fe, New Mexico

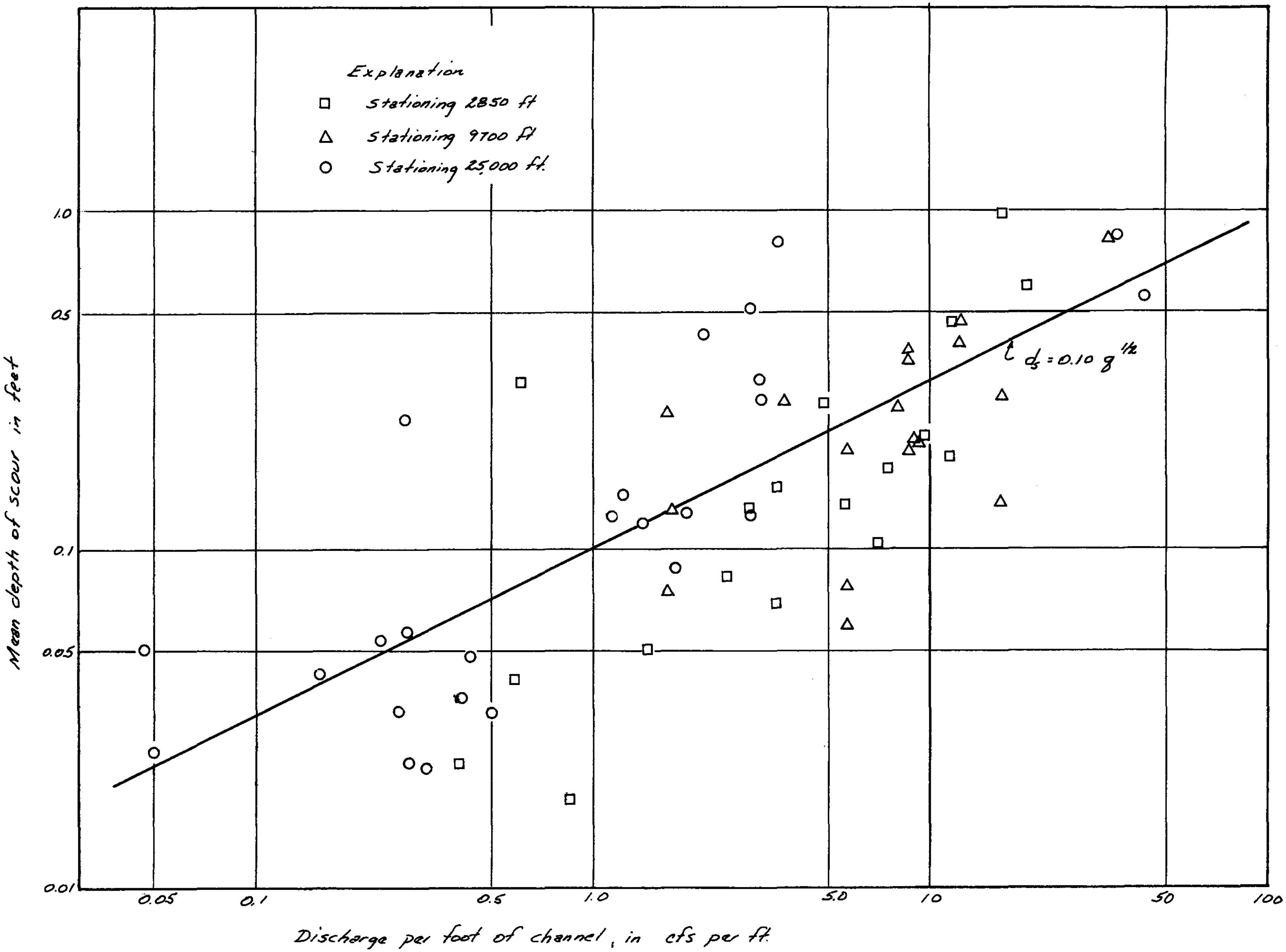

Figure 2.- Depth of Scour as a Function of Unit Discharge.

