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SEDIMENT TRANSPORT AND CHANNEL CHARACTERISTICS OF A SAND-BED PORTION OF THE GREEN RIVER BELOW FLAMING GORGE DAM, UTAH U.S.A.

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ABSTRACT

The Green River is a major tributary of the Colorado River with a drainage area of 115,770 km^2 in Colorado, Utah, and Wyoming. The influence of Flaming Gorge Dam on sediment transport and the potential for future channel change were studied using comparative analysis of historical aerial photography covering 1952 - 1987 and Geographic Information Systems (GIS), published sediment (1951 -1986) and discharge (1965-1987) records, and sediment data collected during 1986-1988. Since dam closure in 1964, new equilibrium channel widths were apparently achieved by 1974 in the reach 161 - 279 km below Flaming Gorge Reservoir and by 1981 in the reach 465 - 509 km below the reservoir. Recent high flows have resulted in an increase in average channel width in both reaches as measured on aerial photographs taken in 1986 and 1987. Sediment data from U.S. Geological Survey gauges on the Green River and its primary tributaries and three sites established on the Green River for this study suggest that bed-material sediment transport in the Green River has now attained a quasi-equilibrium, with the river transporting just the load supplied to it. The potential for future channel changes exists, as evidenced by the response of the channel (i. e. channel widening) to the increased flows during 1983, 1984, and 1986. Future adjustments in channel characteristics should be limited to responses to changes in discharge and sediment supply and transport in the basin.

INTRODUCTION

River regulation typically induces major alterations in sediment dynamics and channel morphology in downstream reaches. Williams and Wolman (1984) summarized the observed changes in several alluvial rivers downstream of reservoirs in the semiarid Western United States. Flood peaks were frequently reduced following reservoir completion, but changes in other water discharge characteristics were variable. Suspended sediment loads decreased for long reaches below the reservoirs studied. The majority of observed channel degradation below the dams occurred during the first decade or two after dam closure. This observation supports the conclusions of Langbein and Leopold (1964); quasi-equilibrium conditions are reached rapidly compared to processes such as uplift or general land degradation.

Graf (1980) demonstrated that the influence of major dams may extend far downstream. He described changes in rapids of the Green River in Utah and Colorado downstream of Flaming Gorge Reservoir. He found an increase in the number of stable rapids under post-dam flow conditions.

Graf (1977), who examined the temporal responses of fluvial systems to perturbations, concluded that the time required for geomorphic adjustment after disruption is not the same for all geomorphic systems, but the same model - the rate law - provides a framework for prediction and comparison. Graf further stated that a good fit to a negative exponential form by field data suggests a system that is influenced by a negative feedback mechanism, resulting in a decreasing rate of change that approaches a steady state. In a dynamic equilibrium situation, a steady state condition is not approached and a linear or power curve may best fit the data.

Geomorphic thresholds, as used by Bull (1979), attempt to explain the interrelationships between process and form in fluvial systems. Bull concluded that stream channels tend toward a stream power threshold as a result of the interaction of bed slope change and deposition. At the stream power threshold, a reach of river will respond to changes in climate, base level or changes induced by man by establishing a new stream power threshold. These changes may affect stream and/or critical power, resulting in aggradation or degradation.

Bull noted that most fluvial systems are usually responding to several changes in several independent variables, each having its own time lag associated with attainment of a new equilibrium condition. Thus, evaluating the equilibrium status of a reach of river involves measurement of channel changes and consideration of the status of the independent variables: climate, man-caused changes, and flood history.

In discussing the processes that influence channel shape and form, Wolman and Miller (1960) re-examined the concept of "effective force" and concluded that the largest portion of total work is associated with a discharge where the product of frequency of occurrence and rate of sediment transport is maximized. This maximum relates to a relatively frequent discharge, occurring on the average once or twice a year for the data reviewed by these authors. From a morphologic standpoint, Wolman and Miller demonstrate that the bankfull discharge should be the most "effective" discharge controlling the development of the floodplain and the channel shape. The bankfull discharge is attained every one to two years on the average so that the channel shape and floodplain are controlled by a force of moderate magnitude which recurs relatively frequently.

According to Wolman and Miller, regional analysis is necessary to fully evaluate the relative importance of various geomorphic processes on landform shape. Rare discharges of unusual magnitude are more influential in situations where stresses associated with frequent events are incompetent to transport the available materials. Also, precipitation, temperature, and vegetation interact with erosion to determine sediment availability in a watershed.

The Green River, a major tributary of the Colorado River (Figure 1), offers an opportunity to examine the influence of river regulation on sediment transport and channel morphology. The surface water and sediment yield data for the Green River Basin were described by Iorns *et al.* (1965). The principal areas of water source are the headwater areas in the northern and eastern edges of the Green River basin whereas semiarid portions of the basin at lower elevations contribute the majority of sediment. Originating in southwestern Wyoming, the Green River is controlled by two reservoirs, Fontenelle and Flaming Gorge. Flaming Gorge Dam, downstream of Fontenelle, was completed in 1962 and has an active capacity of 4.3 million cubic dekameters (dam^3). The average annual inflow to Flaming Gorge Reservoir is about 1.5 million dam^3. The dam is located 660 km upstream of the confluence of the Green and Colorado Rivers.

The impact of Flaming Gorge upon channel morphology and suspended sediment transport of the Green River has been previously studied by Andrews (1986). He described post-reservoir changes in flow pattern and suspended sediment transport as measured at stream-gauging stations along the Green River. Channel width trends for short reaches of the Green River following dam closure in 1963 were also reported. Andrews concluded that before 1962, a condition of quasi-equilibrium existed on the Green River with no net aggradation or degradation. Following regulation, different flow and sediment patterns existed and channel adjustments followed.

Andrews reported channel degradation in the reach between Flaming Gorge Dam and the confluence with the Yampa River. Sediment-free releases from Flaming Gorge predominate in that segment, and the majority of sediment load is obtained from the bed. In the reach between the Yampa and Duchesne rivers, Andrews noted a new quasi-equilibrium. Below the Duchesne River confluence, he described aggrading river conditions. Andrews concluded that the quasi-equilibrium that appears to have existed before the reservoir no longer occurs along the majority of the

Green River. He also stated that the potential for future significant channel narrowing existed and he estimated, that this narrowing may not be complete for about 30 years in the area about 170 km below Flaming Gorge Dam.

Andrews and Nelson (1989) studied the response of a mid channel bar, located about 250 km below Flaming Gorge Dam, to variations in discharge. Their comparison of historical aerial photographs taken about the time of construction of Flaming Gorge (1964) to those taken in 1986 demonstrated the long-term stability of this bar.

The objective of this study is to describe the Green River sediment transport and channel width during the post-reservoir period from 1965 to 1987. By using a more extensive length of channel to monitor channel width changes and focusing on the portion of the suspended sediment load that represents the majority of particle sizes found in the bed material, we employ supplementary data to that of Andrews (1986) in describing the sediment transport and channel width characteristics of the Green River during 1965-1987.

METHODS

The impact of Flaming Gorge Dam upon channel morphology and sediment transport of the Green River was quantified in our study using [comparative analysis of aerial photography and GIS (Geographical Information Systems) techniques,] [published discharge and sediment records from U.S. Geological Survey gauges,] and [analysis and interpretation of sediment data collected from 1986 to 1988.] The stability of the channel is of special interest as progressive channel changes may adversely impact the habitat conditions required by endangered species endemic to the Green River (Tyus and Karp, 1989).

