Sediment Hydrology on the Colorado River

The Impacts of Draining Lake Powell

December 7, 1998

by

Tom Myers, Ph.D.
Hydrologic Consultant
200 Bartlett St.
Reno, NV 89512
702-348-1759
fax 702-348-1986
tom@black-rock.reno.nv.us

Executive Summary

The Colorado River once varied from a trickle in late fall to torrents in early summer snowmelt. The sediment volumes transported varied even more depending on the source of the flow because of the variable sediment production capabilities throughout the watershed. Reservoir construction and management completely changed the basin hydrology. Variable seasonal flows have been replaced by relatively constant monthly flow and daily flows that vary by the hour in response to hydropower production. The reservoirs trap most of the sediment so that the Colorado River currently flows clean downstream from Lee's Ferry. Clean water flows have caused degradation and armoring of channel bottoms in the Grand Canyon and along the lower river in Topock, Cibola and Imperial reaches. There is very little replenishment of sand to upper beach levels any where in the river. Controlled flows have allowed riparian vegetation to encroach on the channel in many locations.

Current sediment inflow to Glen Canyon is about 36,000 af/y. However, sediment inflow prior to 1941 was about four times as high due to high tributary sediment production. At the current rate and considering compaction and lost trap efficiency, Lake Powell will be totally full of sediment in about 800 years. If the rates that occurred prior to 1940 return, the reservoir will fill in less than 200 years. The actual life is probably somewhere in between. The intake to the powerplant may be reached in about 400 years, but there are many assumptions made about the depositional distribution that renders this prediction very uncertain.

Draining Lake Powell will allow the Grand Canyon to return to its predam state eventually, although there could be a period where the river may not be able to transport its sediment load through the Grand Canyon. The drainage of Lake Powell should be timed so as not to cause major flooding, erosion or deposition. Lake Mead will receive up to 860,000 af of sediment scoured from Glen Canyon and then begin to fill at rate of near 40,000 af/y.

Glen Canyon will recover quickly from the 860,000 af of sediment that buries the mainstem and side channels. Flows in the mainstem rivers and side channels all exceed critical velocities for incipient motion. Many tributaries flood most years which will clean them. Slot canyons do not likely have more than a few feet of sediment unless they are immediately adjacent to a delta which may bury the slot mouth in tens of feet of sediment. There is no evidence from any of the sediment survey range lines that reservoir currents move sediment up the slots.

Most mainstem sediment accumulated in deltas with a little in a wedge at the base of the dam. Between a point 60 miles upstream of the dam and below the delta toes at about 3400' MSL, there is very little sediment. As the reservoir is lowered, the deltas will erode and deposit sediment further downstream in the reservoir. The river will cut a channel leaving high terraces. The migrating river will occasionally undercut these terraces that probably will become rapidly vegetated. Not all of the current 850,000 af of sediment will be removed.

Sediment flow in the river below Hoover Dam will not be affected very much unless high river flows coincide with high tributary flows because very little sediment remains on the river bottom. The Gila River is the primary source. The USBR's current dredging operations removes most sediment from the river and armors the banks thereby decreasing bank erosion. Increased flows during floods after drainage of Lake Powell may further degrade the river. Overbank flooding will not likely contain enough sediment to replenish and nourish overbank areas.

Heavy metals, including mercury and selenium, exist in the sediments in Glen Canyon. The mercury concentrations are not high enough to raise levels in Lake Mead to levels of concern. Selenium levels in the lower river are very high and currently causing avian reproductive problems. Draining Glen Canyon should not affect this as long as sediments are captured in Lake Mead and most selenium remains bound to sediment particles.

This report raises questions as well which lead to recommendations for future study.

1. As Lake Powell is drained, there is the possibility that large amounts of sediment will be released and be redistributed within the draining reservoir. The rate of drainage at different

reservoir levels will control the release and the redistribution of sediment. As a part of the Glen Canyon EA, the Glen Canyon Institute should perform a detailed reservoir release analysis. This will allow the institute to propose a release scenario that will protect existing resources in the Grand Canyon and allow the canyons currently inundated by Lake Powell to be cleansed.