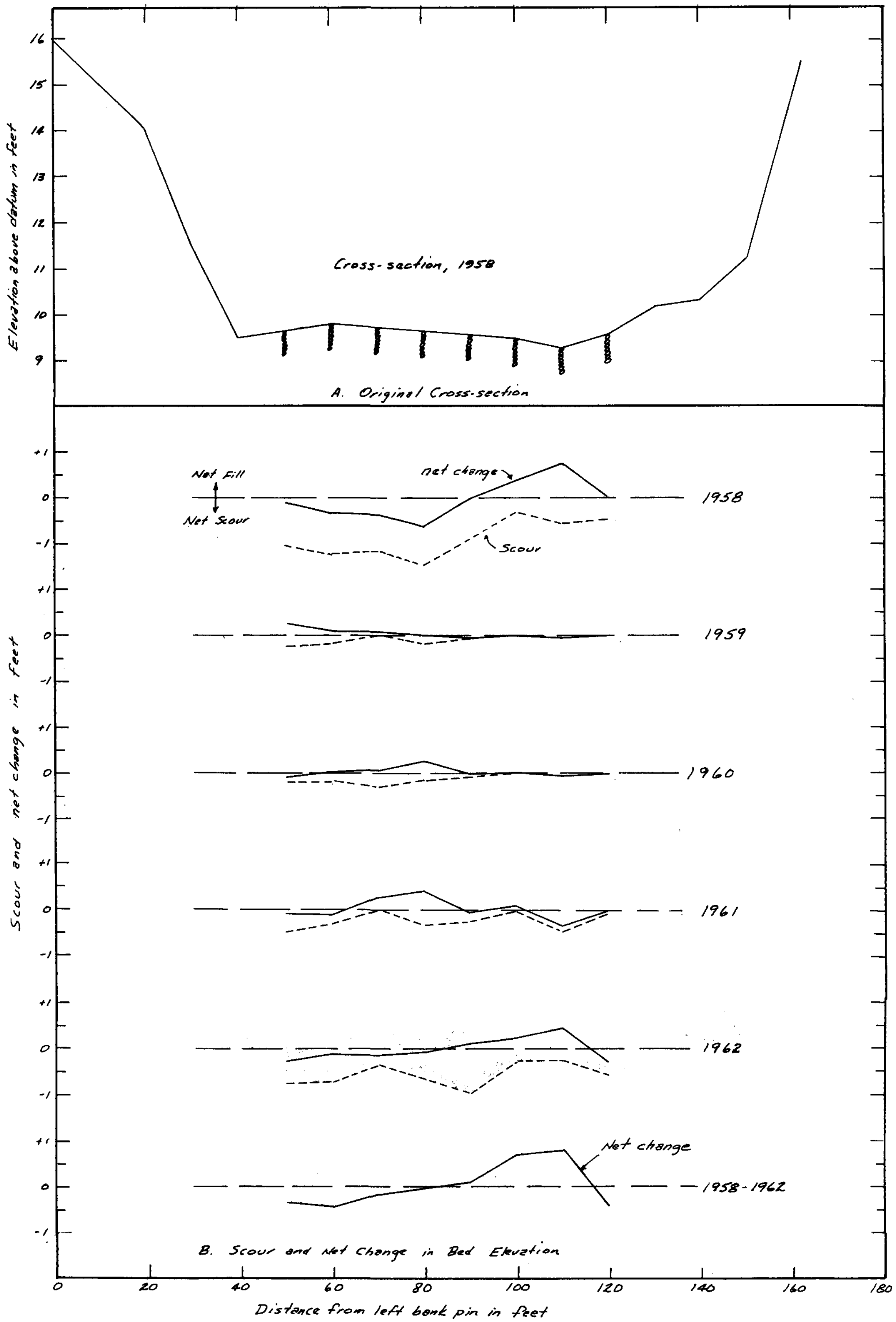

Figure 3.- Scour and Net Change in Bed Elevation at Stationing 25,000 ft.