Trends in Channel Width

The portions of the Green River investigated in this report (Figure 1) include study reach 1 extending from 161 to 279 km below Flaming Gorge Dam (near U. S. Geological Survey gauge 09261000 and including gauge 09307000 at 155 km and 269 km below the dam, respectively, and sediment sampling points A, B, and C located 164, 250, and 275 km below Flaming Gorge Dam, respectively) and study reach 2 extending from 465 to 509 km below the dam (including gauge 09315000, 465 km below the dam). These reaches were selected to examine the effect of distance from the dam on channel morphology.

Black and white aerial photographs from five time periods were examined for reach 1: 1952, 1963-1964, 1974, 1978, and 1986. The 1952 and 1963-1964 photographs represented pre-construction conditions. The 1952 photography covers only 51 km of river, 39 km at the north end of the reach and 12 km at the south end. The incomplete 1963 and 1964 photography sets were combined to cover the entirety of reach 1 and designated 1964. Changes in channel morphology between 1963 and 1964 were assumed to be insignificant. Photographs differed in scale: 1952 -- 1:20,000, 1964 and 1986 -- 1:24,000, 1974 -- 1:31,680, and 1978 -- 1:33,000. Photographic scale was verified by measuring distances between known points on the photographs and comparing them to distances on topographic maps.

Reach 1 was divided into A. alluvial and B. geologically-confined segments. This division was accomplished using aerial photographs, topographic maps, and aerial reconnaissance of the valley. Allowing for the discontinuous nature of the 1952 photography, three segments were analyzed for changes between 1952 and 1964 (pre-dam): 161 km to 193 km below the dam -- alluvial, 193 to 200 km downstream from the dam -- confined, and 269 to 279 km below the dam -- alluvial. Four segments were analyzed for changes in channel morphology between 1964, 1974, 1978, and 1986: 161 to 193 km below the dam -- alluvial, 193 to 238 km downstream of Flaming Gorge -- confined, 238 to 256 km downstream of the dam -- alluvial, and 260 to 279 km below the dam -- alluvial. Total alluvial and confined river lengths analyzed were 69 km and 45 km, respectively.

Four dates of photography were examined for reach 2: 1952, 1974, 1981, and 1987. The 1952, 1974, and 1987 photographs were black and white, and the 1981 photographs were color-infrared. The photographs differed in scale: 1952 -- 1:20,000, 1974 -- 1:34,500, 1981 -- 1:38,500, and 1987 -- 1:26,000. The entire lower reach is alluvial.

Each photograph was fitted with a mylar overlay on which the river channel was drawn. The river channel was defined by delineating the high water embankments and vegetated islands. A stereoscope was employed to assist in locating high water embankments. Following photointerpretation, the river channel was transferred to 1:24,000 scale overlays using a projection transfer machine to adjust the photographic scale. To maintain transfer accuracy, roads, trails, and creeks were aligned in the photographs and map bases.

The river channel was then digitized into a GIS utilizing a digitizing tablet and puck. River channel surface area was determined for each reach by year. The length of each river reach was calculated by digitizing the center line of the channel for each data set. Channel surface area was divided by this length to calculate channel width.

Sediment Transport

Sediment data collection for this study began in 1986 at three locations within reach 1. At sample point A, 15 samples were collected over a discharge range of 30.6 m^3/s to 292.5 m^3/s. At site B, 18 samples were collected over a range of 31.3 m^3/s to 305.5 m^3/s. At site C, 16 samples were collected over the range of 75.0 m^3/s to 393.4 m^3/s. Discharge and sediment samples were obtained using boat-mounted equipment including: Marsh-McBirney velocity meter (model 201)[1], model A-55 depth sounding reel, D-49 suspended sediment sampler, BMH-60 bed material sampler and a calibrated tagline. Water surface slope for a reach length of about one channel width was measured during each sampling period.

The median diameter of the bed material at the three sampling sites ranged from 0.25 mm at site B to 0.40 mm at site A. About 1 percent of the bed was made up of particles smaller than sand size. Gravel comprised about 1 to 3 percent of the bed. Thus, the bed-material load, that portion of the total sediment load that is similar in size to the bed materials of the channel is essentially equal to the sand-sized portion of the total sediment load. Bed-material load is defined for this study as that portion of the total sediment load coarser than 0.0625 mm.

Using the Modified Einstein procedure (Colby and Hembree,

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[1] Mention of trade names does not constitute an endorsement by the United States Government.

1955), the bed-material load discharge was computed for each sample collected at the three sampling locations. Figure 2 contains the computed sand loads for the samples collected at sites A and B and the suspended sand loads measured at the upstream gauge from 1951 to 1986. The data collected from 1986 to 1988 at these two sites fall within the scatter of the gauge data. Thus, a suspended sand load rating curve was developed for the data from this gauge and used to describe the bed material load transport at these sample sites (Table I). A satisfactory rating curve was developed using a power function equation with an empirically derived offset value.

Figure 3 contains the computed bed material loads for the data collected at site C and the suspended sand loads measured at the middle gauge from 1951 to 1966. The data collected in 1986-1988 fall within the scatter of the gauge data. The suspended sand load rating curve developed for this gauge was used to describe the bed-material load transport at site C (Table I).

Suspended sand load rating curves were also developed for the downstream gauge 09315000 (1951-1982), and a gauge on the White River near the confluence with the Green (1974-1986). A suspended sediment rating curve was developed for the Duchesne River from the data for a gauge near the confluence with the Green River (Table I).

Effective Discharge

Effective discharge is defined as the modal value of the sediment load - duration function developed for a given location. Using mean daily flow data from the upstream and downstream gauges and the sediment load rating curves described above, the effective discharges at the sample points A, B, and C were computed. These data were categorized into 35 flow ranges of equal size. The effective discharge was defined as the midpoint of the flow range in which total sand load for the time period studied was maximized. Total sand load is the sum of the computed sand loads (from the suspended sand rating curves developed from the gauge data) for all the discharges in a given flow range.

The time period used in this analysis was 1965-1987. For site C, 275 km below the dam, mean daily flow values were obtained by adjusting mean daily flow records for the downstream gauge. A linear correlation between mean daily flow data for the downstream gauge and the middle gauge for 1963-1966 yielded an R^2 value of 0.97 when a 2-day lag period was used. This correlation was used to adjust the 1965-1987 flow record for the downstream gauge for use in computing the effective discharge at site C.

RESULTS

Trends in Channel Width

Little change in average channel width between 1952 and 1964 was detected from the aerial photography study of reach 1. The total channel surface area of the portion of the river common to both photography sets increased from about 989 ha in 1952 to 1,003 ha in 1964, or only 1.4 percent (Table II). Channel surface area change among the alluvial and confined segments ranged from a slight loss (-1.5 percent) to a slight gain of 2.4 percent. The average channel width for reach 1 increased by only 1.6 percent from 210 m in 1952 to 213 m in 1964.

Table III presents the reach 1 channel surface area and width for 1964, 1974, 1978, and 1986. The largest changes in channel surface area and width occurred between 1964 and 1974. Channel surface area decreased 6 percent from about 2,412 to 2,268 ha, ranging from -2.6 percent for the segment between 160 km and 179 km below Flaming Gorge Dam (alluvial) to -12 percent for the segment between 138 km and 156 km below the dam (alluvial). Average channel width for reach 1 decreased from 217 m in 1964 to 204 m in 1974.

Channel surface area was stable from 1974 to 1978 ranging from a small decrease (-2 percent) for the alluvial segment between 200 km and 279 km below Flaming Gorge Dam to a slight increase of 0.9 percent for the 32-km alluvial segment starting

161 km downstream from the dam. Channel surface area for reach 1 increased by only 0.2 percent from approximately 2,268 ha in 1974 to 2,273 ha in 1978.

