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Geomorphic and Hydrologic Control of Sediment and Salt Loads in the Colorado River Basin: Significance for Conservation and Land Management

by

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Abstract

Suspended sediment and dissolved-solid (salt) loads decreased after the early 1940s in the Colorado Plateau portion of the Colorado River Basin, although discharge of the Colorado, Green, and San Juan Rivers did not change significantly. This decline followed a period of high sediment yield from about 1880-1940 that was caused by arroyo cutting and stream entrenchment in most tributary streams. Reduced sediment yield has been explained by a change in sediment sampling procedures in the 1940s, by changes in land use and conservation practices, and by channel-sediment storage caused by hydrologic change. Sampling procedures and conservation practices, however, do not adequately explain the reduced salinity and sediment load. New sampling procedures were biased toward a slight increase in sediment load, and the effect of conservation practices was probably local. Sediment storage in channels of tributary basins was coincident with the decline in sediment load and salinity, and stratigraphic studies show that sediment storage in two gaged basins resulted from a change in flood frequency and magnitude. This hydrologic explanation, however, may not apply to all basins, and study of the deposits in each basin is necessary to determine the effectiveness of hydrologic change. Experimental studies and field observations suggest that on a regional basis both geomorphic and hydrologic factors contributed to sediment storage and decreased sediment yield. Arroyo evolution, a model described here for sequential channel deepening, widening, and partial refilling, probably affected sediment yield of tributary basins. According to this model, the widespread channel incision of the late 19th century resulted in high sediment yield, but yield has decreased during the period of record and especially in the early 1940s as incised channels evolved to a new aggrading condition.

Introduction

The evolution of landforms with time and their response to climatic change are important topics of geomorphologic research. Interest in these topics has been largely academic, but the current need to predict river and hillslope stability has created an incentive to document and understand recent, short-term (e.g. 50 years) landform adjustments. This has led to different explanations of channel incision, floodplain formation, and sediment-yield variation. At one extreme, these changes are thought to be inherent in arroyo evolution (Patton and Schumm, 1975, 1981; Womack and Schumm, 1977), whereas at the other, the changes are attributed to climatic change or fluctuations (Emmett, 1974; Leopold, 1976). Stream processes in semiarid regions, however, have wide spatial variation (Graf, 1982; 1987), and it is unlikely that a single explanation is appropriate to all streams. In this report, we suggest that understanding recent changes of channel morphology and sediment and salt loads in the Colorado River Basin involves multiple explanations.

The Colorado River (fig. 1) drains all of one and parts of four physiographic provinces: Colorado Plateau, Middle and Southern Rocky Mountains, Wyoming Basin, and Basin and Range (Graf, 1985). In this paper, we discuss the sediment yield of the Colorado Plateau, which is the principal sediment-producing region of the basin. Water from the Colorado River is used by more than 18 million people, and 69,000 hm^2 of agricultural land is irrigated with this water (U.S. Dept. Interior, 1987). The variety of demands on the water places great emphasis on its quantity and quality. In the Colorado River Basin, where vegetational cover is sparse, water quality is severely degraded from the erosion of salt bearing bedrock. This erosion produces large quantities of sediment and dissolved solids that significantly effect reservoir life, engineering structures, and channel stability. At Hoover Dam, the Colorado River transports annually 8.1 million tonnes of dissolved solids (salt). Almost half (47 percent) of the dissolved solids are contributed by natural diffuse sources (Jonez, 1984), and 84 percent of the natural sources are due to erosion of saline soils and marine shales (Blackman and others, 1973). In 1971, salinity at Imperial Dam was estimated at 865 mg/l, and by the year 2000 salinity is predicted to be 1340 mg/l (U.S. Bureau Land Management, 1978).

Water quality and quantity are complicated legal and economic issues. Seven states (Wyoming, Colorado, Utah, New Mexico, Arizona, Nevada, and California) each have water allotments of 16,000 hm^3 specified by law, and Mexico is allotted 1,850 hm^3 (Mann and others, 1974). Dissolved-solid loads are legislatively mandated at Hoover, Parker, and Imperial Dams at 723, 747, and 879 mg/l respectively, and the salt content of the water delivered to Mexico must be between 85 and 145 mg/l (Holburt, 1977). Dissolved-solid concentration increases downstream from about 90 mg/l at Hot Sulphur Springs, Colorado, to about 850 mg/l at Imperial Dam, Arizona (Kircher, 1984). In 1986 dollars, it cost approximately $610,200 to decrease total salt concentration by 1 mg/l, when concentration is in the range of 879 to 1225 mg/l at Imperial Dam.

During the early part of this century many channels in the Colorado Plateau portion of the Colorado River basin incised to form deep arroyos (Graf, 1985). This erosion delivered vast quantities of sediment and salt to the Colorado River. Between 1941 and 1944, however, sediment load decreased abruptly by 45-154 million tonnes/year at the Grand Canyon gaging station, but discharge did not change substantially. Associated with the decrease of sediment load was a decrease of salinity (Mueller and Moody, 1983; Moody and Mueller, 1984; Kircher, 1984).

If the causes of the decreased sediment and salt load were known, they could be used to evaluate sediment and salt-control techniques that have been proposed or that are in effect. The result would be more effective use of conservation funds and prevention of a return to the high sediment and salt loads of the early part of the century.

Alluvial History and Sediment Yield Since About 1880

The initiation of high sediment yield began in the late nineteenth century with arroyo cutting in many Colorado Plateau streams--streams that drain the principal sediment-producing region of the Colorado River Basin. The literature on this topic is large, and the causes of regional stream entrenchment are still not well understood (Cooke and Reeves, 1976; Graf, 1983). Although beginning dates vary regionally (Webb, 1985; Graf, 1987), from 1865-1915 hundreds of arroyos were incised in several states, in many drainages, and in a wide variety of environments (fig. 1). Valley floors were deeply incised with devastating effects on the fragile agricultural economy of the region, and many pioneer settlements and farms were abandoned.

Archeologic and geologic investigations show that widespread stream incision and subsequent channel filling have occurred several times in the late Holocene (Bryan, 1941; Hack, 1942; Cooley, 1962). Therefore, this modern episode of arroyo cutting and partial channel refilling has analogues in the recent geologic past.

The extent of arroyo cutting in these valleys was substantial. In 1849, Chaco River in northwest New Mexico was 2.4 m wide and 0.5 m deep. In 1925, the river was 46-137 m wide and 6-9 m deep (Bryan, 1925). Early reports indicate that arroyos incised rapidly and produced large amounts of sediment; for example, in three years (1885-1888) Kanab Creek, Utah formed a gully 18 m deep, 21 m wide, and 24 km long (Gregory, 1917). The channels in the Paria River basin of southern Utah were incised between 1883-1890 (Gregory and Moore, 1931).

In the early 1940s, sediment yield of the Colorado River Basin declined substantially, coincident with aggradation of floodplains in many tributaries (Hereford, 1987a). This aggradation has been reported by several workers for a number of stream channels throughout the Colorado River Basin (Emmett, 1974; Leopold, 1976; Hereford, 1984, 1986, 1987a; Graf, 1987). The sedimentology of the floodplain deposits indicates that sediment was deposited by vertical rather than lateral accretionary processes, suggesting that sediment was stored in channels, rather than moved laterally (Hereford, 1984).

Large quantities of sediment were stored in stream channels during floodplain aggradation. Geologic mapping shows that in the Paria River basin, about 40 million m^3 of sediment having an area of 20 km^2 accumulated between about 1940 and 1980 (Hereford, 1987b). Substantial changes in width and depth occurred because of sediment storage and floodplain development. The Little Colorado River at Cameron, Arizona was a broad, braided stream in 1914; presently, the channel is confined, has a well vegetated floodplain, and is only 50 percent of its earlier width (fig. 2). Abundant photograph evidence, such as figure 2, indicates clearly that sediment has accumulated in tributaries of the Colorado River (Graf, 1987; Hereford, 1984, 1986,1987a).

Temporal Variation of Suspended Sediment and Salt Load

Suspended Sediment

Data were assembled on sediment and dissolved solids loads in the Colorado River Basin to determine the nature, magnitude, and timing of changes in salt and suspended-sediment load. Suspended sediment is the sediment that at any given time is either maintained in suspension by the upward component of turbulent currents or sediment that exists in suspension as a colloid. Suspended-sediment loads and water discharge data were retrieved from the U.S. Geological Survey WATSTORE (Hutchinson, 1975) hydrologic database. Because of the limited number of stations that obtain daily suspended-sediment records and the numerous short or discontinuous records, data from four stations with records of about 55 years each were studied most extensively (fig. 1; stations 3, 10, 13, 17; fig. 3). These stations record the sediment load and discharge of the principal tributaries of the Colorado River, except the Little Colorado and Paria Rivers. Data for these tributaries and adjoining areas were estimated by subtracting the sediment load and discharge of the Green River at Green River Utah, Colorado River near Cisco, Utah, San Juan River near Bluff, Utah from sediment load and discharge of the Colorado River near Grand Canyon (fig. 1), this provides an estimate of sediment yield from a major sediment producing region of the Colorado River basin, referred to as the 'Plateau Country'(fig. 3E).

Mean annual suspended-sediment load (megagrams/day) decreased substantially in the early 1940s at the four stations (Table 1), although the decrease is not clearly defined until the late 1940s to early 1950s in the Little Colorado and Paria River basins (fig. 3e). Water discharge, however, did not decrease, except in the Paria and Little Colorado River basins. The water and sediment-retaining effect of dams built in the Colorado River Basin during the early 1960s is also apparent in figure 3a, which shows reduced runoff and sediment load of the Colorado River near Grand Canyon. Flaming Gorge reservoir on Green River became operational in 1962 (Andrews 1986) as did Glen Canyon Dam on the Colorado River in 1963. After the early 1960s, therefore, sediment load and runoff shown in figure 3 do not reflect natural conditions in the drainage basin. Table 1 is a summary of average suspended-sediment loads and average water discharges at the four stations. Selected time periods were based on significant changes in sediment loads, during the early 1940's and in 1963. Substantial decreases in the average sediment load occur at the early 1940's. The Colorado River near Cisco decreased it's average load by 52 percent, the Green River at Green River decreased 38 percent, the San Juan River near Bluff decreased 60 percent, and the Colorado River near Grand Canyon decreased 44 percent. Reservoir construction in 1963 greatly affected sediment loads at the Colorado River near Grand Canyon but was negligible at upstream sites (Table 1).

To account for discharge variations, the suspended sediment data of figure 3 was normalized by dividing sediment load by discharge. The results show a striking decrease in normalized sediment load beginning in the late 1930s or early 1940s at the four stations (fig. 4).

Dissolved Solids

Several studies have found that dissolved-solid load is decreasing in much of the Colorado River basin (Moody and Mueller, 1984; Kircher, 1984). The decrease is not as large as the decrease of sediment load, nevertheless, it appears to be significant, as illustrated in figure 5. Moreover, fourteen of the 20 salinity sampling stations in the Colorado River Basin have decreasing dissolved-solid load (U.S. Department Interior, 1987), and Kircher (1984) found a decrease in dissolved-solid load at 20 of 26 stations. The large salinity increase after 1980 (fig. 5) probably resulted from the period of high runoff in the early 1980s.

Other studies support our conclusion that reduced salinity is probably associated with the decline in sediment load. Nezafati and others (1981) found that the dissolved load increases as the suspended and bedloads increase, and Jackson and others (1984) demonstrated that salt release by erosion is 3.8 percent of sediment load. Salt production, therefore, varies directly with runoff and erosion. Decreased salt load (fig. 5) is at least partly related to decreased sediment load (figs. 3, 4), which in turn is related to reduced sediment production and sediment storage in tributary channels.