2. The potential for heavy metal release is a significant concern. The institute should obtain updated sediment quality data especially including mercury and selenium. In addition to analyzing content, the tests should include analysis of the release of metals to the water as sediment flows through turbulent rapids. Also, the analysis should include fish flesh in Lake Powell, the Grand Canyon, and Lake Mead.

3. More detailed analyses of flow in the river without Lake Powell should be performed. Monthly predictions would be useful. The removal of Lake Powell will free about 500,000 af of water annually for environmental uses. The analysis should consider release scenarios that will maximize the environmental benefits from these releases. This should include estimates of how flows could be used to move sediment in the lower Colorado River and into the delta region of Mexico.

Table of Contents

Executive Summary . . . 1

Introduction . . . 6
    Units of Measurement . . . 7

Basics of Sediment Transport . . . 7

Study Area . . . 9

Glen Canyon . . . 9
    Hydrology . . . 11
        Hydrology of the Bureau of Reclamation and the Compact . . . 13
    Sediment Inflow . . . 15
        1925-41 . . . 15
        1941-1957 . . . 18
        1960- 1997 . . . 19
        Sediment Inflow to Lake Powell . . . 22
    How Long Before the Reservoir is Full? . . . 24
        Reservoir Deposits . . . 24
        Rate of Accumulation . . . 26
        Life of the Reservoir . . . 27
    Impacts of Draining Glen Canyon Reservoir . . . 28
        Rate of Canyon Recovery . . . 28
        Shear Stress Analysis . . . 31
        Regional Flood Frequency Analysis . . . 37
        Summary of Canyon Recovery . . . 39

Grand Canyon 41
    Hydrology 42
    Sediment Inflow 44
    Sediment Transport 45
    Effects of Reoperating Lake Powell 46
    Impacts of Draining Lake Powell 47

Below Lake Mead 50
    Sediment Transport 50
    Sources of Sediment 51
        Colorado River Sediment Transport Data 51
    Changes Expected from a Drained Lake Powell 56

Conceptual Sediment Model for the Colorado River Basin 59

Toxic Metals in the Sediment 62

Conclusion 64

Recommendations 66

Acknowledgments 67

References 67

Introduction

> *The Colorado River was named by a Spanish explorer for the reddish color of its waters, which comes from sediments contributed by the colorful sandstones and other rocks along its course. Historically, the river's sediment load was high due to the low volume of vegetation in the arid Colorado Plateau and force for eh river coursing down its steep gradient. Sediments moved downstream with spring floods, forming marginal sand bars and terraces and a vast delta at its mouth in the Gulf of California, known in Mexico as the Sea of Cortez. These sediments provided substrate for riparian vegetation habitat and for wildlife. Today, dams trap much of the vast quantity of sediment that once flowed through the river.*
> (Pontius, 1997)

Glen Canyon Dam and the impounded Lake Powell destroyed one of the most beautiful canyons in North America. A lesser known fact is that the reservoir is a sink into which much of the sediment produced by the Colorado River will be trapped. The deep canyons carved by the river provide an idea of the erosive power of the river. "Too thick to drink, too thin to plow" was the expression that many old-timers gave to the Colorado River to express their frustration with the amount of sediment in the river before it was dammed.

The Glen Canyon Institute has embarked on a unique public process of environmental assessment of the Glen Canyon Dam, its impacts and the impacts of draining or removing it. This report supplements that effort by considering sediment and erosion issues throughout the basin.

The purpose of this report is to develop a conceptual model of sediment movement in the Colorado River basin both before the current reservoir management began and in its current state. The report then considers the impacts of draining Lake Powell on the sediment movement in the basin. The second objective is to estimate the rate that sediment will be removed from the canyons inundated by Lake Powell.