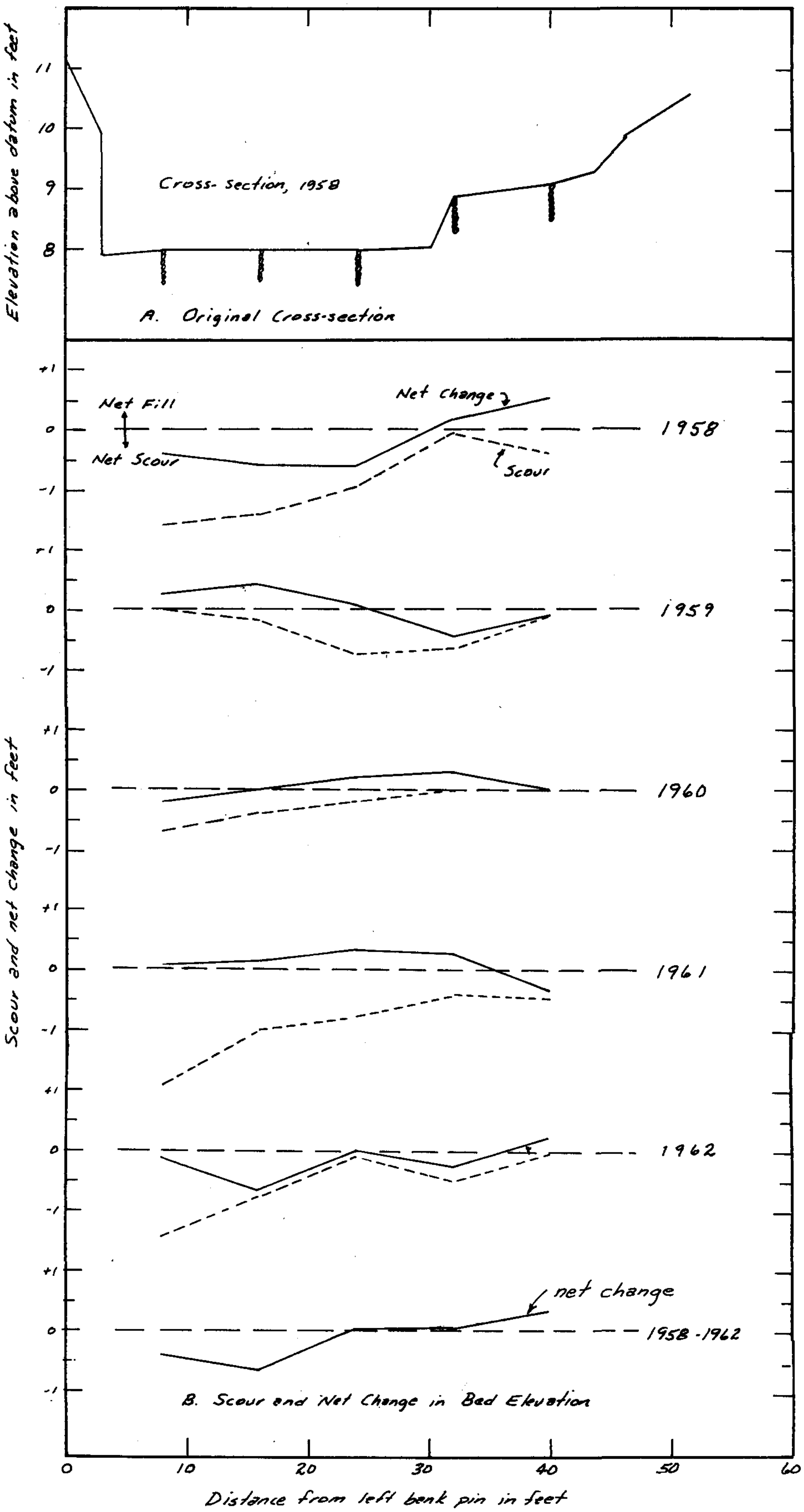

Figure 4.- Scour and Net Change in Bed Elevation at Stationing 9700 ft