In summary, the suspended-sediment and dissolved-solid load in the Colorado River basin decreased from 1940 to 1980 at most stations, although discharge remained relatively constant. The percentage change is much less for dissolved-solid load than for suspended sediment; nevertheless, the similarity in timing suggests that the two are related.

Possible Causes of Reduced Salinity and Sediment Load

Previous studies have put forth three explanations of reduced Colorado River sediment load since the early 1940s. Generally, these explanations attribute reduced sediment load to 1) a change of sampling procedures by the U.S. Geological Survey in the early 1940s (Thompson, 1982), 2) hydrologic change in the major sediment-producing areas of the drainage basin (Thomas, 1962; Hereford, 1984, 1986, 1987a; Graf, 1986), or 3) to improved land use through a major reduction in livestock numbers and erosion control (Hadley, 1974, 1977). In this paper, we suggest a fourth explanation of reduced sediment load that combines elements of the hydrologic explanation with arroyo evolution--an intrinsic process of channel incision and widening leading to floodplain sediment storage.

Sampling Procedures

Before the early 1940s, field techniques for obtaining suspended-sediment samples were inexact and varied throughout the United States. A committee was established in 1939 to investigate the matter, and a standard sampler was designed (U.S. D-43) and put into use in the 1940s. Comparative tests (U.S. Interagency Committee on Water Resources, 1944) of the U.S. D-43 and the old Colorado River Sampler indicate that the new sampler gave 16 percent higher suspended-sediment concentrations (Table 2). Thus, sediment load after introduction of the U.S. D-43 sampler should have been higher rather than lower. Moreover, a significant decrease in suspended-sediment load occurred in 1942 at the San Juan River at Bluff, Utah (Figs. 3D, 4D), but the sampler was not changed at this station until May 1, 1944 (Thompson, 1982). We conclude that decreased suspended sediment in the early 1940s probably cannot be related to a change in sampling methods.

Hydrologic Change

The decreased sediment load partly reflects a climate fluctuation or change that altered flood regimen. In two gaged tributary basins, a period of low peak flows in the 1940s to mid-1950s was coincident with the beginning of sediment storage. Hereford (1984; 1986) showed that flood-plain development and sediment storage in the Paria River basin and lower Little Colorado River resulted from low peak flows and below-normal average annual precipitation. These low flows enabled vegetation to colonize channel floors, thereby promoting vertical accretion and aggradation, which in turn reduced sediment delivery to the Colorado River. This is a reasonable explanation for increased sediment storage in these basins, because similar channel response to reduced peak flood peaks has been documented for Cimarron River in Kansas and for North and South Platte Rivers (Schumm and Lichty, 1963; Schumm, 1977, p. 159-164).

It is possible, however, that peak flows can be attenuated by arroyo evolution or the morphologic changes in ephemeral streams through time. As the incised channels widen, aggrade, and form mature floodplains, overbank flooding and backwater effects reduce the peak discharge. Burkham (1976) and Walling et. al. (1986) showed that formation of floodplains induces overbank flooding and decreases peak discharges and causes sediment deposition. In addition floodplain vegetation increases the hydraulic roughness (n) of the channel, which decreases velocity and floodpeak discharges.

Land-Management Practices

Significant decreases in grazing pressures and improved land use may have partly decreased sediment yield (Hadley, 1977). Between 1941 and 1955 the number of sheep and goats in parts of the Colorado River Basin was reduced by nearly 750,000, and thousands of small reservoirs and erosion-control structures were built. In much of the Little Colorado River basin, however, the number of sheep actually increased by a factor of three between the mid-1950s and 1979 (Reno, 1981, p. 32). Moreover, Graf (1986) found that variations of the Palmer Drought Index accounted for 38 to 66 percent of the variability of water and sediment yield of the Little Colorado and San Juan Rivers between 1930-1960. Stocking levels, however, accounted for only 1 to 5 percent of water and sediment yield in in the same period.

The effect of small reservoirs and erosion-control structures on the sediment and salt load of major tributaries such as the San Juan, Green, and Colorado Rivers is difficult to evaluate. These structures are designed to retain sediment and reduce peak flows (Lusby, 1970); thus some reduction of sediment loads in the large rivers can be expected, but the effect of the structures would decrease rapidly downstream because channel scour and bank failure will replace the sediment that is stored in the stored in the reservoirs.

Arroyo Evolution Model

Recent field and experimental investigations suggest a geomorphic reason for the decreased sediment yield in those channels lacking bedrock control of longitudinal gradient. Following a period of channel incision and subsequent high sediment production, a progressive decrease of sediment yield occurs because incised channels widen and produce less sediment. They become less efficient at transporting sediment (Schumm and others, 1987), and sediment is stored in floodplains that develop after the channels widen (Schumm and others, 1984). This geomorphic explanation implies that sediment yield might have been steadily declining before the early 1940s and that the abrupt decrease in the 1940s (fig. 3) recognized by Thomas (1962) was the result of a hydrologic change that was imposed on a system that was already changing.

Arroyo evolution can be described by using a "location-for-time" substitution (Paine, 1985). When erosion begins in an alluvial valley, downstream locations will be affected first as erosion proceeds upstream. Thus, the first evolutionary stage is the farthest downstream, and the last stage is the farthest upstream. Therefore, a comparison of different channel reaches provides a temporal record of channel change, a record that can be used to predict changes at a single cross-section through time (Schumm and others, 1987).

Figure 6 illustrates the five-stage arroyo evolution model applied to the post-1880 alluvial stratigraphy of Colorado River tributary streams as described by Hereford (1987a). Stages 1, 2, and 3 consist primarily of channel incision and widening after about 1880. The stratigraphic record of these events is poorly preserved, although a relatively thin, coarse-grained channel sand deposit called the "older channel alluvium" is present locally. Stage 4, from about 1940 to 1960, is the beginning of sediment storage and floodplain development. During this time a thin, widespread unit called the "basal and intermediate units" was deposited. Stage 5, lasting from about 1960 to 1980, was characterized by channel stability, sediment storage, and extensive floodplain aggradation. During this time the "upper unit" of the floodplain alluvium was deposited. This is the thickest of the floodplain stratigraphic units. However, it should be noted that only the lower reaches of most arroyos have evolved to stages 4 and 5 (fig. 6). Upstream reaches are still in stages 1 and 2.

Artificially straightened and deepened channels in the southeast United States document the morphologic and hydraulic changes that occur during channel incision (Harvey et al., 1987). For example, the channel of Hotopha Creek in Mississippi was deepened and straightened in 1961 in order to reduce the frequency of overbank flooding. Table 3 and figure 6 show average channel and sediment load characteristics at each stage of development. Stage 1 is the initial stage of incision after channelization. The steepened gradient and confining of previously overbank flood waters in the incised channel caused further incision (stage 2), bank collapse, and channel widening (stage 3). The result was a large increase in sediment load, which was deposited as the channel widened, increasing bank stability (stage 4). Stage 5 was reached after formation of an inner channel and vegetative colonization of the recently deposited sediment, and sediment loads decreased significantly. In this region of high annual precipitation (1270 mm/yr), channel evolution (fig. 6) took place in less than 30 years.

Studies of channelized streams in Tennessee confirm this change of sediment yield with time (Simon, 1989). Sediment load of the South Fork Obion River increased progressively from 45 tonnes/day before channelization (1958-65) to 566 tonnes/day immediately following incision (stages 2 and 3, 1966-70). In contrast, sediment load decreased to 250 tonnes/day as the channel adjusted (1977-85) to stage 5. These artificially straightened channels demonstrate that channel evolution occurs independently of local climate, climatic change, or other extrinsic factors.

In the southwest United States, the Rio Puerco, a tributary of the Rio Grande, has a history of sediment production and channel evolution similar to the channelized streams. Suspended-sediment load of Rio Puerco has decreased since 1947, contemporaneous with Colorado River Basin streams (fig. 3). Bryan and Post (1927) calculated that 490 hm^3 of sediment was transported out of the Rio Puerco valley between 1887 and 1928: in 42 years an annual average of 12 hm^3, or 30 million tonnes, of sediment was eroded. During the period 1948-1968, however, annual sediment load was only 5.4 million tonnes. There is deposition and floodplain formation in the Rio Puerco arroyo, which provides evidence of a major decrease in sediment load passing through the system, as channel evolution progresses.

Field and Experimental Studies of Arroyo Evolution

A geomorphic study in Dinnebito and Oraibi Washes of northern Arizona documents channel evolution in a portion of the Colorado River basin (Gellis ,1988). Channel cross sections were surveyed along Dinnebito Wash and Oraibi Wash in northern Arizona (fig. 7). Upstream arroyo reaches (fig. 8) are characterized by steep walls with straight confined channels that are actively widening. Large quantities of sediment derived from upstream tributaries and from the collapse of arroyo walls increase sediment supply to the main channel causing the channel to braid and shift laterally, which further widens the channel. Vegetation on the incipient floodplains is scarce, and it is periodically removed by high flows.

Middle arroyo reaches (fig. 8b) have high steep walls that confine a sinuous channel that is actively constructing point bars and a floodplain. Vegetation colonizes these deposits and dense stands of salt cedar occur on the point bars and floodplains.

Lower reaches (fig. 8C) represent the highest stage of maturity in arroyo evolution, which is characterized by high width-depth ratios and a densely vegetated floodplain with gently sloping channel banks. The changes in the morphology of these channels resemble the incised channel evolution model illustrated in figure 6.

Experimental studies of drainage network evolution also provide information on sediment production through time (Schumm and others, 1987). Channel incision and base level lowering were induced in an experimental drainage basin by removing a board at the outlet of a 10 by 15 m rainfall-erosion facility. Lowering of baselevel is analogous, in a highly generalized manner, to the beginning of arroyo incision in the Colorado Plateau. Figure 9A shows the change of sediment load with time. Baselevel lowering and subsequent channel incision produced high sediment load as the channels incised and widened, but a rapid decrease followed as channels stabilized and sediment was stored in the channels. As a result, sediment load varied considerably while the system adjusted to a new equilibrium. Nevertheless, following an initial maximum, sediment load decreased logarithmically

$$Qs = 850\ V^{-0.86}.$$

Qs is sediment discharge (g/sec) and V is the volume of rainfall (m^3) applied to the surface of the drainage basin. During other experiments, sediment discharge decreased with time even without baselevel lowering, as the drainage network grew and stabilized. The empirical relation for this second case is

$$Qs = 78\ V^{-0.15}.$$

Similar results were obtained by Begin (Begin and others, 1980) during an experimental study of channel incision (fig. 9b). These workers created an incised channel by lowering baselevel at the outlet of a large flume. The immediate result was a dramatic increase in sediment leaving the flume. This high sediment load reflected nickpoint recession, channel bed degradation, and bank failure. During the 700 minutes of the experiment, sediment load decreased logarithmically from a maximum during the first few minutes of channel incision giving the empirical relation

$$Qs = 135t^{-0.48}.$$

Qs is sediment discharge (g/sec) and t is time since lowering of baselevel. This logarithmic decrease of sediment yield might well replicate the change of sediment yield in the incised channels of the Colorado Plateau. These experimental results, however, cannot be compared directly to small tributaries of the Colorado River because sediment discharge records are not available for any of these tributaries before 1948. Nonetheless, the experiments indicate that following baselevel lowering sediment production will be very high as the channel rapidly incises, but sediment yield will decrease as the system adjusts to a condition of relative stability. Moreover, sediment loads will be highly variable during the period of incised channel evolution, as shown in figure 9.