Channel surface area and width increased somewhat at all sites between 1978 and 1986, ranging from 1.1 percent for a segment between 160 km and 279 km below Flaming Gorge Dam to 4.9 percent for the segment between 138 km and 156 km below the dam (alluvial). Channel surface area for reach 1 increased by about 49 ha or only 2.1 percent over this time span.

The process of channel narrowing occurred later in reach 2 and with less magnitude. There was little or no difference in channel surface area and width between 1952 and 1974, 12 years after dam completion (Table 4). The major reduction in channel surface area occurred between 1974 and 1981, decreasing from about 631 ha to approximately 602 ha, or 4.6 percent. Channel surface area increased only 1.4 percent between 1981 and 1987.

Discharge Patterns

Andrews (1986) reported no changes in mean annual flow at the two mainstem Green River gauges following closure of Flaming Gorge. [However, he demonstrated changes in the frequency of flow pattern of the Green River, reporting that the magnitude of flows that occur less than 10 percent of the time decreased significantly after regulation.]

The annual peak flows for the upstream gauge for the period covered by the aerial photography for reach 1 are shown in Figure 4. The peak recorded in 1984, 1,133 m^3/s, is the largest reported for the entire gauge history. These data were separated into three periods, 1953-1964, 1965-1978, and 1979-1986, corresponding to the photographic intervals. An analysis of covariance showed no statistically significant difference (α = 0.05) in the means of the annual peak flows for these intervals. A similar analysis for the annual peak flow data for the downstream gauge (Figure 5) indicated no statistically significant differences in the means of these data. The peak flows at this gauge were separated into three periods: 1953-1974, 1975-1981, and 1982-1987, based upon the dates of aerial photography for reach 2.

Frequency-of-flow plots (Figure 6) for the photographic intervals for mean daily flow data from the upstream gauge in reach 1 illustrate a different pattern for mean daily flows exceeding 310 m^3/s with lower flows for the same frequency during 1964-1978 than for the other periods. The curve for the 1952-1964 data differs from those for the later periods below 140 m^3/s, yielding a lower flow for a given frequency. A flow of 310 m^3/s was exceeded about 9 percent of the time during 1964-1978.

Analysis of mean daily flow data for the downstream gauge in reach 2 indicates that flows were greater for a given frequency during 1982-1987 than during the earlier portion of the post-reservoir period (1963-1981). The frequency-of-flow curve representing 1982-1987 is very similar to those curves from the pre-reservoir era (1942-1952, 1953-1962) for very infrequent flows which occurred less than 2 percent of the time (Figure 7).

Mean Annual Bed-Material Load

The bed-material load discharge rating curves were used with the mean daily flow data for the upstream and downstream gauges on the Green River for 1965-1987 to compute estimates of mean annual bed-material load at sites A, B, C, and the downstream gauge. For sites A and B, the mean annual bed-material load for this period was 1,343,000 tonnes/year. These estimates are based upon the mean daily flow data collected at the upstream gauge and the suspended sand load rating curve developed for the entire gauge history.

At site C, the mean annual bed-material load was 2,640,000 tonnes/year. The adjusted mean daily flows from the downstream gauge were used in this estimate. The suspended sand load rating curve for the middle gauge was used with the adjusted discharges.

For the downstream gauge, the mean annual bed-material load was 2,803,000 tonnes/year. This estimate was based upon the mean daily flow record and the suspended sand load rating curve for the gauge. For the Duchesne River, the suspended sediment rating curve for gauge was used along with the mean daily flow record for this gauge from 1965 to 1987 to compute the estimate of mean annual suspended load. Assuming about 27 percent (based upon six measurement from 1980-1986) of the suspended load was sand, the annual sand load estimate for the Duchesne River was 42,000 tonnes/year. For the White River, the flow-duration data for the gauge near the confluence from 1974-1986 were used to derive an estimate for suspended sand load discharge of 925,000 tonnes/year.

Bed-Material Load Mass Balance

Table V presents the bed material load mass balance for the reach of the Green River from 164 to 468 km downstream of Flaming Gorge Dam. In reach 1, sites A and B showed equal bed-material loads because both were developed from similar gauge records. Between 150 and 175 km below the dam, the Green River gained 1,297,000 tonnes/year of bed-material load. The White and Duchesne Rivers contribute 967,000 tonnes/year to this reach. The difference, 330,000 tonnes/year, represented about 12 percent of the mean annual sand load at site C. Although no bedload information was available for the White River, streams of similar characteristics often have a significant bedload component ranging from 10 to 35 percent of the total suspended sediment load (Strand and Pemberton, 1982). Assuming a 10-percent bedload correction factor for the mean annual suspended sediment load of the White (3,293,000 tonnes/year for 1975-1986) satisfies the difference computed for the bed-material load estimates for sites B and C.

At the downstream gauge, the mean annual bed material load was about 6 percent larger than the load computed for site C.

The main tributary in the intervening reach, the Price River, is gauged about 56 km upstream of its confluence with the Green River. Inadequate gauge records prevented the calculation of average annual sand load from the Price River. The mean annual discharge of the Price River is about 2 percent of the flow of the Green and is not likely a major contributor to the total sand load of the Green River.

On average for 1965-1987, the bed material load of the Green River at the upstream gauge was nearly 50 percent of the river's bed material load at the downstream gauge. Suspended sand load in the White and Duchesne Rivers account for about two-thirds of this difference, 967,000 tonnes/year. Assuming a 10-percent bedload correction factor for the White River satisfied the difference. The mass balance of bed material loads, calculated from the long-term gauge histories of the Green River at intermediate sampling locations, indicated that the Green River was transporting just the sand load that was delivered to it throughout this reach during 1965-1987.

Effective Flow

For the post-impoundment period 1966-1981, Andrews (1986) defined the effective flow at the upstream gauge to be 326 m^3/s and the effective flow at the downstream gauge to be 581 m^3/s. Our effective flow estimates for 1965-1987 are: 337 m^3/s for sites A and B, 544 m^3/s at site C, and 569 m^3/s at the downstream gauge which are comparable to Andrews' estimates.

For the Green River, the effective flow is an index of a very broad range of discharge that carries significant amounts of bed-material-sized sediments. Approximately 80 percent of the bed material load is transported over the discharge ranges at each site shown in table 6. These ranges cover about 90 percent of the flows measured at the two gauges during the post-reservoir period.

DISCUSSION

Channel Width

The installation of Flaming Gorge Dam has measurably narrowed the Green River channel. Before installation of the dam, the river was said to be in quasi-equilibrium with respect to sediment load (Andrews, 1986). Our comparison of channel area and width between 1952 and 1964 confirms this statement(Table II). In study reach 1, channel adjustment was generally complete within 12 years of dam installation and little narrowing was noted after 1974. Channel width for reach 1 decreased about 6 percent between 1964 and 1974 from 217 to 204 m. Andrews (1986) reported a much larger decrease of 13 percent, from 214 to 186 m, for a shorter reach of the river near the upstream gauge between 1964 and 1978. Our study found a decrease similar to that reported by Andrews only for a portion of reach 1 from 238 km to

256 km downstream from Flaming Gorge Dam. Andrews' measurements were based on only 15 cross sections in a reach about 100 km long, which probably accounts for the discrepancy.

Andrews (1986) predicted a new quasi-equilibrium channel width of about 160 m for the reach near the upstream gauge. He projected that complete channel width narrowing would take about 30 years for the channel width to adjust to the post-reservoir effective discharge. Our results indicate that the majority of channel narrowing was complete by 1974 in the upper reach because average channel width did not change appreciably between 1974 and 1978 (Table II).