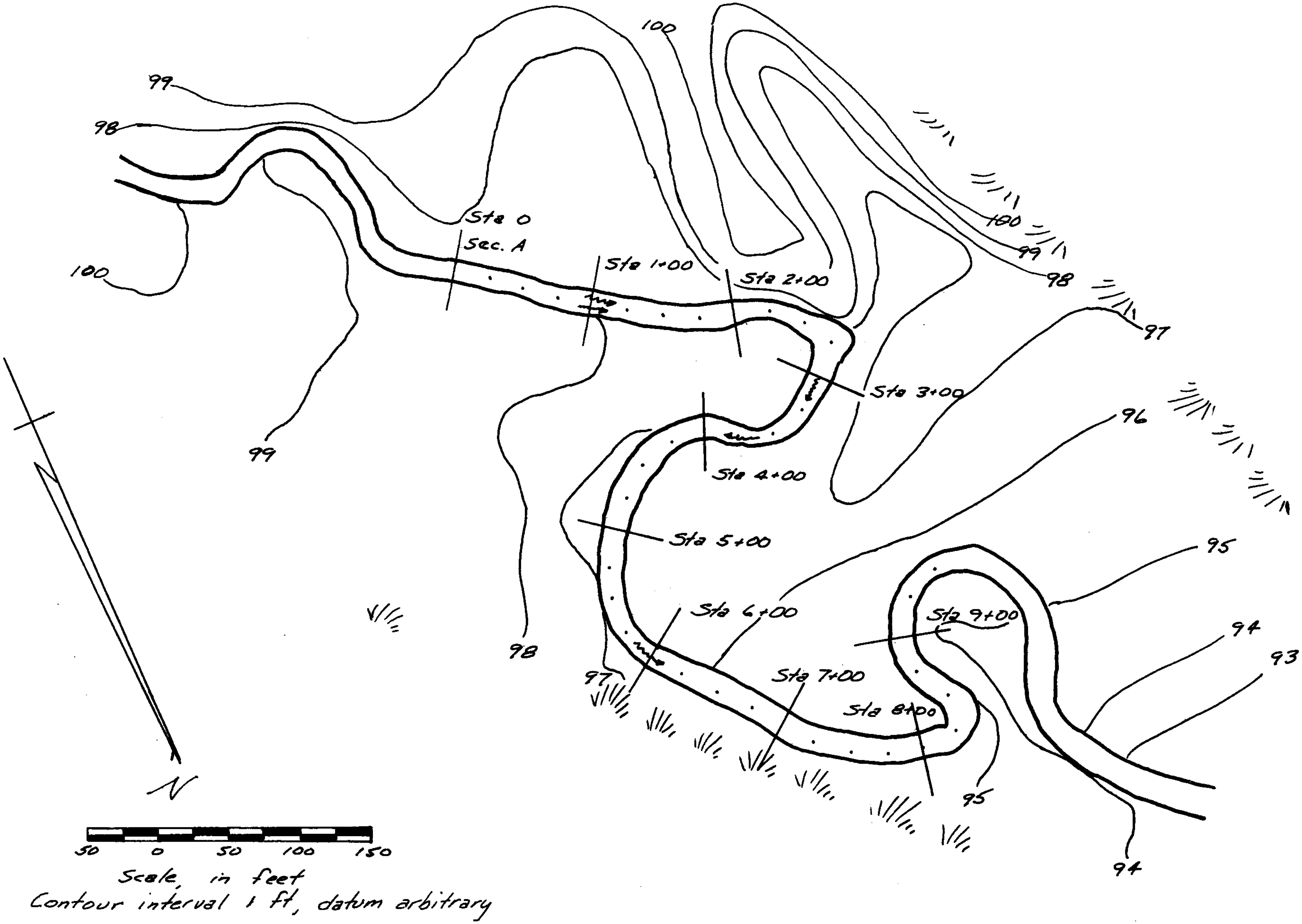

Figure 5.- Rio Grande del Ranchos near Talpa, New Mexico.