Discussion

The relative importance of hydrologic variations and arroyo evolution on decreased Colorado River Basin sediment yield needs to be addressed. Climatically induced hydrologic variations should affect the entire Colorado River basin, but local factors such as size, shape, and bedrock lithology may dominate in a specific basin. In this case, channels probably respond largely to arroyo evolutionary processes. On the other hand, a channel system might respond entirely to hydrologic variations if geomorphic controls are ineffective. In still other basins, a combination of evolutionary and hydrologic controls may dominate such that a hydrologic change may enhance sediment storage or increase the evolutionary rate.

The stratigraphic record of floodplain sedimentation provides a means of evaluating the effectiveness of arroyo evolution on the development of a particular channel system. Floodplain deposits should become younger upstream as sediment storage sites shift progressively upstream; specifically, the deposits will be time-transgressive in the upstream direction. Only two studies have addressed the time-stratigraphy of floodplain alluvium, and it was found that the alluvium was not time transgressive (Hereford, 1984; 1986). The implication is that arroyo evolution was ineffective in the Paria River basin and Little Colorado River valley. However, a large portion of the Paria River is confined in a bedrock channel and the Little Colorado River study was confined to downstream reaches. Although the downstream reaches of the Little Colorado River have evolved to stages 4 and 5, the upstream reaches near Gallup, New Mexico are still in stage 2.

Conclusions and Applications

Many of the deeply incised arroyos that developed in the Southwest during the latter part of the 19th century may have followed an evolutionary pattern similar to that observed in experimental studies and in artificially channelized streams of the southeastern United States. During channel evolution sediment production, which was initially high due to incision and bank erosion, decreased because of reduced erosion and sediment storage in the widened channels. In the Colorado River basin, this intrinsic evolution, and a hydrologic change in the early 1940s to smaller peak floods in tributary streams triggered sediment storage and floodplain development, which in turn decreased significantly sediment yield of the Colorado River and its principal tributaries.

This decrease in sediment yield is generally thought to have resulted from either a change in sediment samplers, improved land use and conservation measures, climate and hydrologic changes, or arroyo evolutionary processes. The decrease probably was not caused by a change in sediment samplers because the replacement sediment sampler introduced in the early 1940s gave higher sediment concentrations than did the earlier model. Thus, basin-sediment yield should have increased after the early 1940s rather than decreased.

Decreased grazing intensity and numerous soil conservation works were locally effective, but the influence on total sediment and salt production in the Colorado River system is unknown. Nevertheless, it seems unlikely that decreased sediment and salinity were totally the result of human activity.

Hydrologic change and arroyo evolutionary processes emerge as the two principal factors responsible for reduced Colorado River sediment yield and salinity. At present, however, it is not possible to determine whether climate or intrinsic evolutionary processes were dominant, or whether some combination of the two prevailed. Nevertheless, a reasonable explanation of reduced sediment yield involves climatically induced hydrologic change altering a naturally evolving channel system. The effect of hydrologic change was to permit vegetational colonization and floodplain formation, which increased sediment storage in a system that had evolved to the point of intrinsic sediment storage.

The results of this study may have important practical applications. The regional picture developed here of drainage basin response to arroyo evolution and hydrologic change can be used to develop new methods of sediment and salt control for the Colorado River Basin and other semiarid regions. Specifically, the recently deposited floodplain sediment should be protected from renewed channel erosion, which can be prevented if channel stabilization techniques are employed. Grade-control structures, when placed at critical sites will prevent renewed channel incision and maintain sediment storage. These techniques have been successfully employed in the incised channels of the southeast (Schumm and others, 1984) and elsewhere. Even if a further decrease of sediment and salt production cannot be achieved, an increase to the former high sediment and salinity levels can be prevented if the emphasis of conservation efforts is changed from upland control to control of channel-sediment storage sites.

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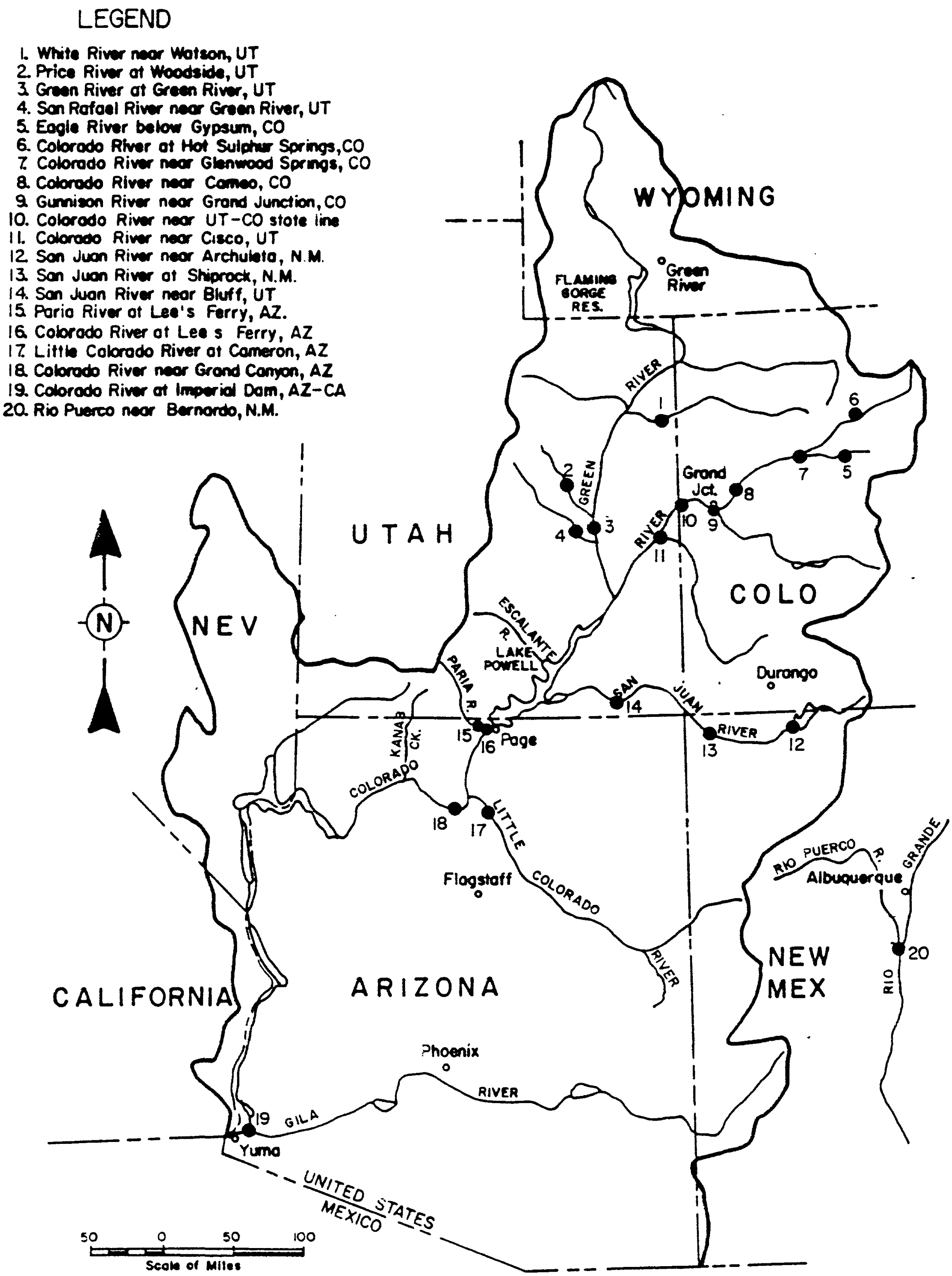
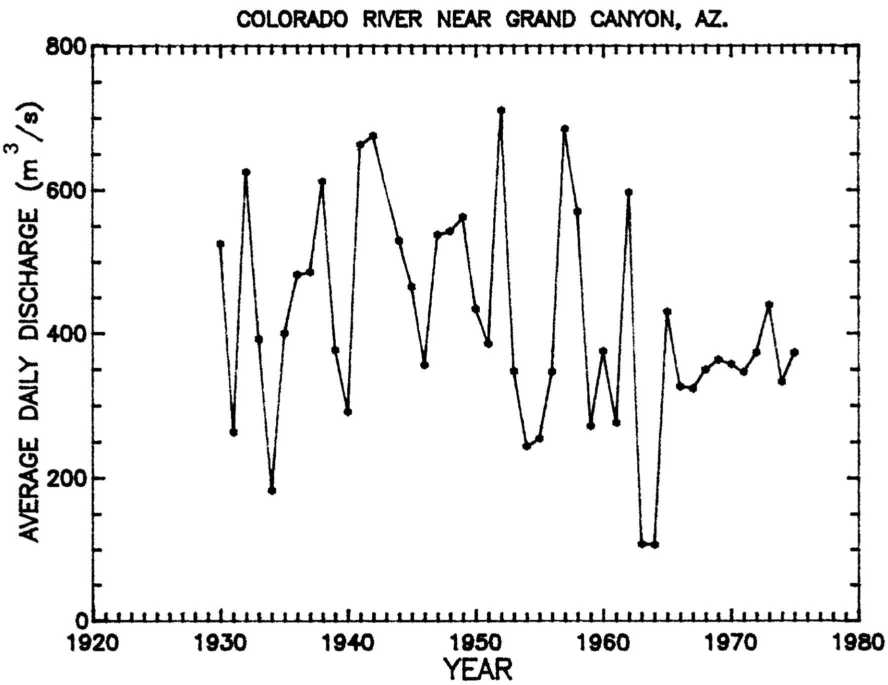

LEGEND
1. White River near Watson, UT
2. Price River at Woodside, UT
3. Green River at Green River, UT
4. San Rafael River near Green River, UT
5. Eagle River below Gypsum, CO
6. Colorado River at Hot Sulphur Springs, CO
7. Colorado River near Glenwood Springs, CO
8. Colorado River near Cameo, CO
9. Gunnison River near Grand Junction, CO
10. Colorado River near UT-CO state line
11. Colorado River near Cisco, UT
12. San Juan River near Archuleta, N.M.
13. San Juan River at Shiprock, N.M.
14. San Juan River near Bluff, UT
15. Paria River at Lee's Ferry, AZ.
16. Colorado River at Lee s Ferry, AZ
17. Little Colorado River at Cameron, AZ
18. Colorado River near Grand Canyon, AZ
19. Colorado River at Imperial Dam, AZ-CA
20. Rio Puerco near Bernardo, N.M.
WYOMING
Green River
FLAMING GORGE RES.
UTAH
COLO
NEV
CALIFORNIA
ARIZONA
NEW MEX
N
GREEN RIVER
Grand Jct.
ESCALANTE R.
LAKE POWELL
PARIA R.
SAN JUAN RIVER
Durango
Page
KANAB CK.
COLORADO
LITTLE COLORADO RIVER
Flagstaff
RIO PUERCO R.
RIO GRANDE
Albuquerque
Phoenix
GILA RIVER
Yuma
UNITED STATES
MEXICO
50 0 50 100
Scale of Miles

Figure 1

A

B

Figure 2


COLORADO RIVER NEAR GRAND CANYON, AZ.
AVERAGE DAILY DISCHARGE (m^3/s)
0
200
400
600
800
1920
1930
1940
1950
1960
1970
1980
YEAR