No discernable difference existed in the magnitude of channel narrowing between alluvial and confined reaches. The best fit of the data in Table III was found to be a power function model ($y = ax^b$) with a = 208.5 and b = -0.0132. A moderate correlation coefficient of -0.66 was calculated for these data. Using this model can account for about 45 percent of the variation in measured channel width. The predicted channel width (201 m) at 15 years following reservoir completion does not differ appreciably from the predicted width of 199 m after 30 years.

A slight increase in average channel width occurred for study reach 1 between 1978 and 1986. The flow-frequency analysis for the upstream gauge shows a corresponding increase in the frequency of occurrence of flows greater than 310 m^3/s during the same period. A similar response is apparent in the channel widths reported for the reach 2 between 1981 and 1987 which corresponds to a time period for which occurrence of large flows resembled pre-impoundment conditions. This evidence indicates that the majority of channel widening in both reaches occurred during the high flow years of 1983, 1984, and 1986 when flows in the Green River resembled pre-reservoir conditions.

Andrews (1986) reported that the most significant process of channel narrowing in his study reach near the upstream gauge occurred when a side channel filled with bed material and the mid-channel bar became attached to the bank. We estimate that 46 percent of the channel area lost between 1964 and 1974 in reach 1 was related to increases in the number of islands and island size, and the loss of side channels that filled with bed material. The island area decreased slightly from 1974 to 1986, which accounts for the slight increase in channel area during this period.

The loss of side channels from 1964 to 1974 may represent a significant loss in potential backwater habitat associated with these areas. Reduction in the frequency of flood discharges may encourage vegetation encroachment which stabilizes deposits, traps sediment, and reduces active channel erosion (Petts, 1984). Our data show a decreasing rate of channel narrowing following dam closure. A subsequent survey in 1990 (Lyons, 1990) of the reach of the Green River studied by Andrews and Nelson (1989) revealed channel shape changes since 1986. However, no appreciable changes in average channel width or depth were apparent for the 2-km reach.

The Green River channel is considerably narrower in reach 2 (Table IV); however, the magnitude of reduction in channel width, 5 percent, resembled that of reach 1. Channel width reduction in reach 2 occurred between 1974 and 1981, between at least 10 to 17 years later than reach 1.

Andrews (1986) reported a 10 percent decrease in channel width, from 157 to 142 m, for a 24-km reach downstream from the downstream gauge between 1952 and 1981. His estimate of channel width for the lower reach in 1952 was about 9 percent greater than that of our study. His measurements were based on only 14 cross sections taken in a relatively short section of reach 2. Other studies have reported similar discrepancies; cross sectional measurements were shown to overestimate channel area on the Platte River in central Nebraska, U.S.A. (Sidle *et al.*, 1989).

Andrews (1986) predicted that adjustment of the Green River downstream from the downstream gauge was nearly complete and would reach a quasi-equilibrium width of 137 m. Our data indicate that adjustment of the river channel was complete by 1981, when average channel width was 138 m in this reach.

Effective Discharge

As reviewed by Ashmore and Day (1988), the magnitude of the effective discharge for sediment transport may not always equal that of the dominant discharge for channel morphology. The dominant discharge for channel morphology depends on environmental conditions, the recovery time for large floods (Wolman and Gerson, 1978), the sequence of large floods and the presence and interactions of thresholds and feedback mechanisms that are likely unique to the river studied (Carling, 1988).

Andrews (1986) equated effective discharge and channel-forming discharge for pre-reservoir and post-reservoir periods for the Green River. He based this upon his findings of similarity between effective discharge (total sediment load) and measured bankfull discharge in the Yampa River Basin (Andrews, 1980). Andrews and Nelson (1989) estimated bankfull flow to be about 475 m^3/s for the channel reach they studied near site B. This channel-morphology discharge is about 45 percent greater than the sediment transport flow reported by Andrews for this reach and confirmed in our study. Our studies of open channel flow at site B indicate that overbank flow would commence at about 500 m^3/s in this reach. Thus, the available field evidence for the Green River suggests that the computed effective discharge in this reach is less than the bankfull channel discharge.

Several factors in the Green River Basin could cause the dissimilarity in magnitude between the computed effective discharge for sediment transport and the bankfull discharge. The amount of sediment stored in the channel is much greater than the average annual bed material load of the Green River. Channel margin changes in response to the change in sediment load following Flaming Gorge construction could be extremely slow and difficult to detect amidst the fluctuating response of channel width to changes in discharge such as occurred during 1983 - 1986. Such responses are short-term (occurring and persisting on the order of 1-10 years) adjustments in river equilibrium. They are responses in the channel to discharge variations that alter the average form of the river channel for a period of years, but help to define the equilibrium conditions found over a longer (10 - 100+ years) period (Richards, 1982). Presently undetectable feedback mechanisms may be influencing the response in channel morphology and the future sequence of large floods in the basin will also influence on the future channel geometry of the Green River.

Much remains to be studied regarding river channel changes following major perturbations such as construction of large dams. According to our study of the historical gauge records for the basin and interpretation of aerial photography of two long reaches of the Green River indicated that channel changes in response to Flaming Gorge Dam occurred soon after its completion. Because the Green River is a relatively long watercourse draining a diverse watershed, a considerable range of responses could occur in the future.

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Table I. Sediment Rating Curves, U. S. Geological Survey Gauges on the Green River and Tributaries.

Gauge	Type	Equation	R^2
Upstream	Sand Load	$Q_s=0.102(Q-18.4)^{2.055}$	0.8643
Middle	Sand Load	$Q_s=0.627(Q-15.6)^{1.742}$	0.7354
Downstream	Sand Load	$Q_s=0.00864(Q-21.2)^{2.468}$	0.8090
Duchesne River	Suspended	$Q_s=6.69Q^{1.243}$	0.7204
White River	Sand Load	$Q_s=2.54(Q-3.5)^{2.001}$	0.9397

Q_s = Sediment discharge, tonnes/day

Q = Discharge, m^3/s

Table II. Green River reach 1 channel morphology comparisons between 1952 and 1964 for alluvial and confined segments.

Site	1952	1964
161 km - 193 km		
(alluvial)		
area (ha)	664.64	680.32
width (m)	207	211
193 km - 140 km		
(confined)		
area	137.15	138.63
width	229	232
269 km - 279 km		
(alluvial)		
area	187.31	184.45
width	210	206
Total alluvial		
area	851.95	864.77
width	207	210
Total reach		
area	989.11	1003.39
width	210	213

Note: Site descriptions are distances downstream from Flaming Gorge Dam. This analysis does not cover the entirety of reach 1.

Table III. Green River reach 1 channel morphology comparisons for pre-dam (1964), and post-dam (1974, 1978, and 1986) periods at alluvial and confined sites.

Site	1964	1974	1978	1986
161 km - 193 km				
(alluvial)				
area (ha)	680.31	659.28	665.30	676.33
width (m)	211	205	207	210
193 km - 238 km				
(confined)				
area	981.59	913.90	921.51	939.01
width	222	207	209	213
238 km - 256 km				
(alluvial)				
area	382.36	336.35	334.95	351.28
width	215	189	189	198
260 km - 279 km				
(alluvial)				
area	367.99	358.27	350.99	354.76
width	212	207	203	205
Total alluvial				
area	1430.66	1353.90	1351.24	1382.37
width	213	201	201	206
Total reach				
area	2412.25	2267.80	2272.75	2321.38
width	217	204	204	208

Note: Site descriptions are distances downstream from Flaming Gorge.

Table IV. Green River reach 2 channel morphology comparisons for pre-dam (1952), and post-dam (1974, 1981, and 1987) periods.