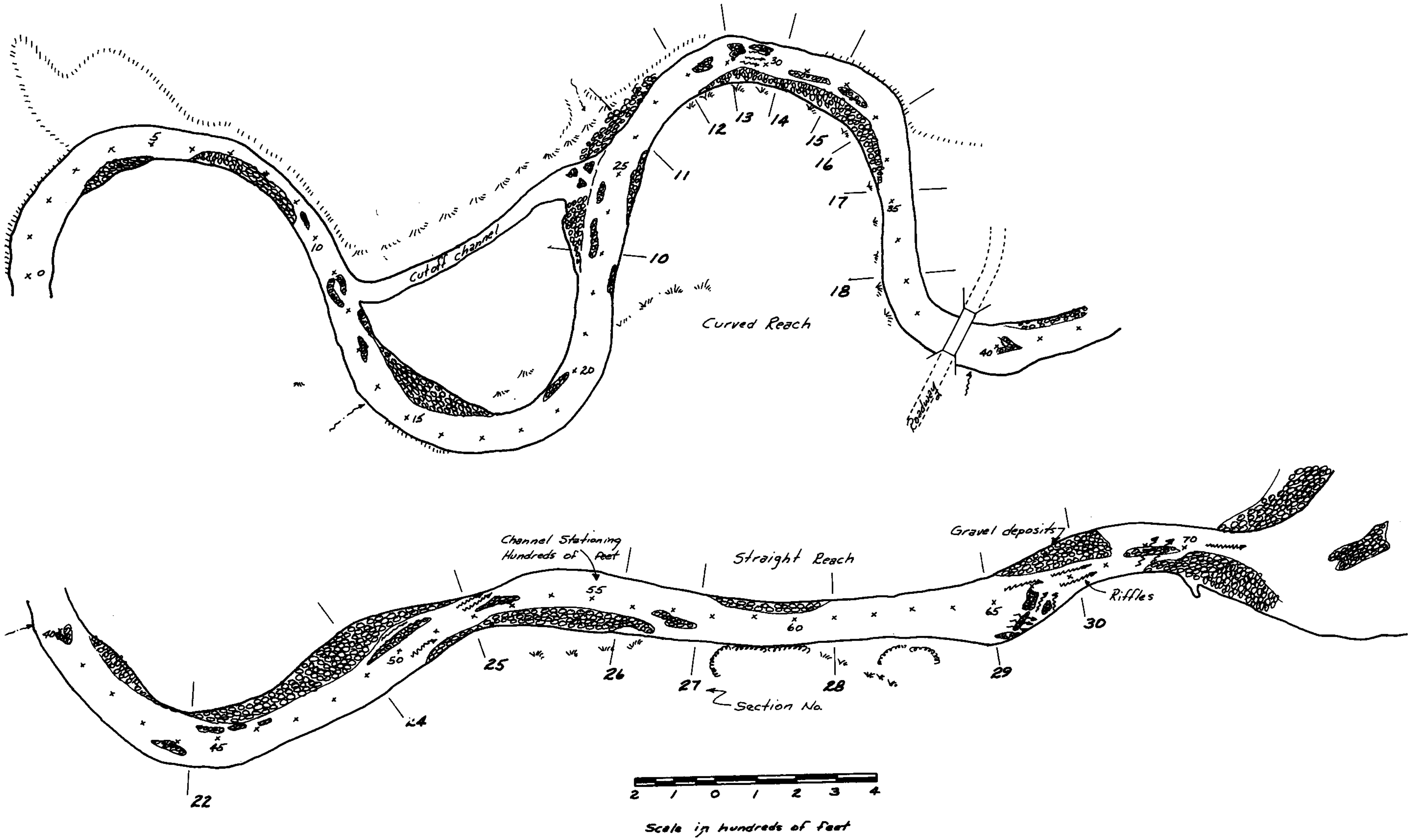

Figure 6.- PopoAgie River near Hudson, Wyoming

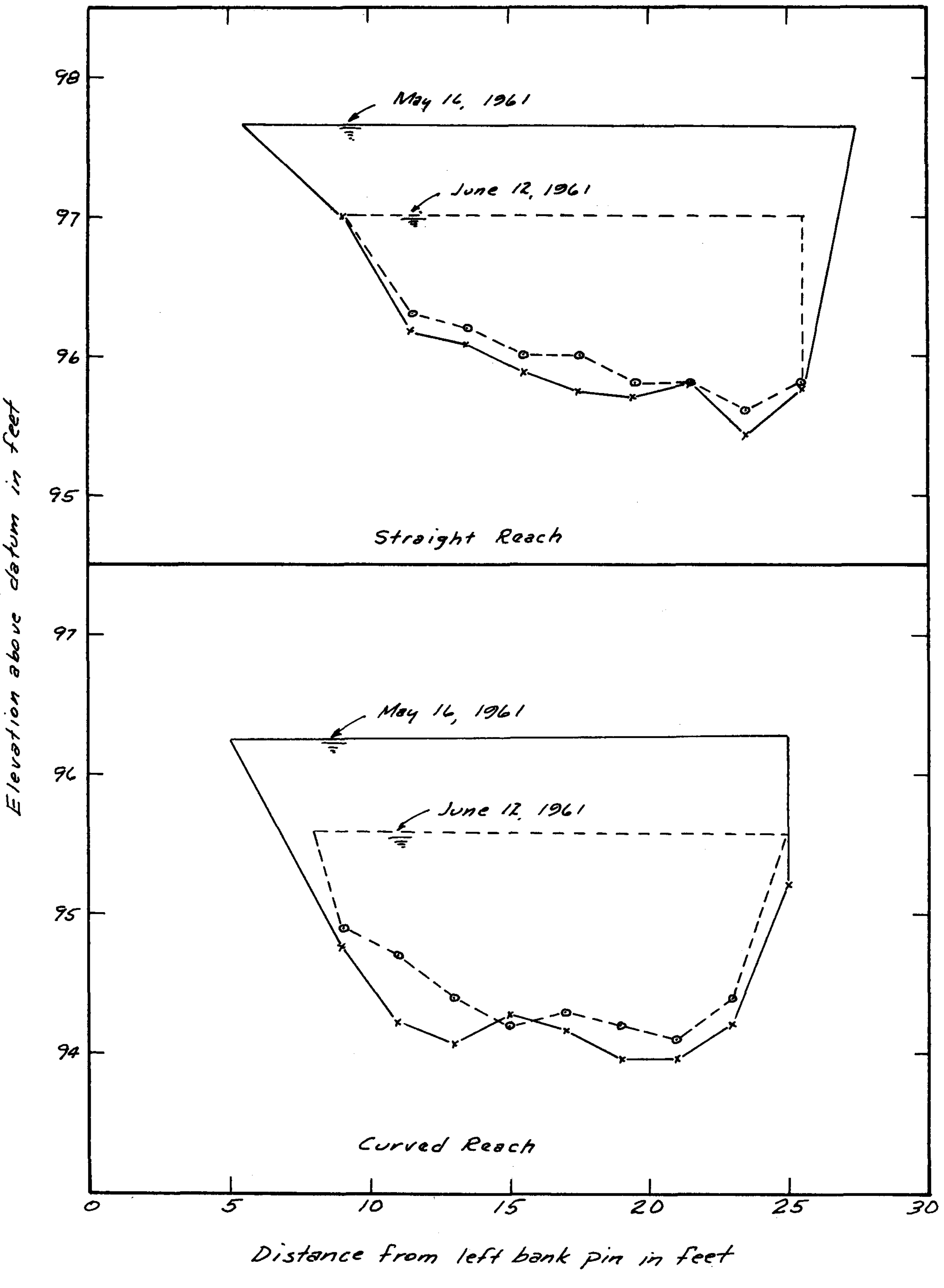