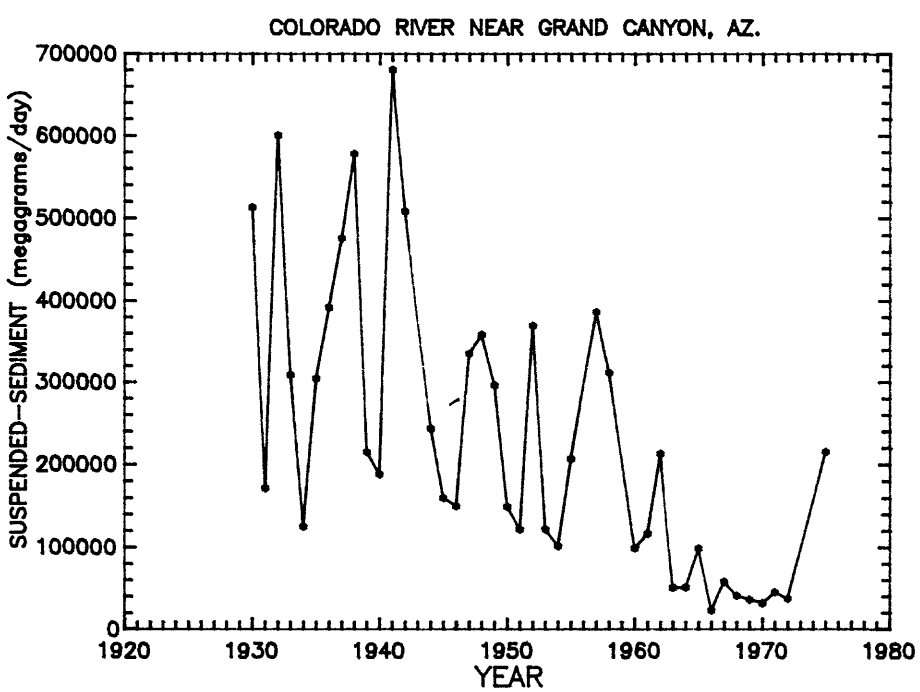
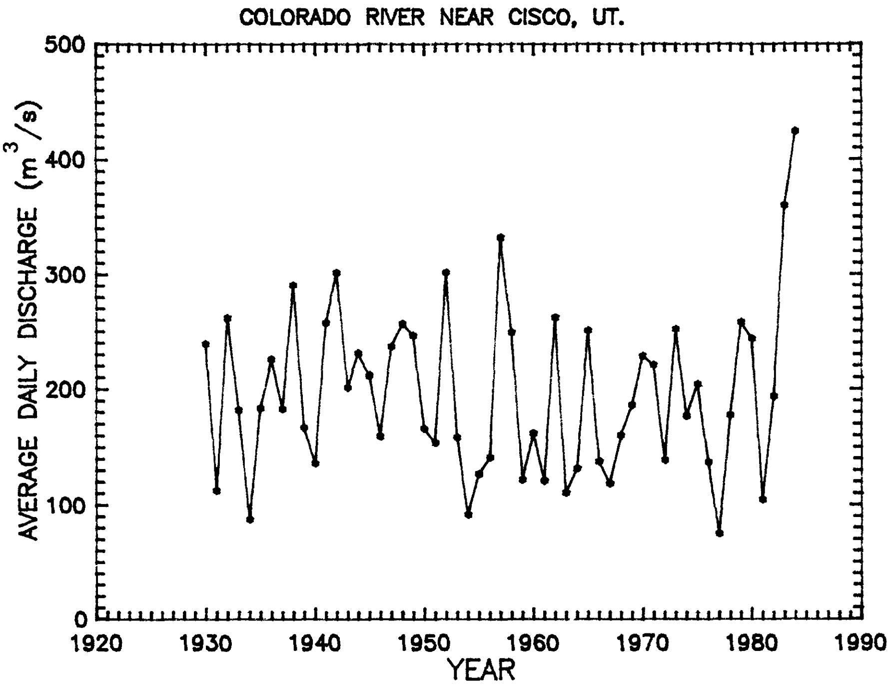

COLORADO RIVER NEAR GRAND CANYON, AZ.
SUSPENDED-SEDIMENT (megagrams/day)
0
100000
200000
300000
400000
500000
600000
700000
1920
1930
1940
1950
1960
1970
1980
YEAR

Figure 3A


COLORADO RIVER NEAR CISCO, UT.
AVERAGE DAILY DISCHARGE (m³/s)
500
400
300
200
100
0
1920
1930
1940
1950
1960
1970
1980
1990
YEAR

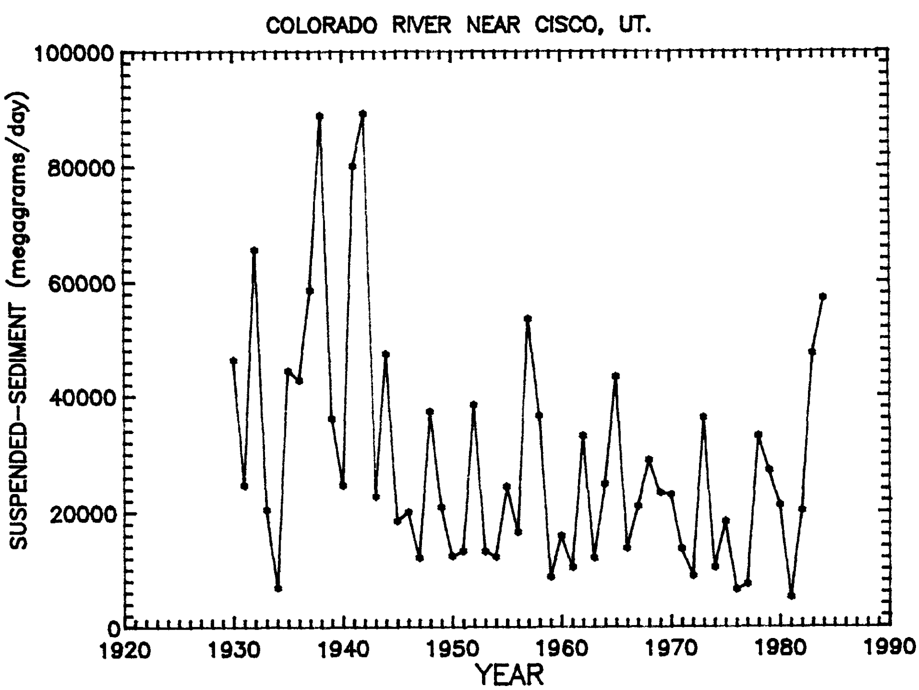
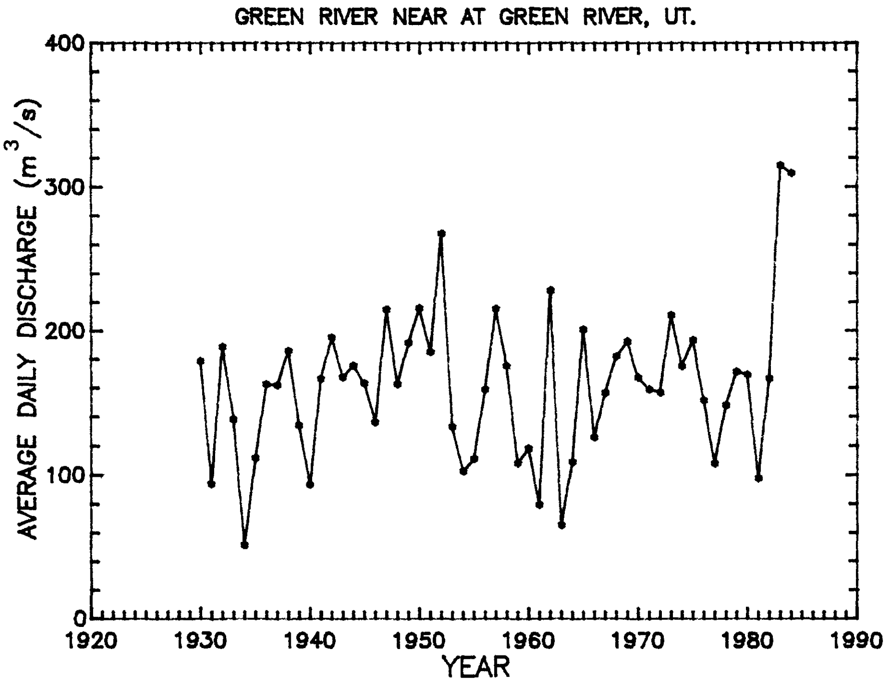

COLORADO RIVER NEAR CISCO, UT.
SUSPENDED-SEDIMENT (megagrams/day)
100000
80000
60000
40000
20000
0
1920
1930
1940
1950
1960
1970
1980
1990
YEAR

Figure 3B


GREEN RIVER NEAR AT GREEN RIVER, UT.
AVERAGE DAILY DISCHARGE (m^3/s)
400
300
200
100
0
1920
1930
1940
1950
1960
1970
1980
1990
YEAR

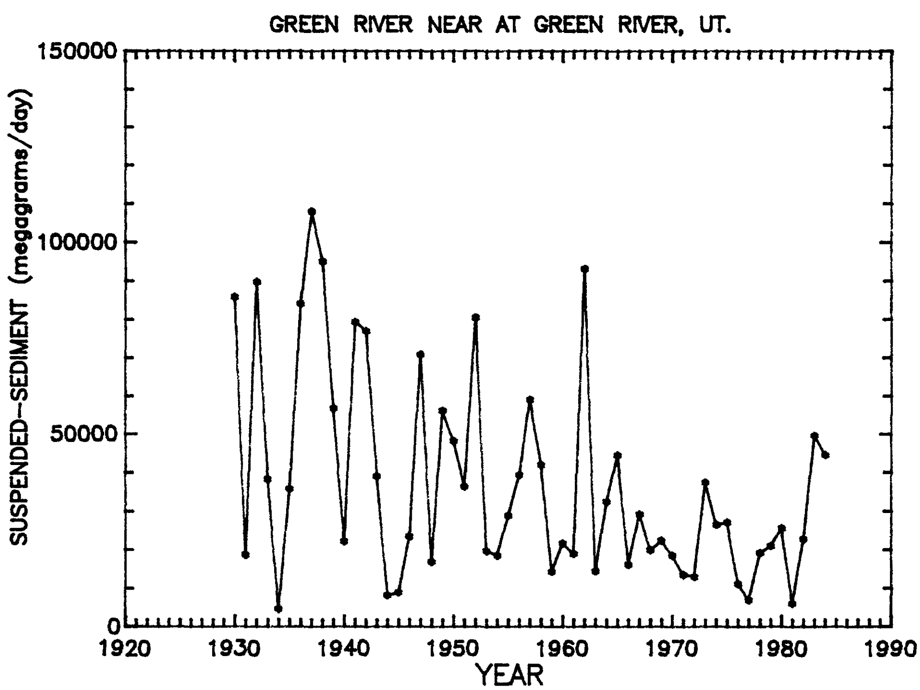
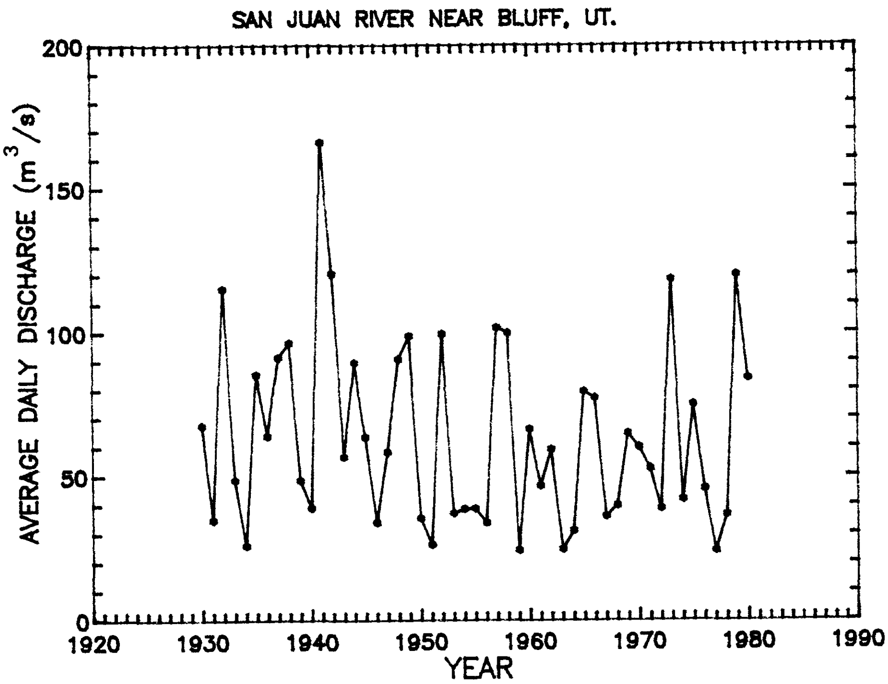