Site	1952	1974	1981	1987
465 km - 509 km				
area (ha)	629.37	630.99	601.83	610.34
width (m)	144	145	138	140

Note: Site descriptions are distances downstream from Flaming Gorge Dam.

Table V. Summary of mean annual sand load of the Green River and major tributary streams.

Mainstem Site	Tributary	Period	Mean Annual Q, m^3/s	Mean Annual Q_s, tonnes/y
A		1965-87	129.9	1,343,000
B		1965-87	129.9	1,343,000
	Duchesne	1965-87	18.1	42,000
	White	1975-86	23.9	925,000
C		1965-87	183.4	2,640,000
	Price	1965-87	4.5	No data
Downstream gauge		1965-87	181.5	2,803,000

Table VI. Effective flow ranges for the Green River, 1965-1987.

Site	Flow Range, m^3/s
A	48.1 to 560.7
B	48.1 to 560.7
C	60.9 to 826.9
Downstream gauge	59.5 to 845.3

Figure Legends

Figure 1. Location map of the Green River showing U.S. Geological Survey gauging stations, sediment sampling sites, and the two study reaches examined by aerial photography. Reach 1 extends from point W to point X, reach 2 from Y to Z. Latitude and longitude of Flaming Gorge Dam are 41°00' N and 109°30' W.

Figure 2. Computed bed material load, Green River at sites A and B, 1986 - 1988 and suspended sand load at the upstream gauge.

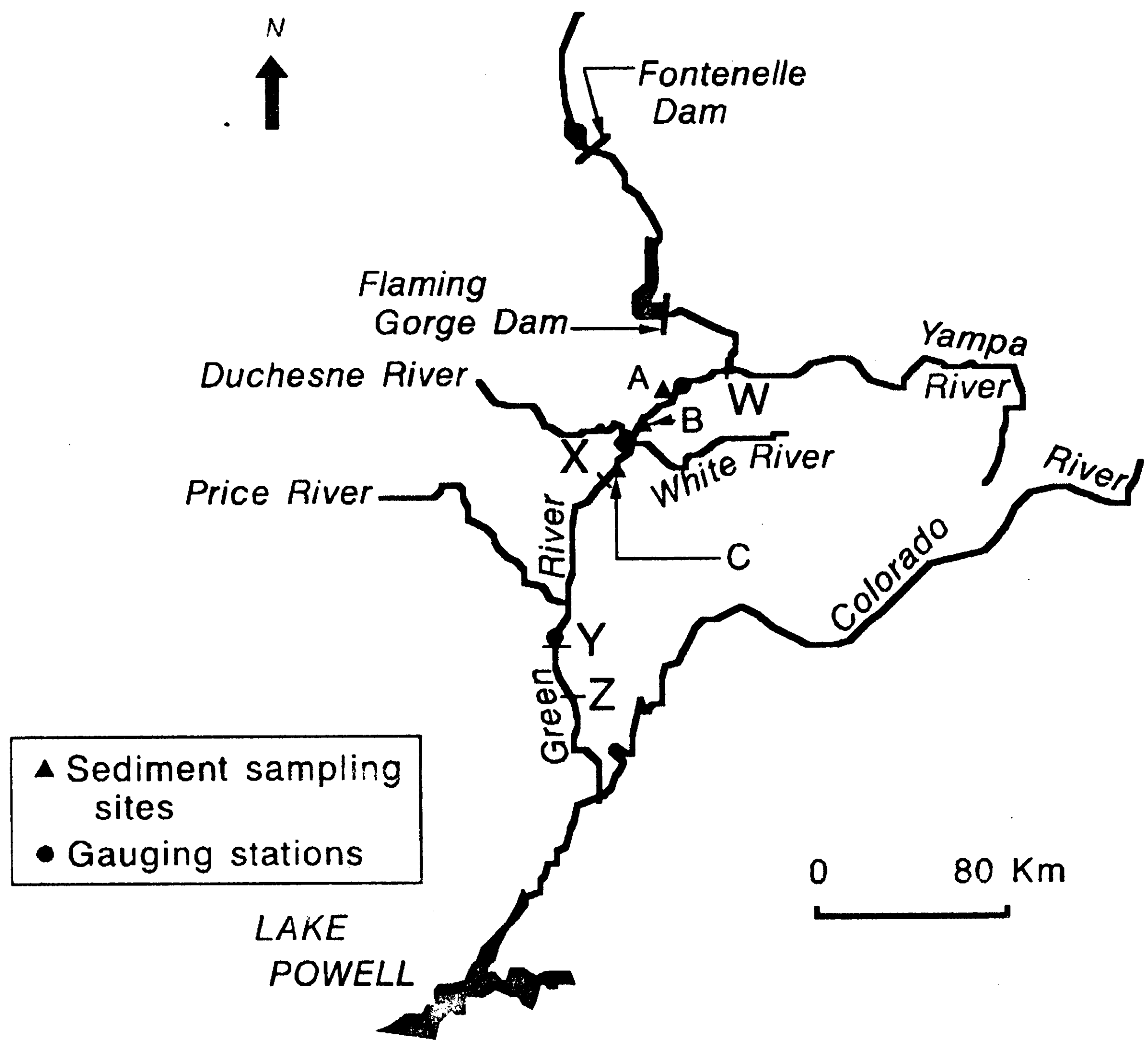
Figure 3. Computed bed material load, Green River at site C, 1986 - 1988 and suspended sand load at the middle gauge.

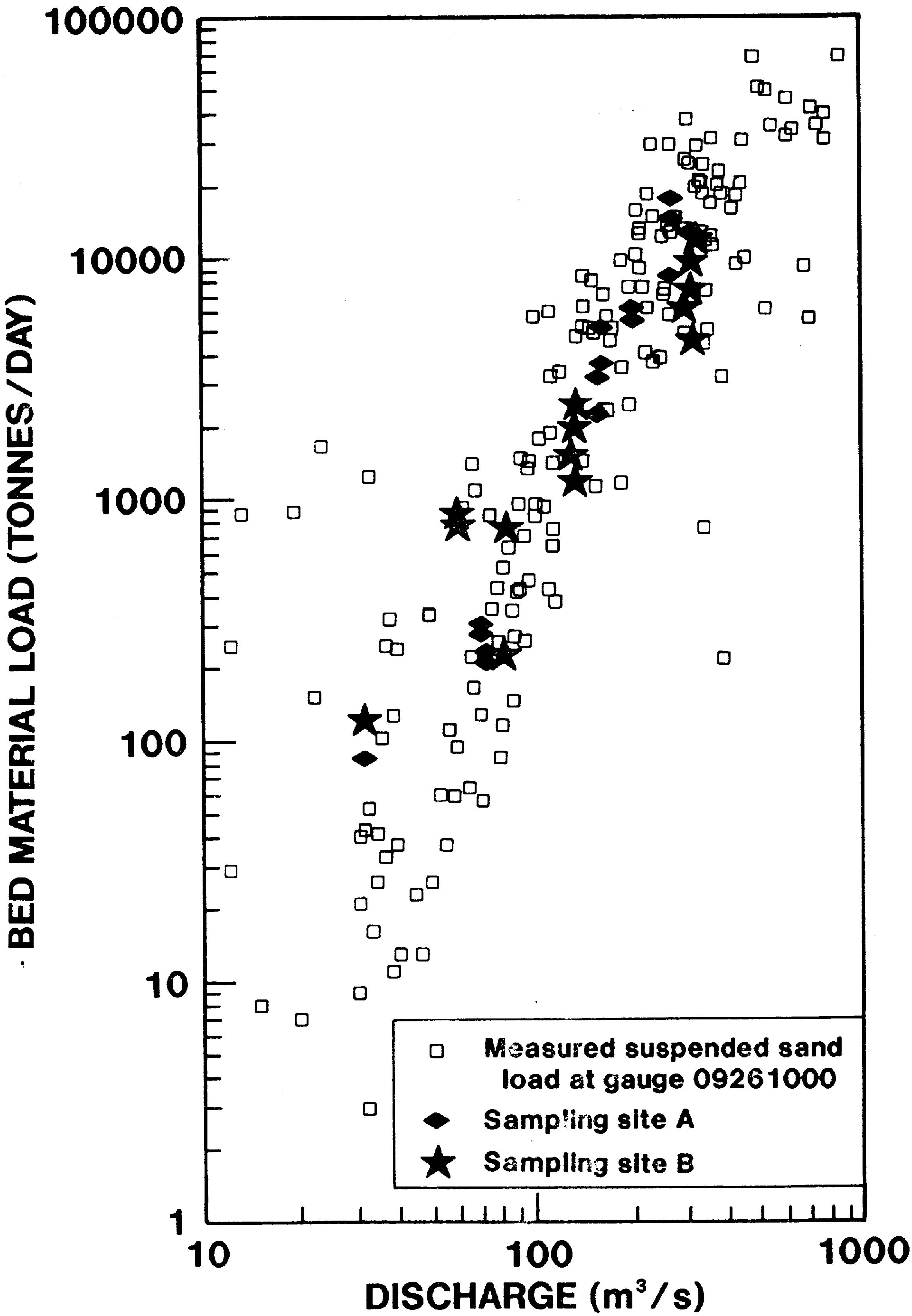
Figure 4. Annual peak flows, Green River at the upstream gauge, 1953 - 1986.