Figure 7.- Typical Cross-sections, Rio Grande del Ranchos, 1961

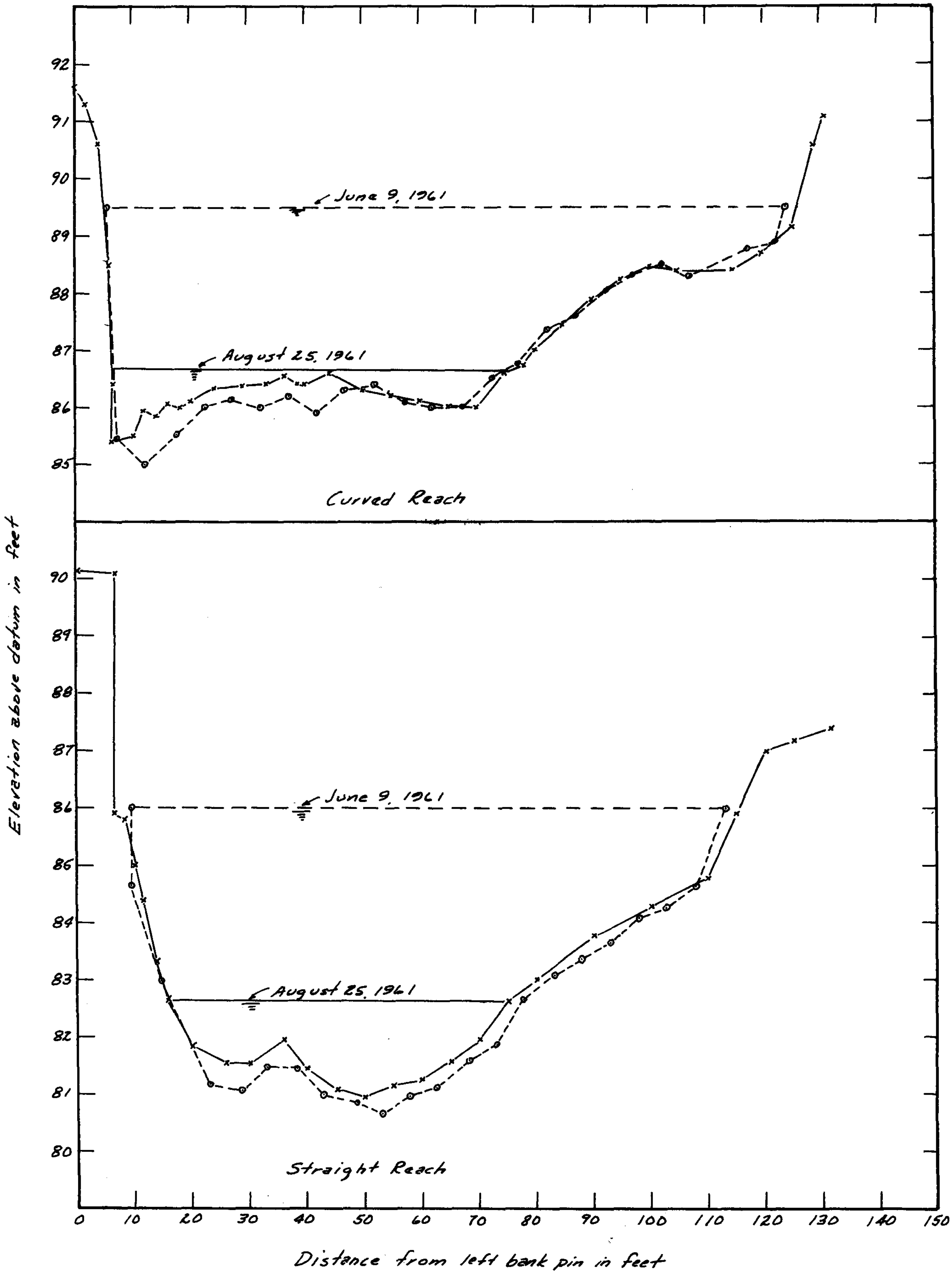

Figure 8.- Typical Cross-sectional