GREEN RIVER NEAR AT GREEN RIVER, UT.
SUSPENDED-SEDIMENT (megagrams/day)
150000
100000
50000
0
1920
1930
1940
1950
1960
1970
1980
1990
YEAR

Figure 3C


SAN JUAN RIVER NEAR BLUFF, UT.
AVERAGE DAILY DISCHARGE (m^3/s)
200
150
100
50
0
1920
1930
1940
1950
1960
1970
1980
1990
YEAR

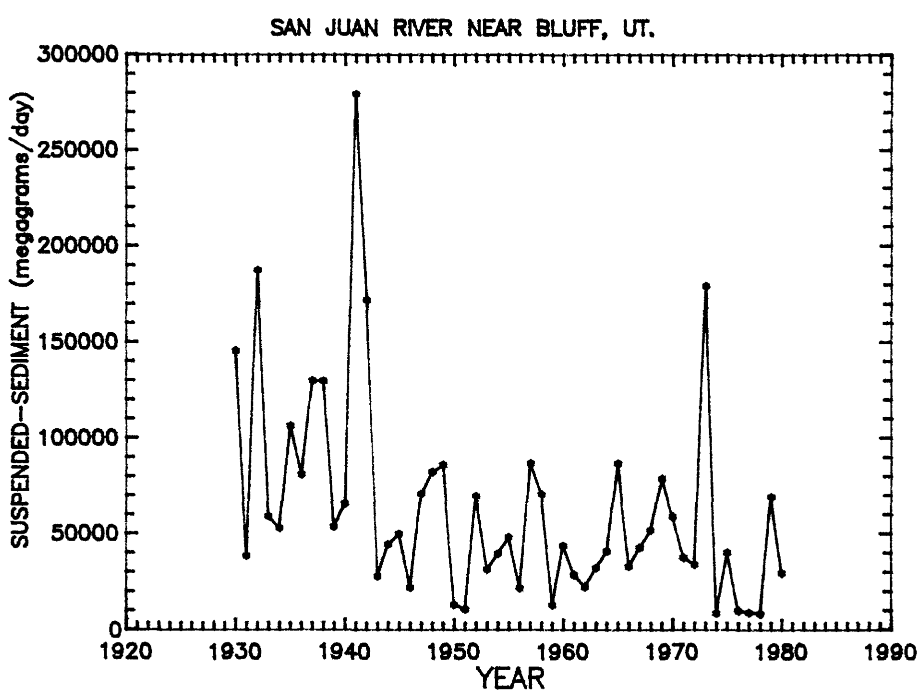
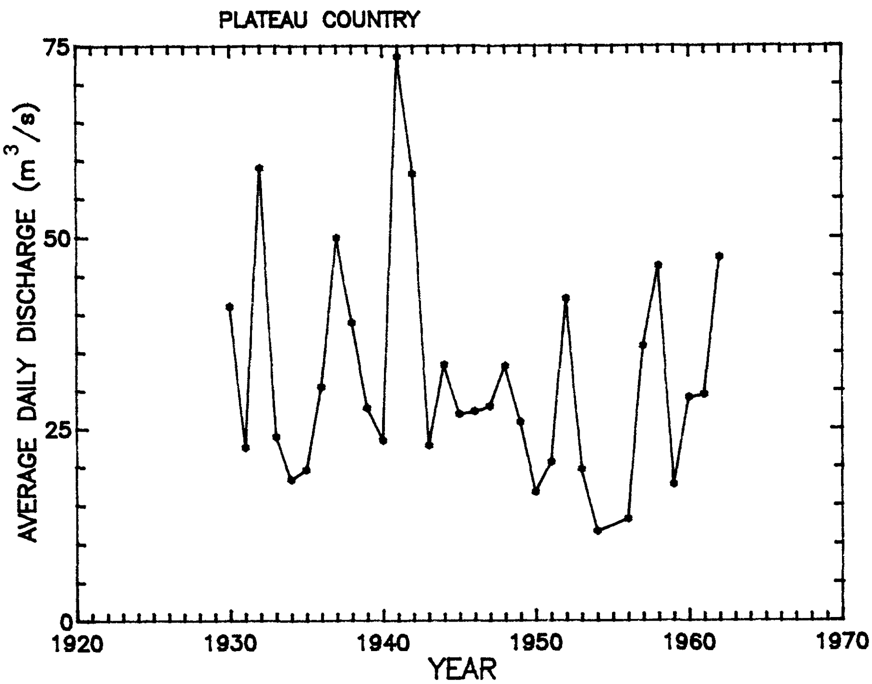

SAN JUAN RIVER NEAR BLUFF, UT.
SUSPENDED-SEDIMENT (megagrams/day)
300000
250000
200000
150000
100000
50000
0
1920
1930
1940
1950
1960
1970
1980
1990
YEAR

Figure 3D


PLATEAU COUNTRY
AVERAGE DAILY DISCHARGE (m^3/s)
75
50
25
0
1920
1930
1940
1950
1960
1970
YEAR

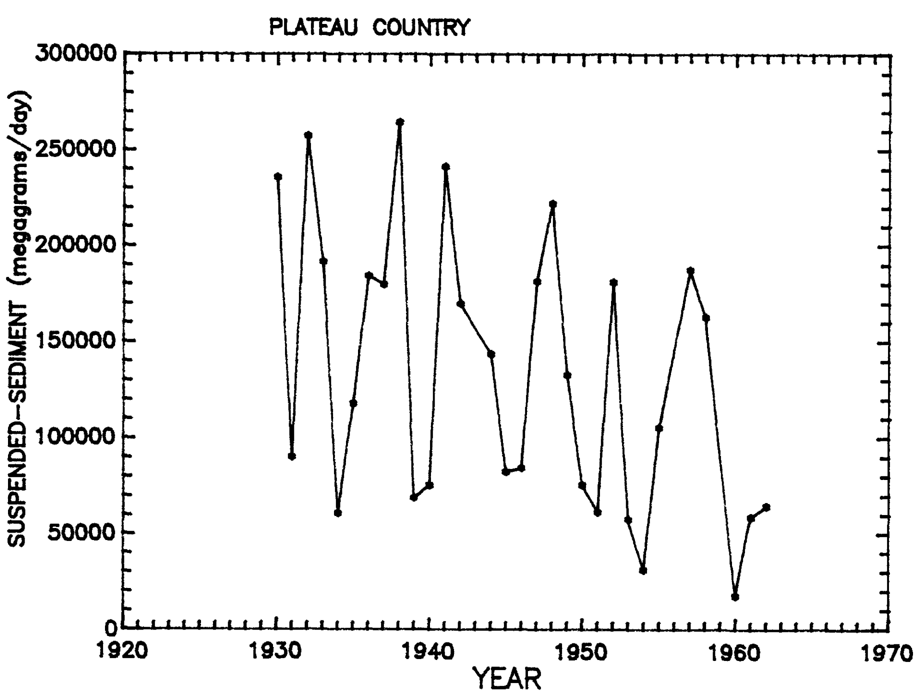
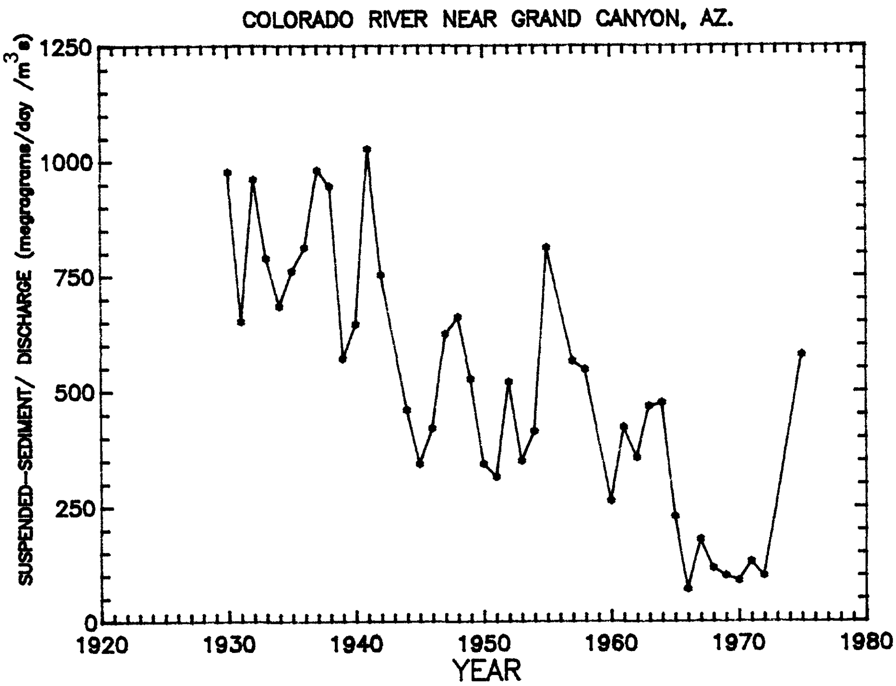
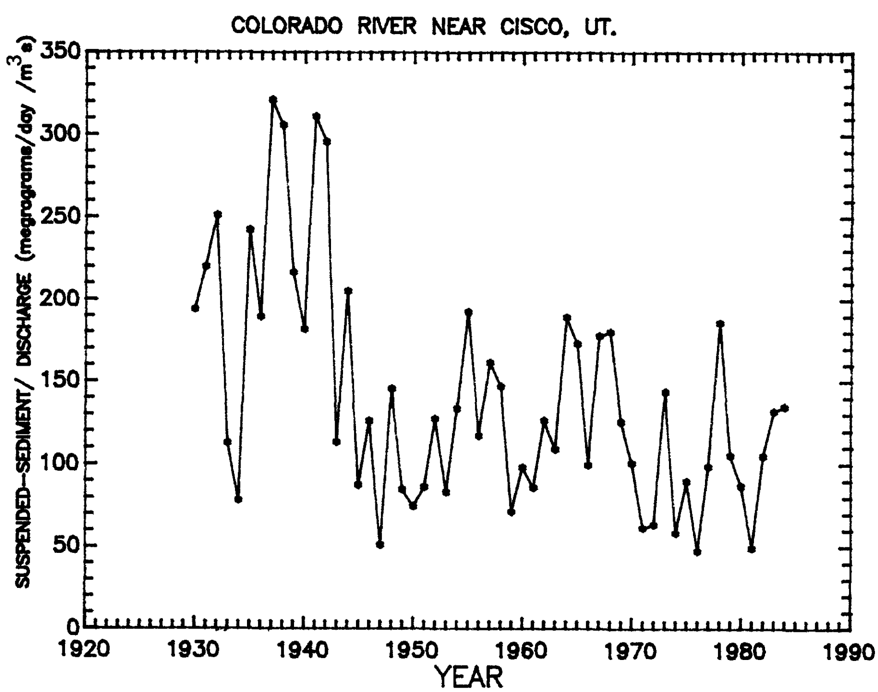

PLATEAU COUNTRY
SUSPENDED-SEDIMENT (megagrams/day)
300000
250000
200000
150000
100000
50000
0
1920
1930
1940
1950
1960
1970
YEAR