Figure 5. Annual peak flows, Green River at the downstream gauge, 1953 - 1987.

Figure 6. Flow - percent of time exceeded for photographic intervals, Green River at the upstream gauge.

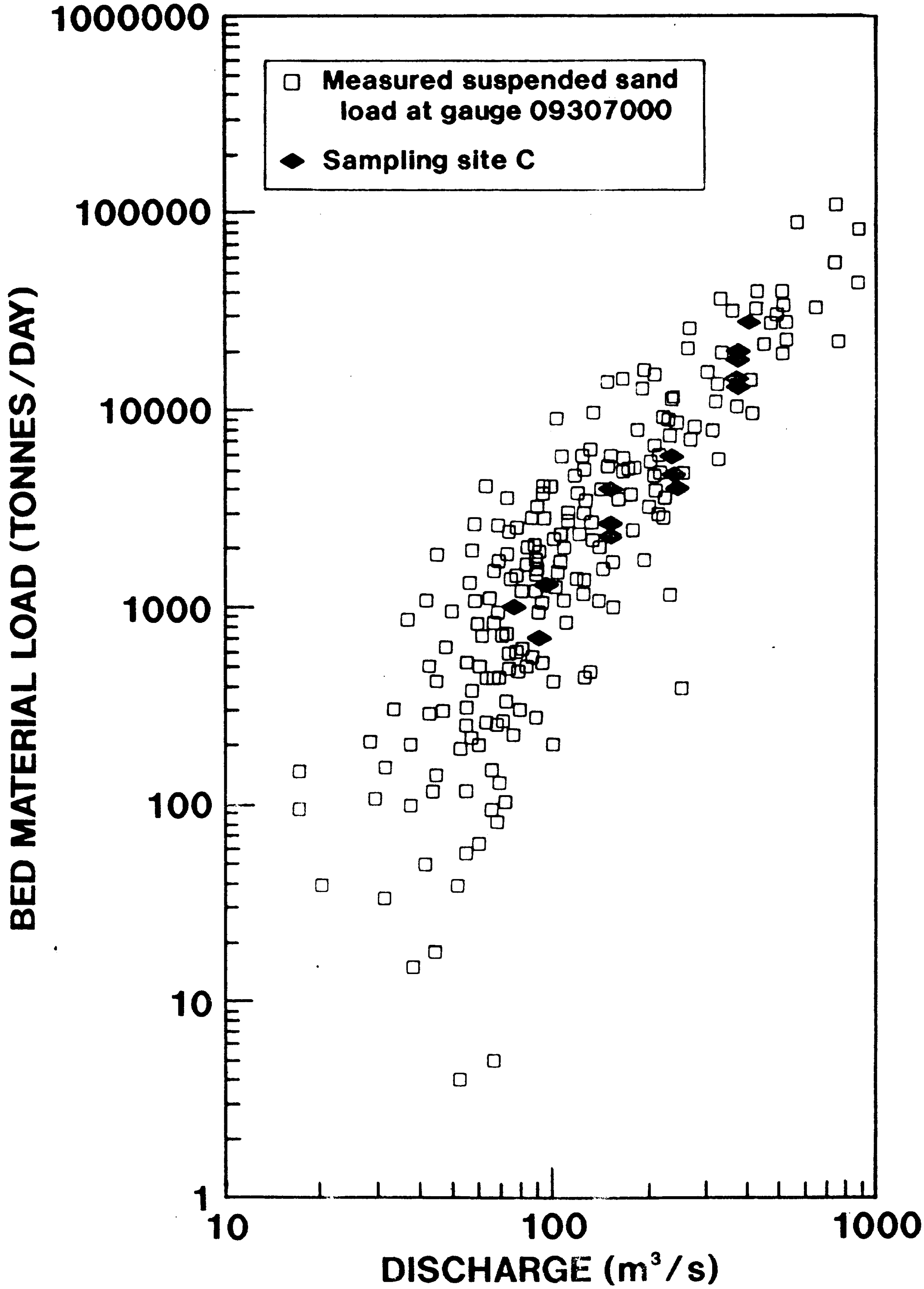
Figure 7. Flow - percent of time exceeded for photographic intervals, Green River at the downstream gauge.


N
Fontenelle Dam
Flaming Gorge Dam
Duchesne River
A
B
W
Yampa River
X
White River
Price River
River
C
Colorado
River
Y
Z
Green
▲ Sediment sampling sites
● Gauging stations
0
80 Km
LAKE POWELL