Data - Popo Agie River, 1961

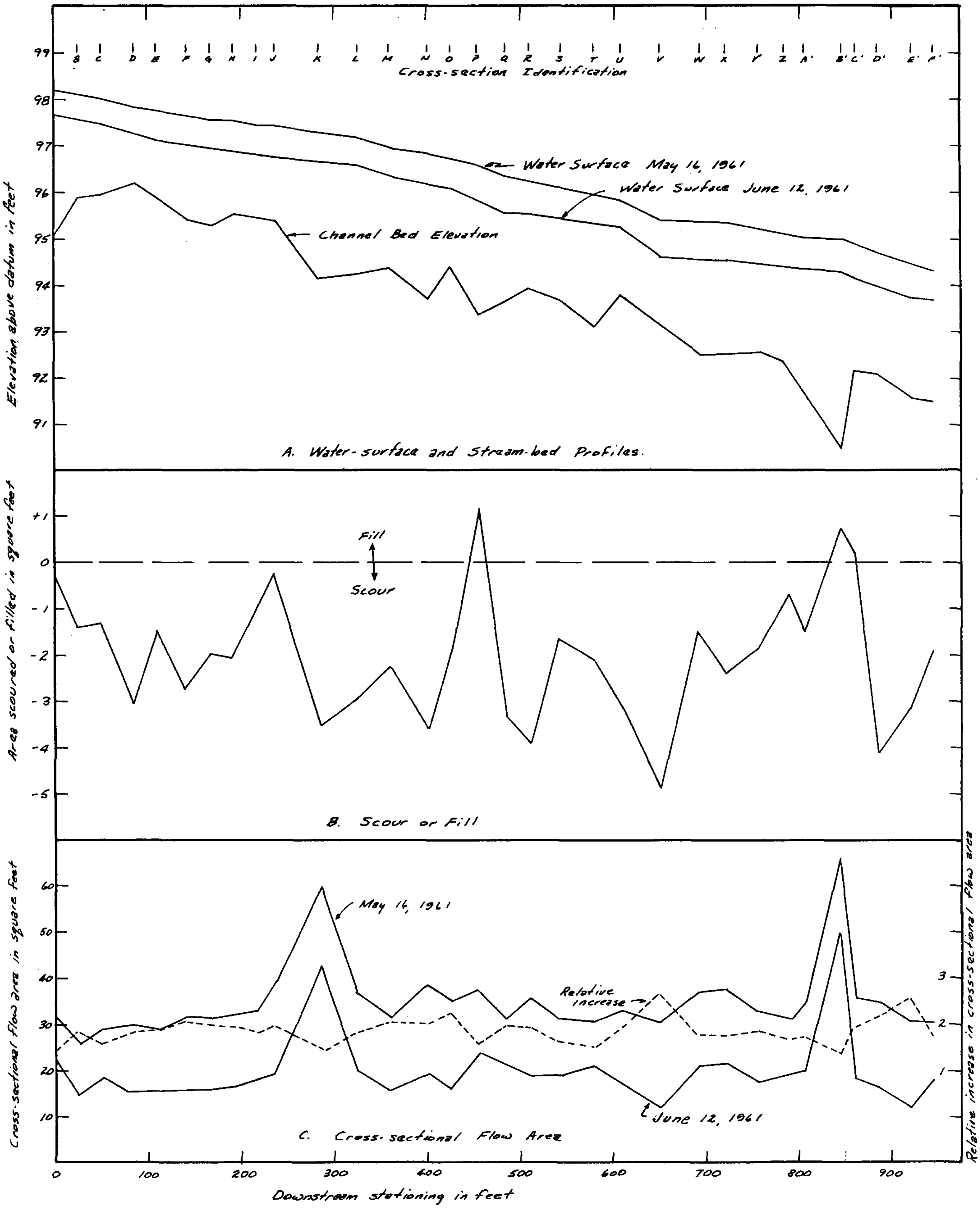

Figure 9 .- Rio Grande del Ranchos near Taos, New Mexico