Figure 3E

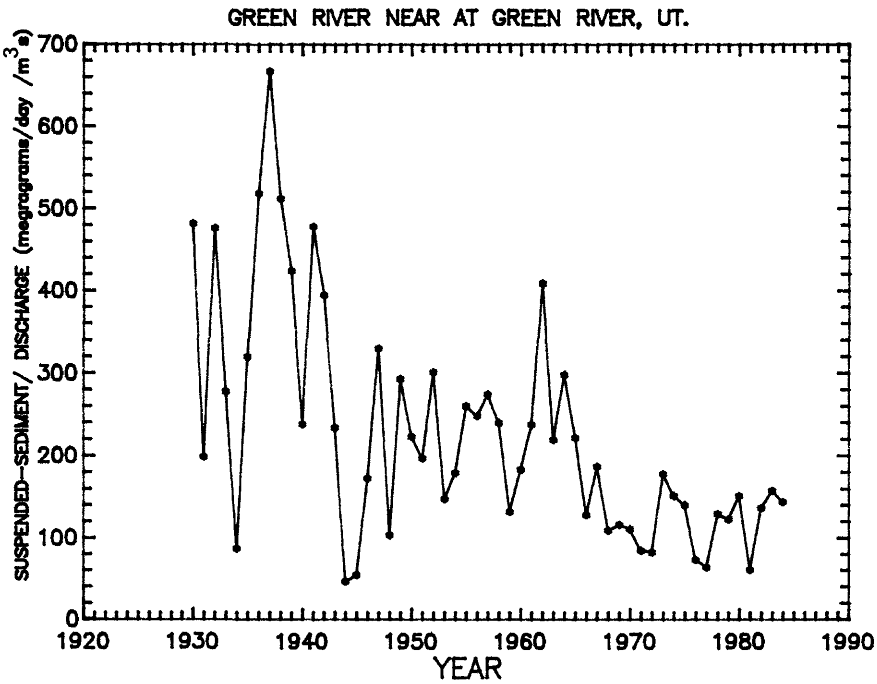


A

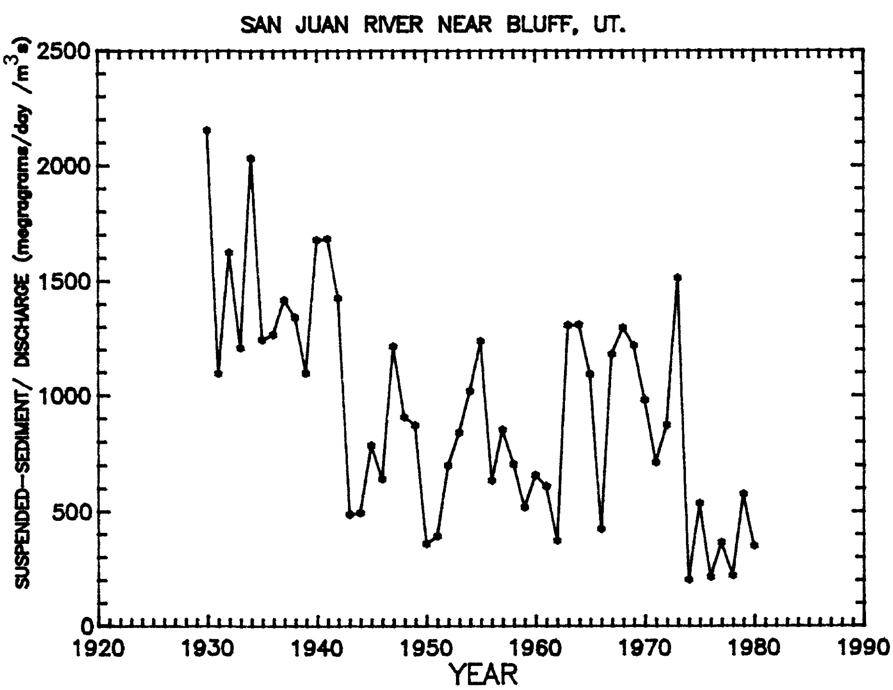


B

Figure 4 A & B



C



D

Figure 4 C & D

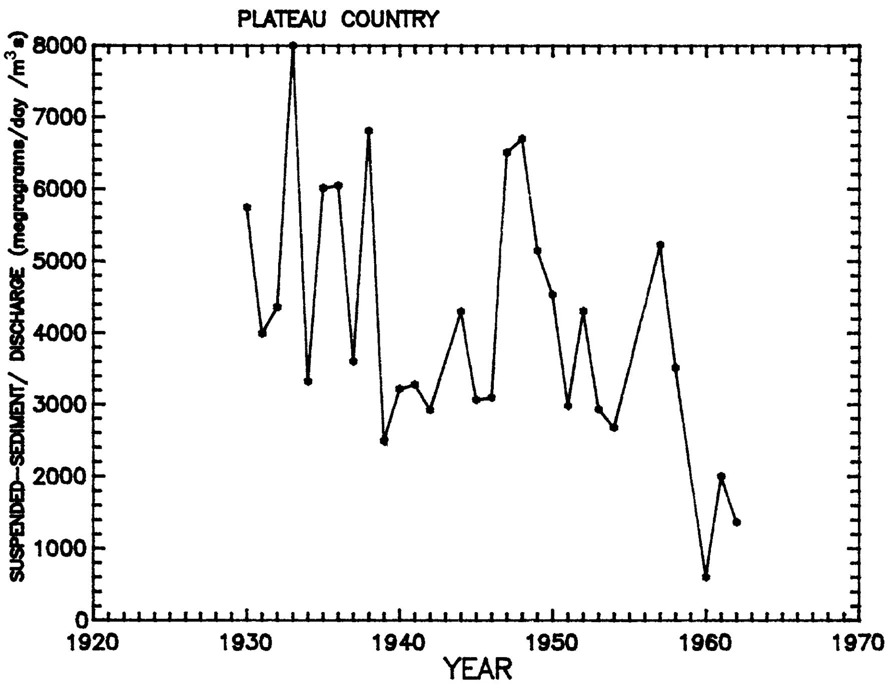
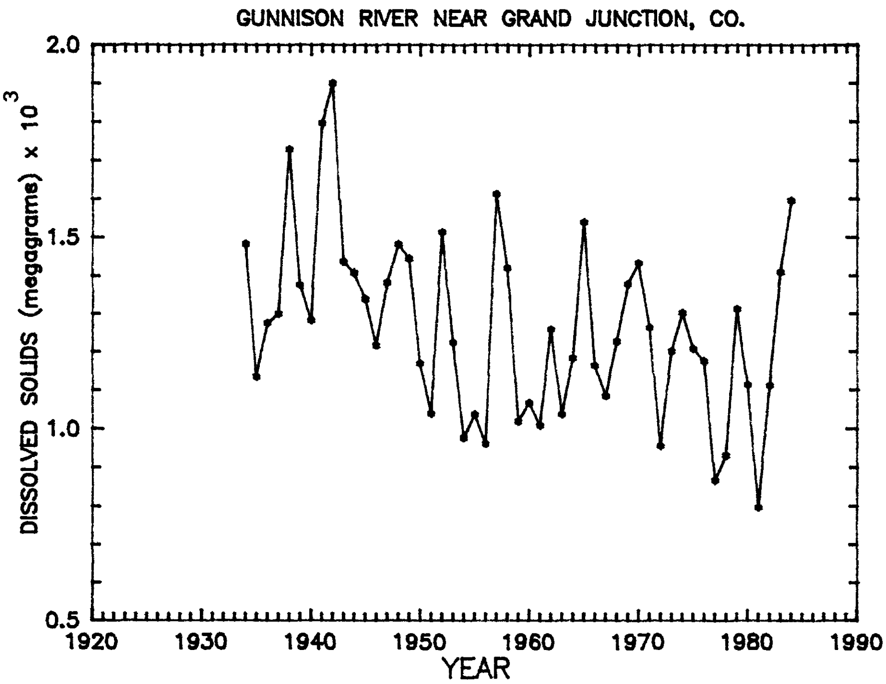
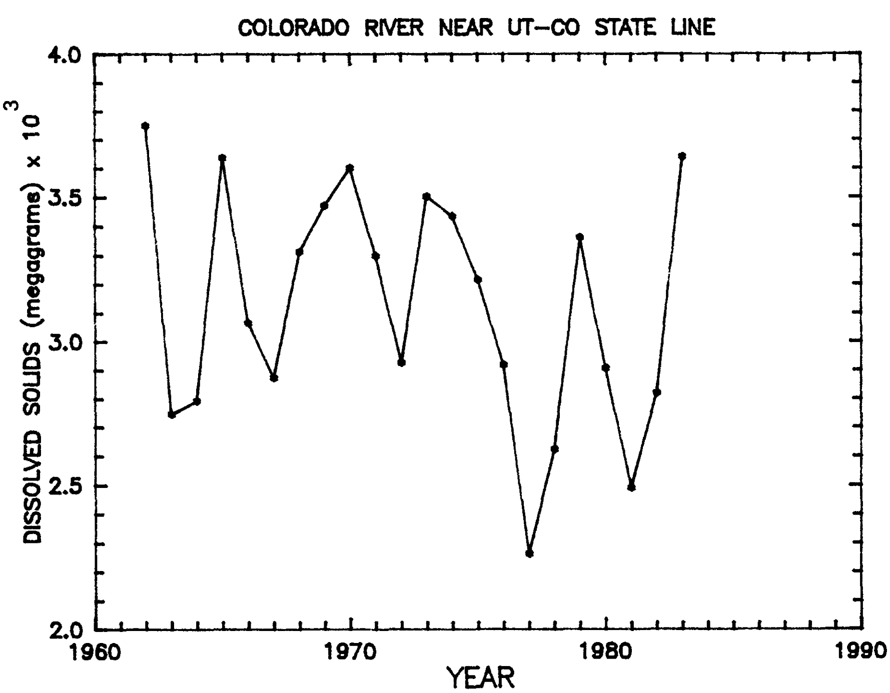

PLATEAU COUNTRY
SUSPENDED-SEDIMENT/ DISCHARGE (megragrams/day /m3 s)
8000
7000
6000
5000
4000
3000
2000
1000
0
1920
1930
1940
1950
1960
1970
YEAR