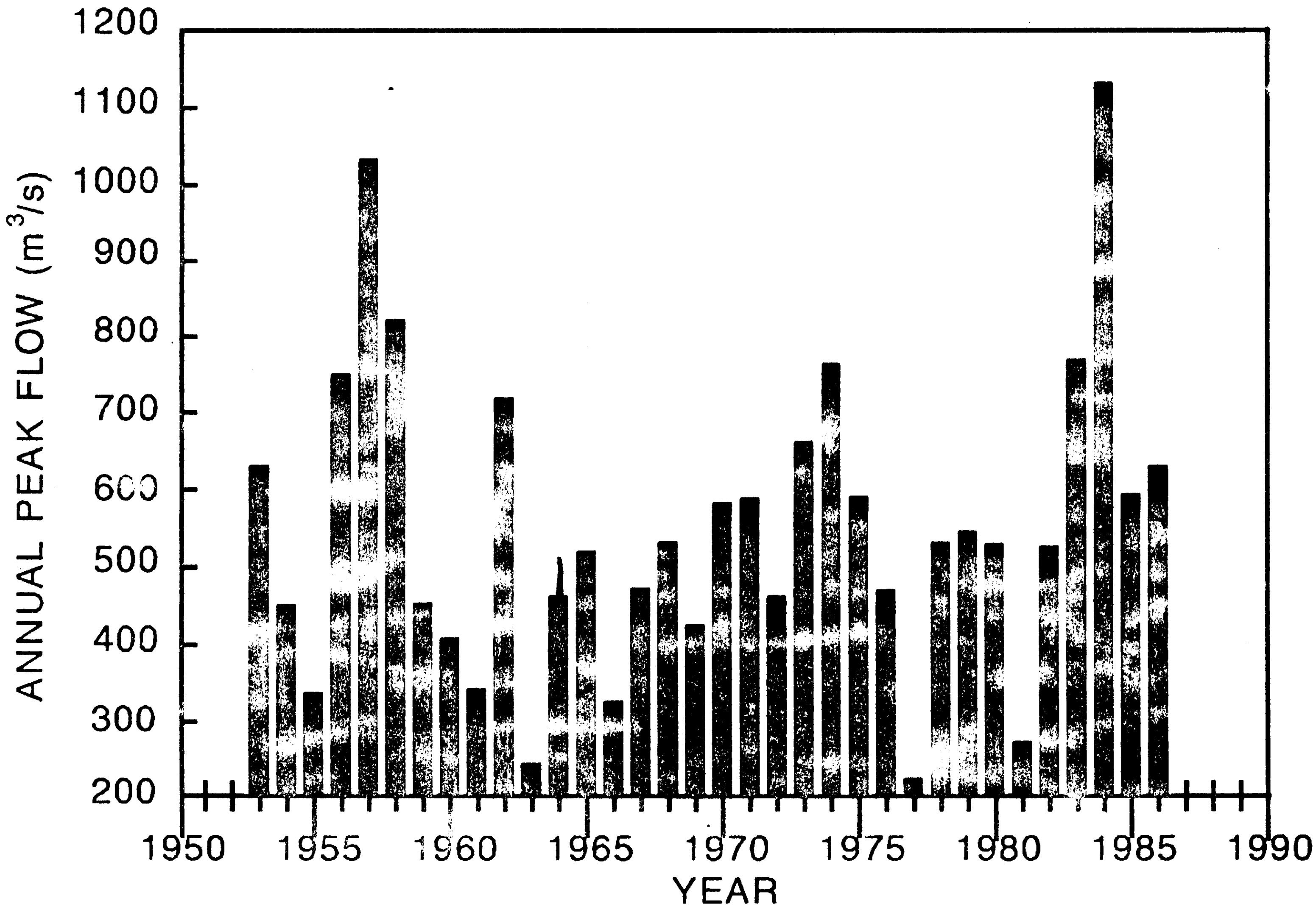
100000
10000
1000
100
10
1
BED MATERIAL LOAD (TONNES/DAY)
10
100
1000
DISCHARGE (m³/s)
Measured suspended sand load at gauge 09261000
Sampling site A
Sampling site B