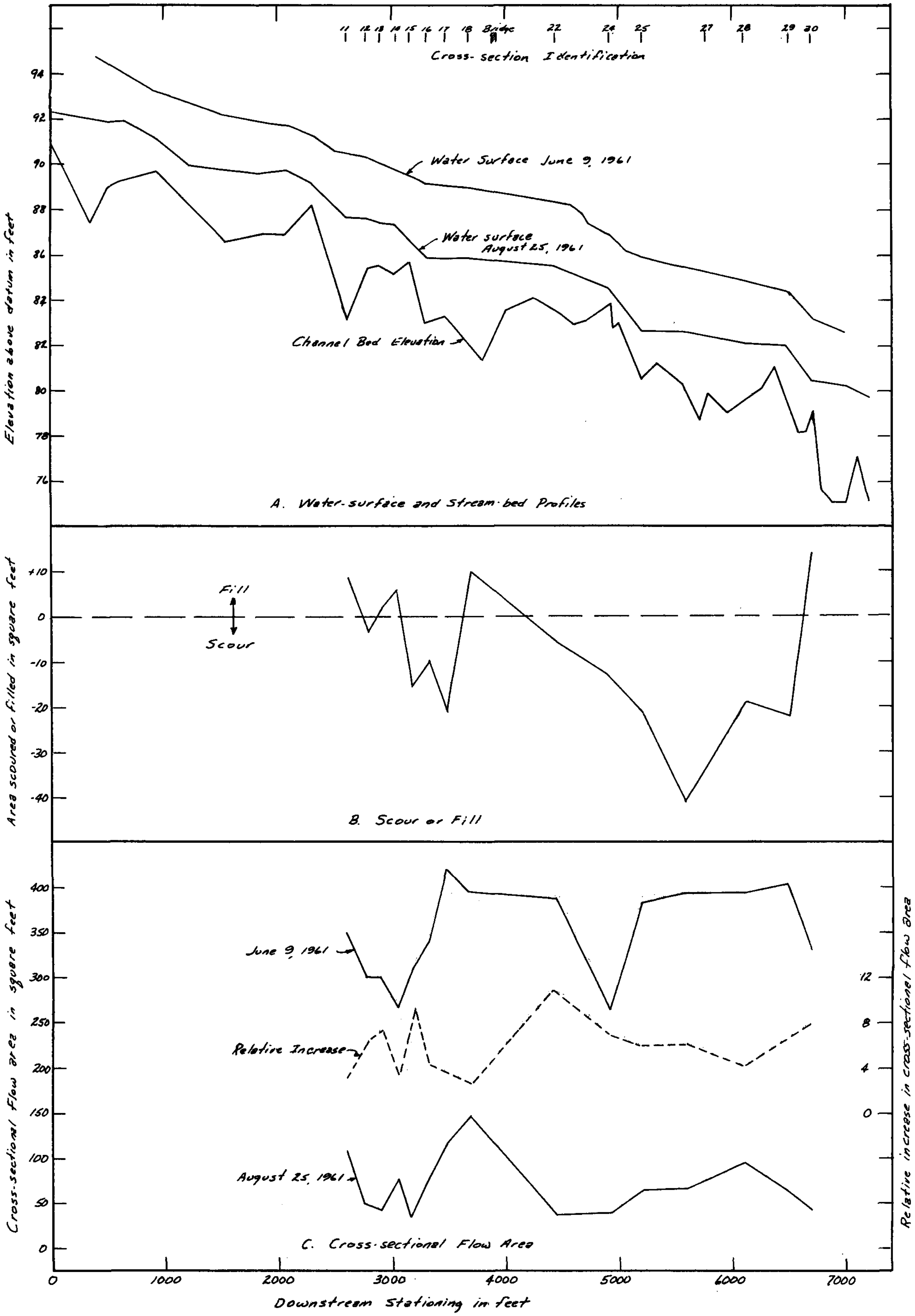

Figure 10.- PopoAgie River near Hudson, Wyoming

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