Figure 4E

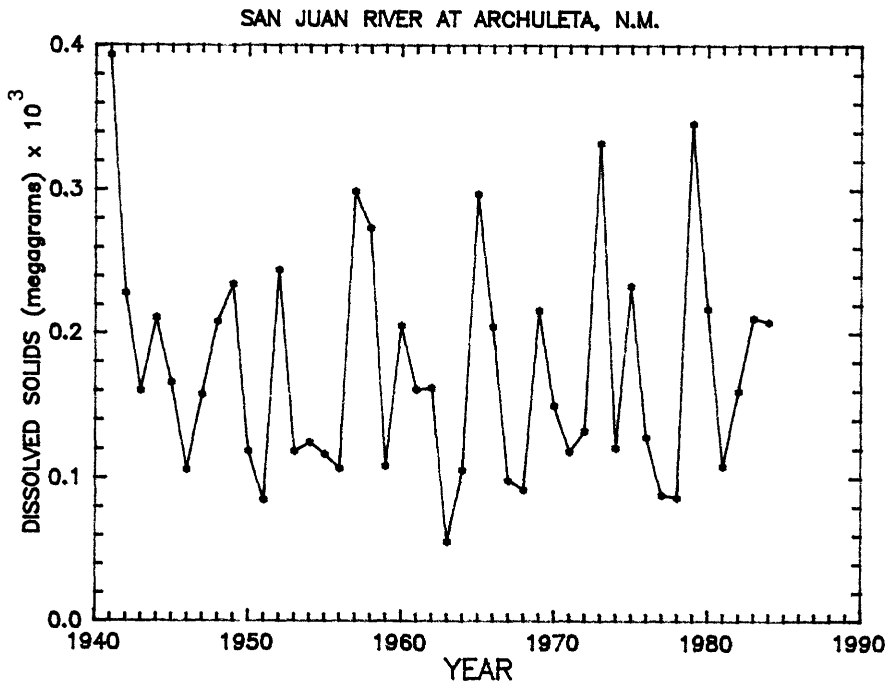


A

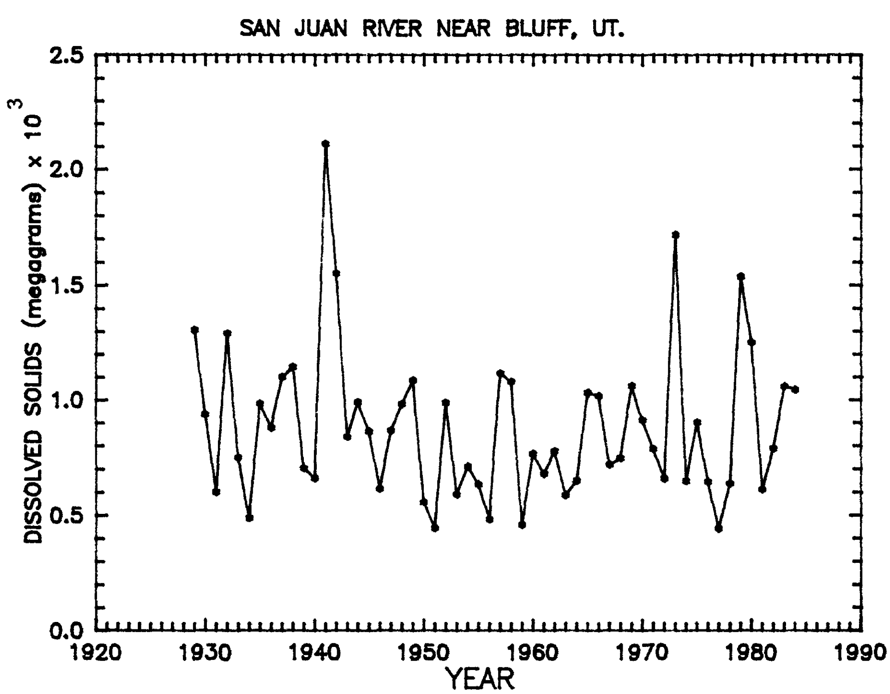


B

Figure 5 A & B

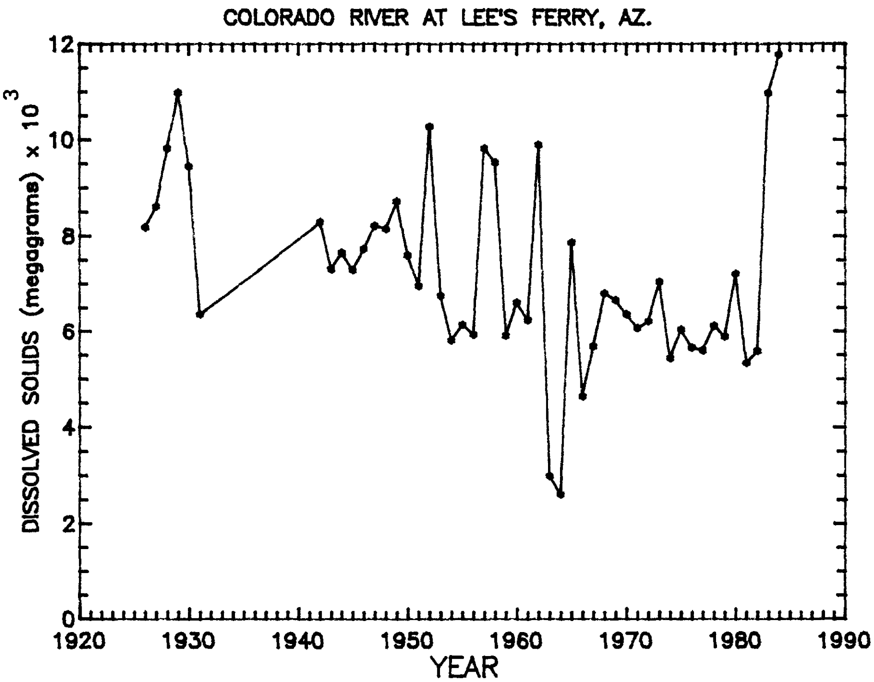


C

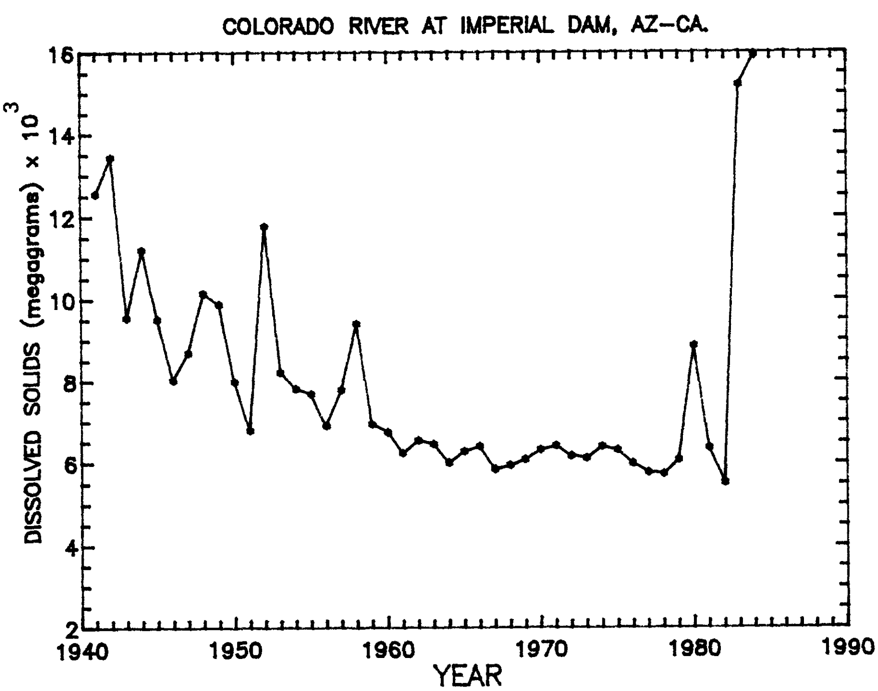


D

Figure 5 C & D



E



F

Figure 5 E & F

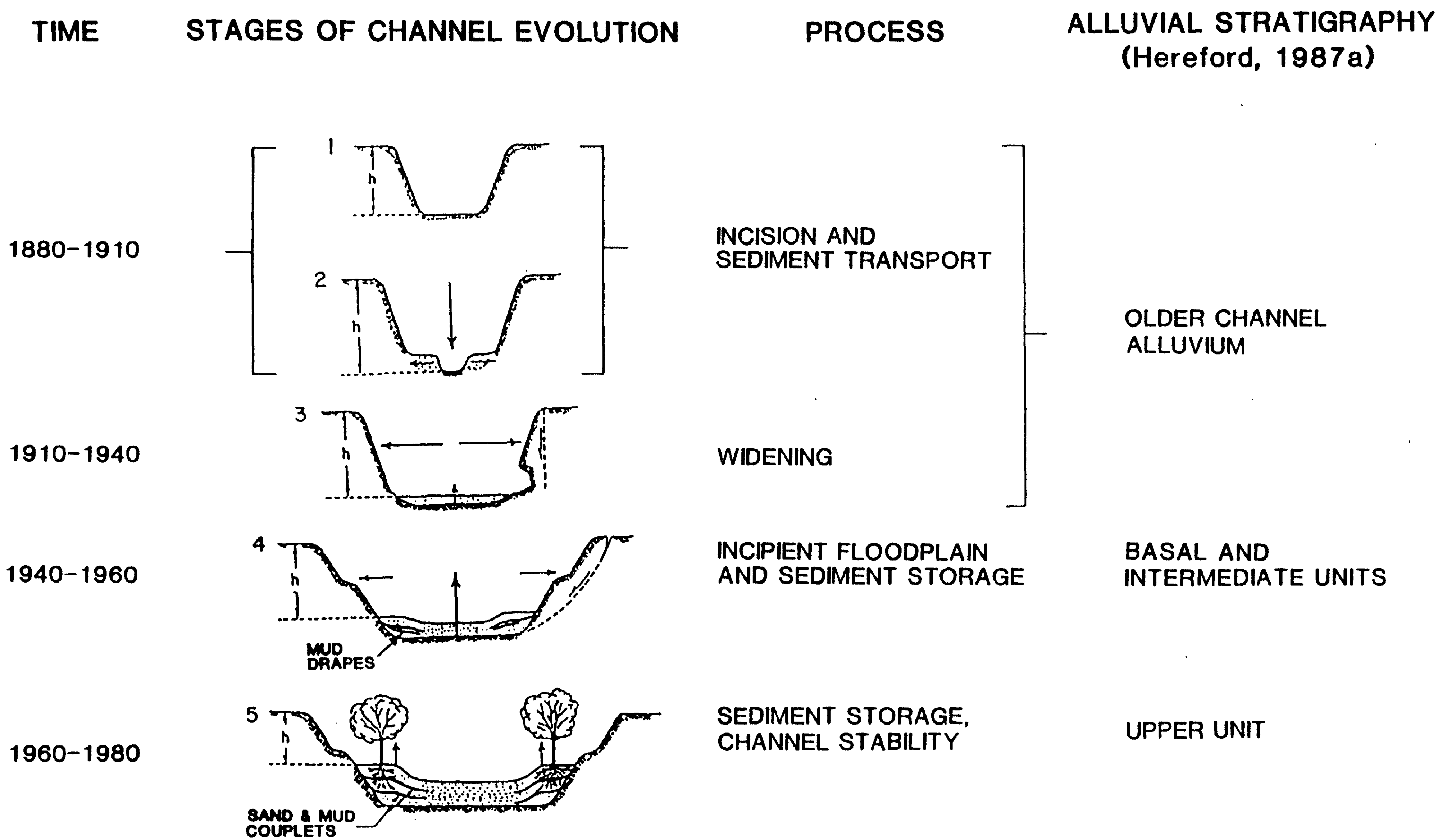

TIME
STAGES OF CHANNEL EVOLUTION
PROCESS
ALLUVIAL STRATIGRAPHY (Hereford, 1987a)
1880-1910
1
h
2
INCISION AND SEDIMENT TRANSPORT
OLDER CHANNEL ALLUVIUM
1910-1940
3
WIDENING
1940-1960
4
MUD DRAPES
INCIPIENT FLOODPLAIN AND SEDIMENT STORAGE
BASAL AND INTERMEDIATE UNITS
1960-1980
5
SAND & MUD COUPLETS
SEDIMENT STORAGE, CHANNEL STABILITY
UPPER UNIT