Figure 2

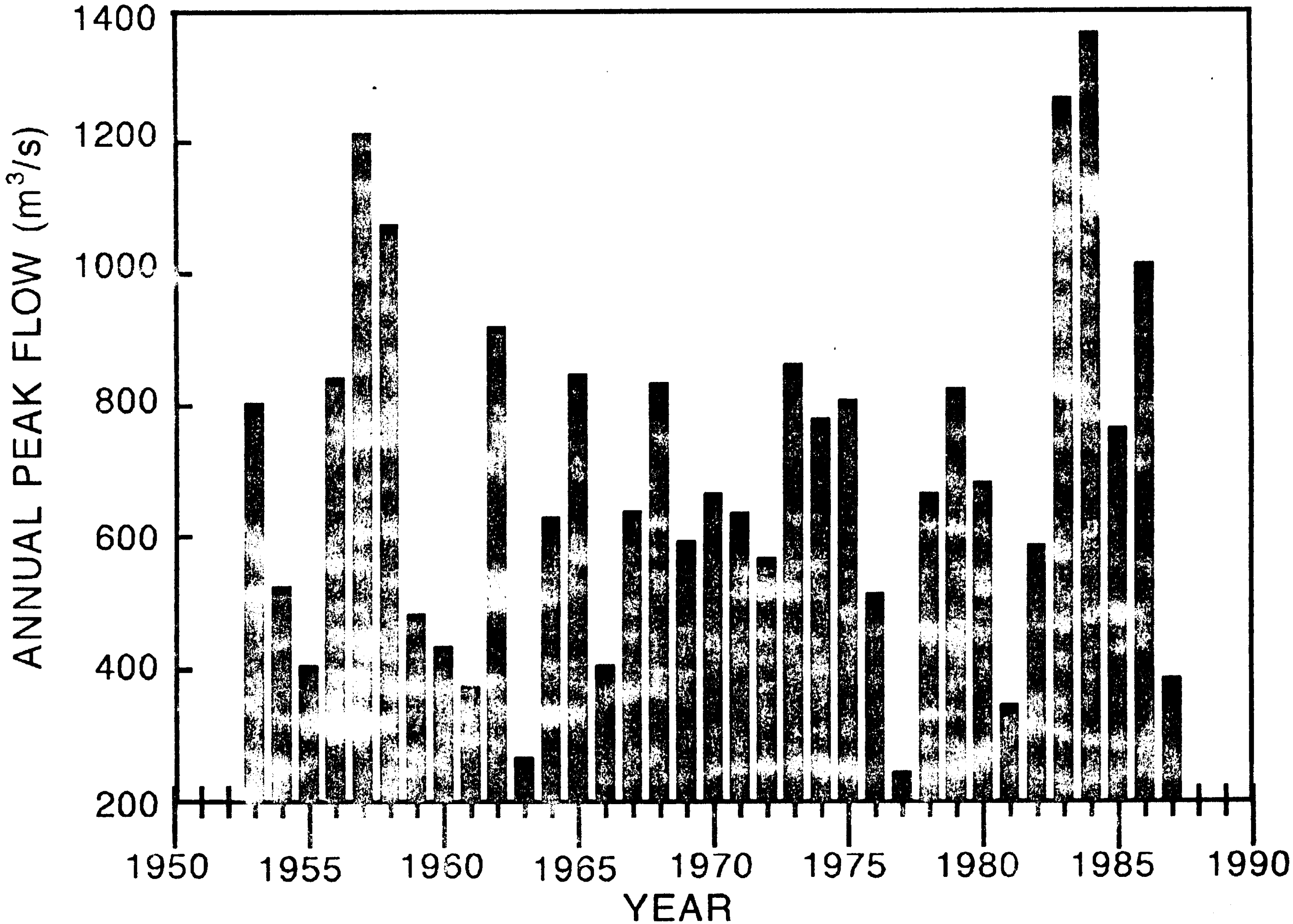


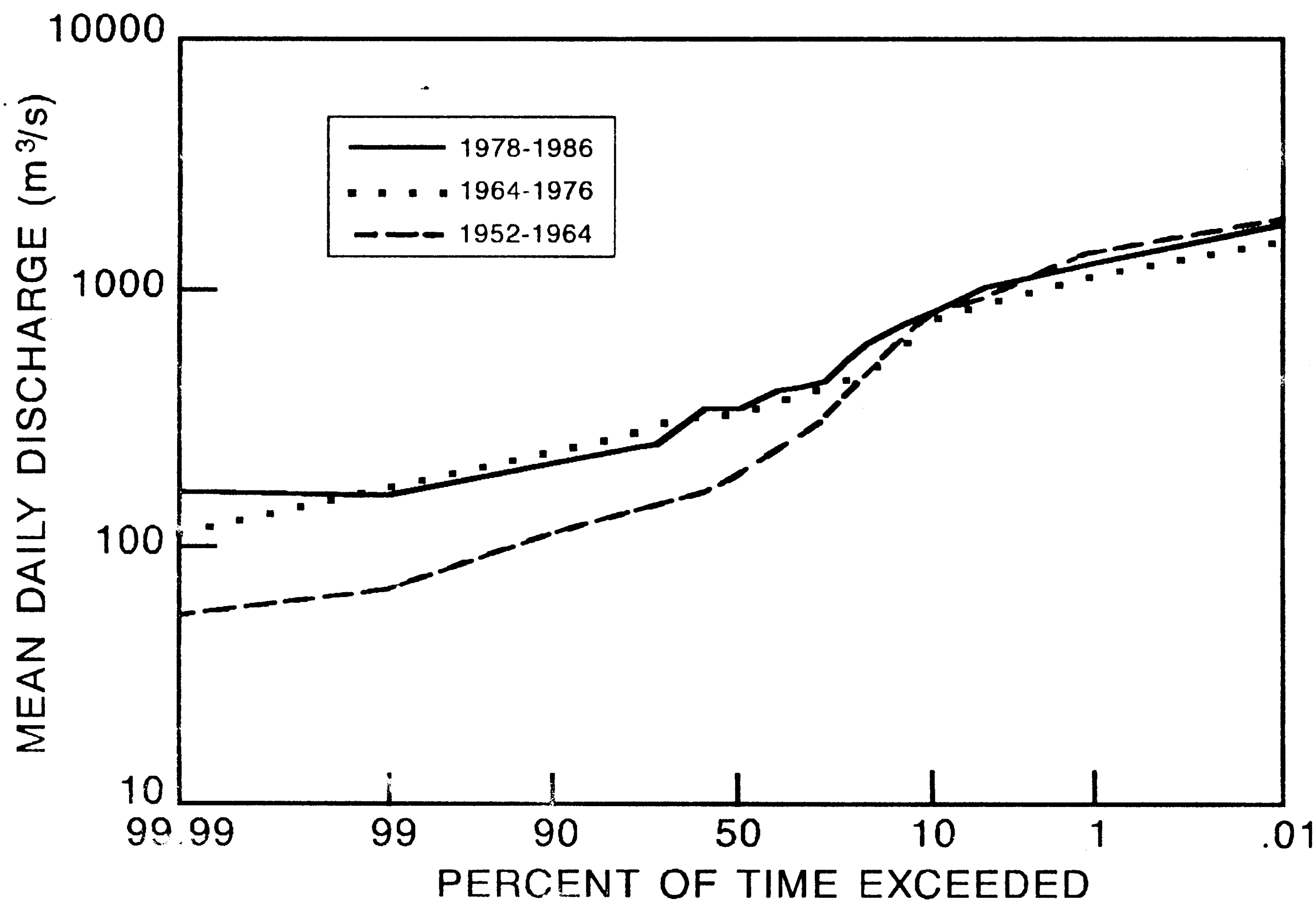
Measured suspended sand load at gauge 09307000
Sampling site C
BED MATERIAL LOAD (TONNES/DAY)
DISCHARGE (m³/s)
1000000
100000
10000
1000
100
10
1
10
100
1000

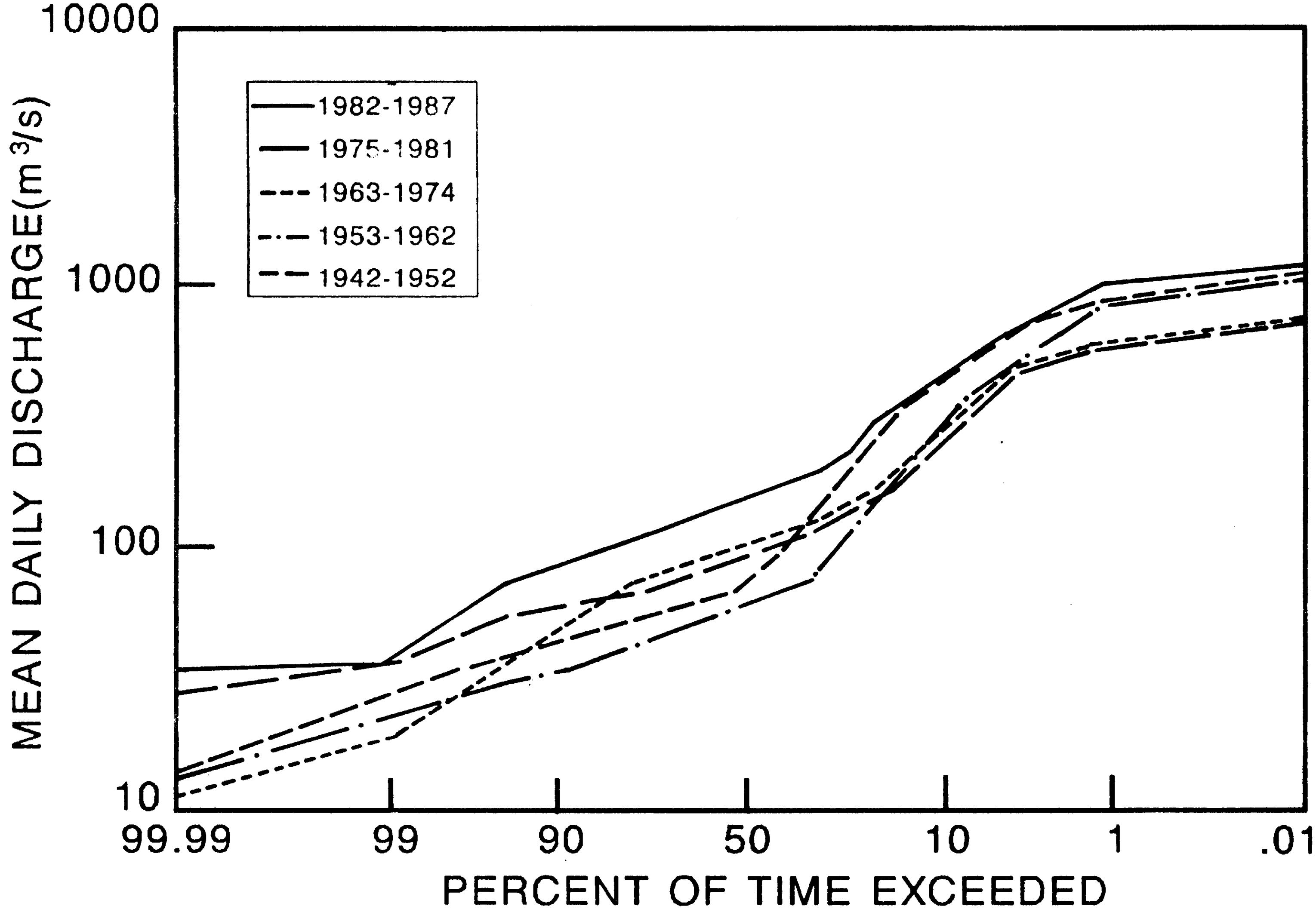
Figure 3



ANNUAL PEAK FLOW (m3/s)
1200
1100
1000
900
800
700
600
500
400
300
200
1950
1955
1960
1965
1970
1975
1980
1985
1990
YEAR


ANNUAL PEAK FLOW (m^3/s)
1400
1200
1000
800
600
400
200
1950
1955
1960
1965
1970
1975
1980
1985
1990
YEAR


1978-1986
1964-1976
1952-1964
MEAN DAILY DISCHARGE (m³/s)
10000
1000
100
10
99.99
99
90
50
10
1
.01
PERCENT OF TIME EXCEEDED



MEAN DAILY DISCHARGE(m3/s)
10000
1000
100
10
99.99
99
90
50
10
1
.01
PERCENT OF TIME EXCEEDED
1982-1987
1975-1981
1963-1974
1953-1962
1942-1952