Figure 6

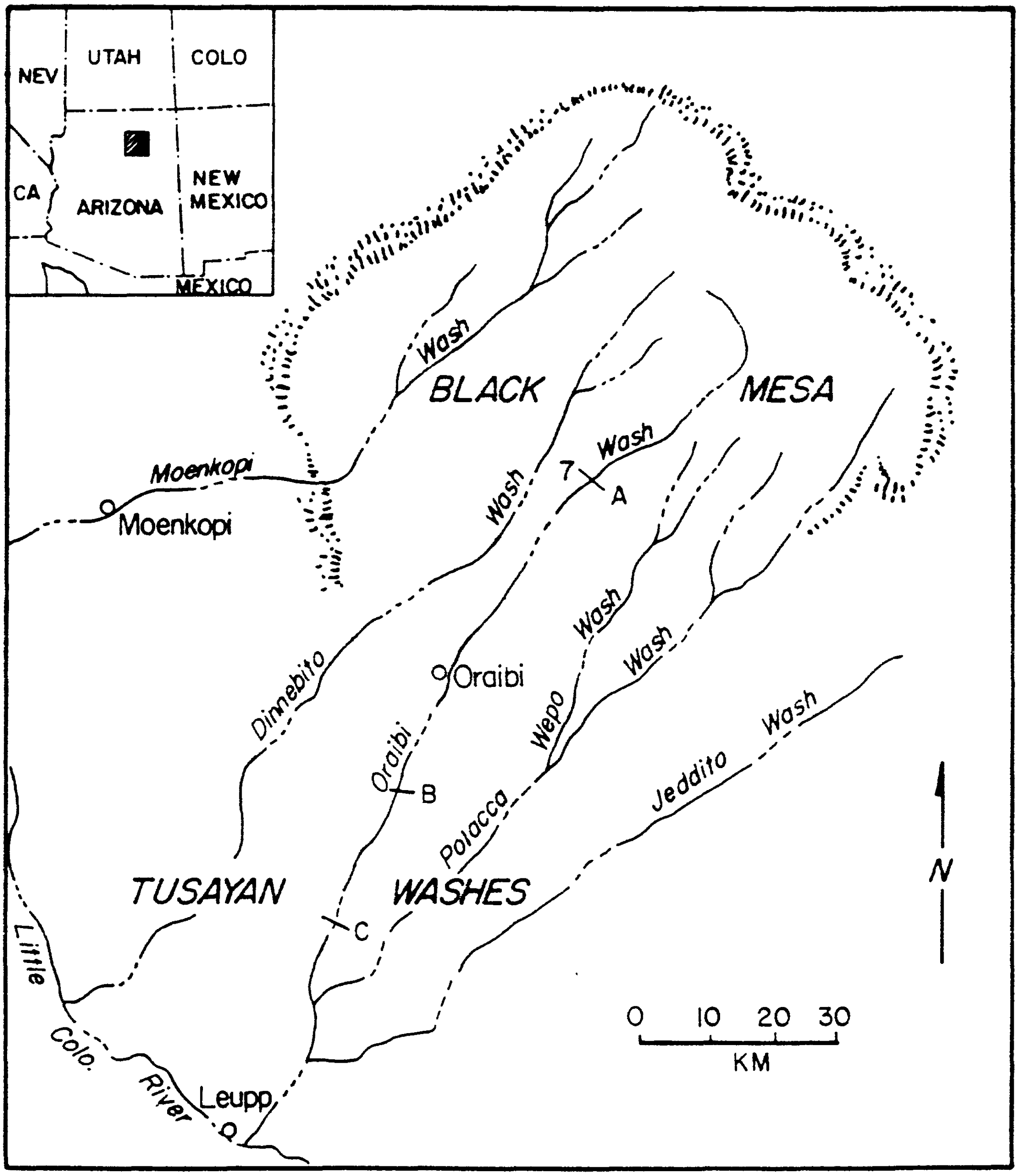

NEV
UTAH
COLO
CA
ARIZONA
NEW MEXICO
MEXICO
BLACK
MESA
Wash
Moenkopi
Moenkopi
Wash
7
A
Dinnebito
Wash
Oraibi
Oraibi
B
Wepo
Wash
Wash
Polacca
Jeddito
Wash
TUSAYAN
WASHES
C
Little
Colo.
River
Leupp
N
0 10 20 30
KM

Figure 7

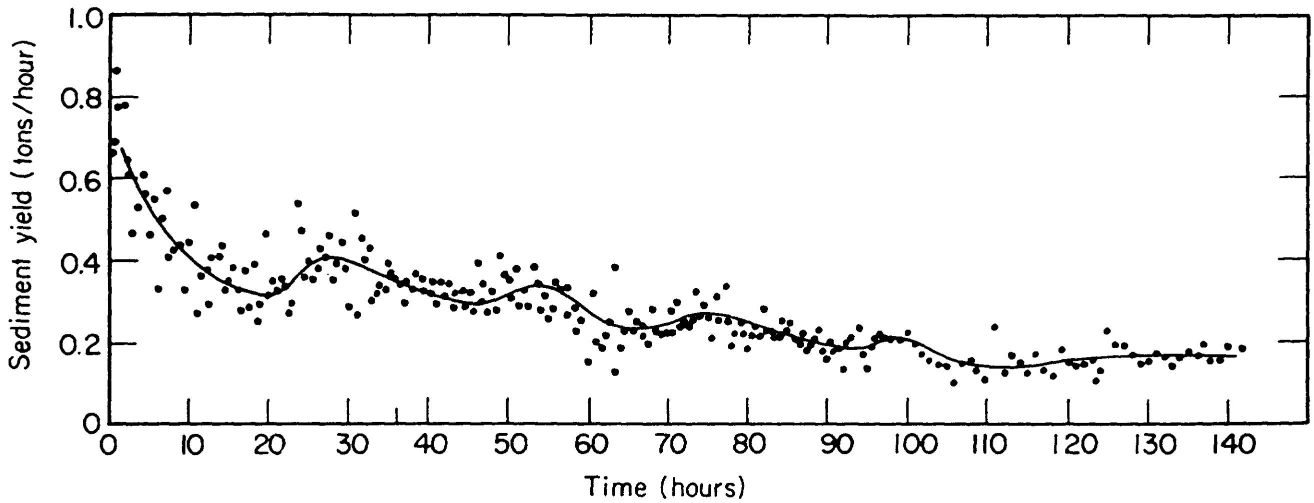
A

B

Figure 8 A + B

C

Figure 8C



Sediment yield (tons/hour)
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (hours)

Figure 9A

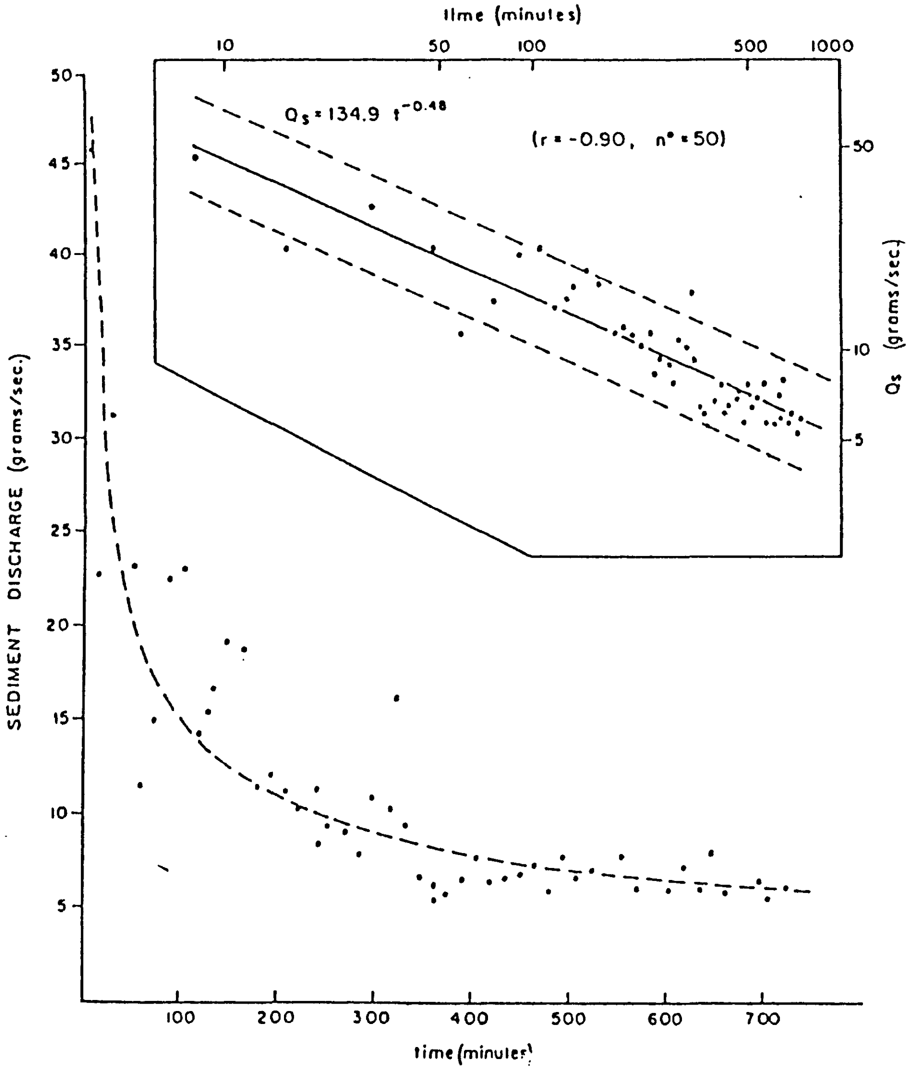

time (minutes)
10
50
100
500
1000
Qs = 134.9 t^-0.48
(r = -0.90, n* = 50)
50
10
5
Qs (grams/sec)
SEDIMENT DISCHARGE (grams/sec.)
50
45
40
35
30
25
20
15
10
5
100
200
300
400
500
600
700
time (minutes)

Figure 9B

Table 1.--Summary of average suspended-sediment loads and average water discharges for selected stations in the Colorado River basin

Location	Period	SEDIMENT (MEGAGRAMS/DAY) Average	SEDIMENT (MEGAGRAMS/DAY) Standard deviation	DISCHARGE (m^3/s) Average	DISCHARGE (m^3/s) Standard deviation
Colorado River nr Cisco, UT	1930-1984	29,000	20,100	200	70
	1930-1942	48,300	25,600	200	60
	1943-1962	23,300	12,800	200	60
	1963-1984	22,800	13,500	200	80
Green River nr Green River, UT	1930-1984	37,400	26,700	160	50
	1930-1943	59,500	31,700	140	40
	1947-1962	37,000	24,300	160	50
	1963-1984	23,600	11,800	170	60
San Juan River nr Bluff, UT	1930-1980	63,200	52,500	60	30
	1930-1942	115,200	64,000	80	40
	1943-1980	45,400	32,500	60	30
Colorado River nr Grand Canyon, AZ	1930-1975	231,000	174,100	420	150
	1930-1943	388,800	176,200	460	150
	1944-1962	219,600	100,000	450	140
	1963-1975	62,200	51,900	320	100
Plateau Country	1930-1962	132,800	70,600	30	20
	1930-1943	164,300	71,500	40	20
	1944-1962	108,800	59,500	30	10

Table 2.--Comparative tests of Colorado River Sampler and the U.S. D-43 Sampler

Report[1]	Test Location	Ratio[2]
A	San Juan River near Bluff, Utah	0.83
B	San Juan River near Bluff, Utah	0.64
C	Green River at Green River, Utah	0.95
C	San Juan River at Shiprock, N. Mex.	1.03
D	Colorado River near Grand Canyon, Ariz.	1.00
Nelson and Benedict (1950)	San Juan River near Bluff, Utah	0.82

[1] Reports A-D of the U.S. Interagency Committee on Water Resources (1944)
[2] Ratio is the sediment concentration of the Colorado River Sampler divided by that of U.S. D-43 sampler

Table 3.--Average channel characteristics and evolutionary stages of Hotopha Creek, Miss. following channelization (from Harvey and others, 1987)

Channel Characteristic	Stages of Channel Evolution				
	1	2	3	4	5
Top Width (m)	20.0	19.1	34.8	35.3	47.6
Bottom Width (m)	7.4	7.5	13.5	17.4	24.3
Depth (m)	4.0	6.7	6.4	6.7	3.1
Width/Depth Ratio	5.1	2.9	5.4	5.3	15.9
Gradient	.00470	.00354	.00360	.00152	.00128
Sediment Load (m^3/s)	.005	.01	.01	.02	.005