Units of Measurement

Sediment transport literature uses a very confusing set of units and conversion factors. The terminology is a mix of English and metric units. Concentration is usually expressed as milligrams/liter (mg/1) or parts per million (ppm). But flow rate is usually cubic feet per second (ft^3/s or cfs) and sediment load is tons per year (t/y). The product of concentration and average annual flow rate gives the annual load. The key is to make all the appropriate conversions. A ton/ft^3 equals $3.121337*10^{-8}$ mg/1. Annual yield in weight is less useful than annual yield in reservoir volume per year. Authors are not always clear on which they are using. An English ton is 0.90718 metric tons. Using the specific weight of the sediment (lb/ft^3), it is possible to convert the weight per year, here t/y, into the volume of inflow. Specific weight is the weight of a substance for a given volume. It is the specific weight of sediment after it has deposited, not as it is flowing , which determines the volume of sediment in the reservoir. Further complicating the issue, deposited sediment compacts and consolidates so the specific weight increases with time so that more sediment occupies a smaller volume. Because of compaction, it is not possible to accurately extrapolate from inflow volume/y to the life of the reservoir.

Specific gravity is the ratio of specific weight to that of water. Quartz particles weight about 2.65 times and equivalent volume of water and have a specific weight of about 165 lb/ft3. The specific weight of water is 62.4 lb/ft3. The specific weight of sediment deposits varies depending on particle size and shape as well as compaction. This will be discussed below.

Basics of Sediment Transport

Sediment transport takes three forms: dissolved, suspended and bed load. Dissolved load includes the products of ionization like the individual sodium and chloride molecules and is not a sedimentation concern. Suspended load is sediment carried in suspension without bouncing off the bottom. Bed load includes particles that bounce irregularly along the bottom of the river.

Suspended particles experience various vertical forces sufficient to overcome the particle weight. The typically much larger bed load particles only occasionally experience such forces which cause the particles to move short distances along the channel bottom before settling again.

A stream's ability to move sediment depends on stream power, or the ability of water to perform work. The rate that energy is lost per unit distance is a measure of stream power. Steeper rivers that lose more energy in shorter distances transport more sediment.

The competence of a given flow is the largest grain size that can be transported. The maximum amount of sediment that can be transported is the capacity of a flow. Most rivers frequently transport less than their capacity because less wash load (very fine particles) is supplied to the river than the river can transport. Sediment load is commonly expressed in t/d. Sediment yield is the amount of sediment produced from a watershed including overland and channel erosion.

Transport capacity varies along river lengths. Sediment transport usually decreases when the river gradient decreases while steepened reaches transport more sediment. Factors that decrease velocity, such as roughness may also decrease transport capacity. It is shear stress that initiates movement rather than velocity, but the two are intimately connected. Shear stress is:

$$\tau = \gamma R S$$

where γ is specific weight, R is hydraulic radius (the quotient of area and wetted perimeter), and S is energy gradient. As rivers become larger (in the downstream direction), slope decreases, but R increases faster. Often, velocity is very similar along the profile because roughness decreases with the smaller bed particles usually found in larger rivers. The resulting aggradation and degradation processes are very complicated. As humans-affect the factors controlling sediment transport, they also affect the location of sedimentation on the river.

Active Channel

A river in equilibrium has an "active channel" shape that corresponds with its average flood flow rate and the sediment input from the basin. The flow just contained within the active channel is usually the flow that transports the most sediment on an annual basis. It is a function of the frequency of the flow and the amount of sediment carried by that flow. Large flood carry huge amounts of sediment but they are so infrequent that they are not as important in the formation of the active channel. Small flows are frequent, but carry little sediment. Research has shown that the channel forming discharge has a return interval from 1.5 to 2.0 years (Leopold, 1994).

Above the active channel lies the geomorphic floodplain, an area inundated during about half of the years. Because these areas frequently have very slow flow velocities, sediment being transported in the river frequently deposits on these floodplains. As the river incises, the river no longer access these formations and they become terraces. In a meandering river, floods frequently rework the floodplains.

Study Area

This study concerns the water and sediment loads in the Colorado River basin (Figure 1). Most analysis is based on the gages shown in Figure 1.

Glen Canyon

> 777/5 *natural tunnel is pure rock, completely devoid of sand, soil and any trace of vegetation. The walls that tower above are so close to one another, overhanging and interlocking, that I cannot see the sky. Through a gold glow of indirect, reflected sunlight I proceed until I come to a very large grotto or chamber, somewhat like the one described by Powell, where a plunge pool and waterfall check any further advance.* (Abbey, 1968)

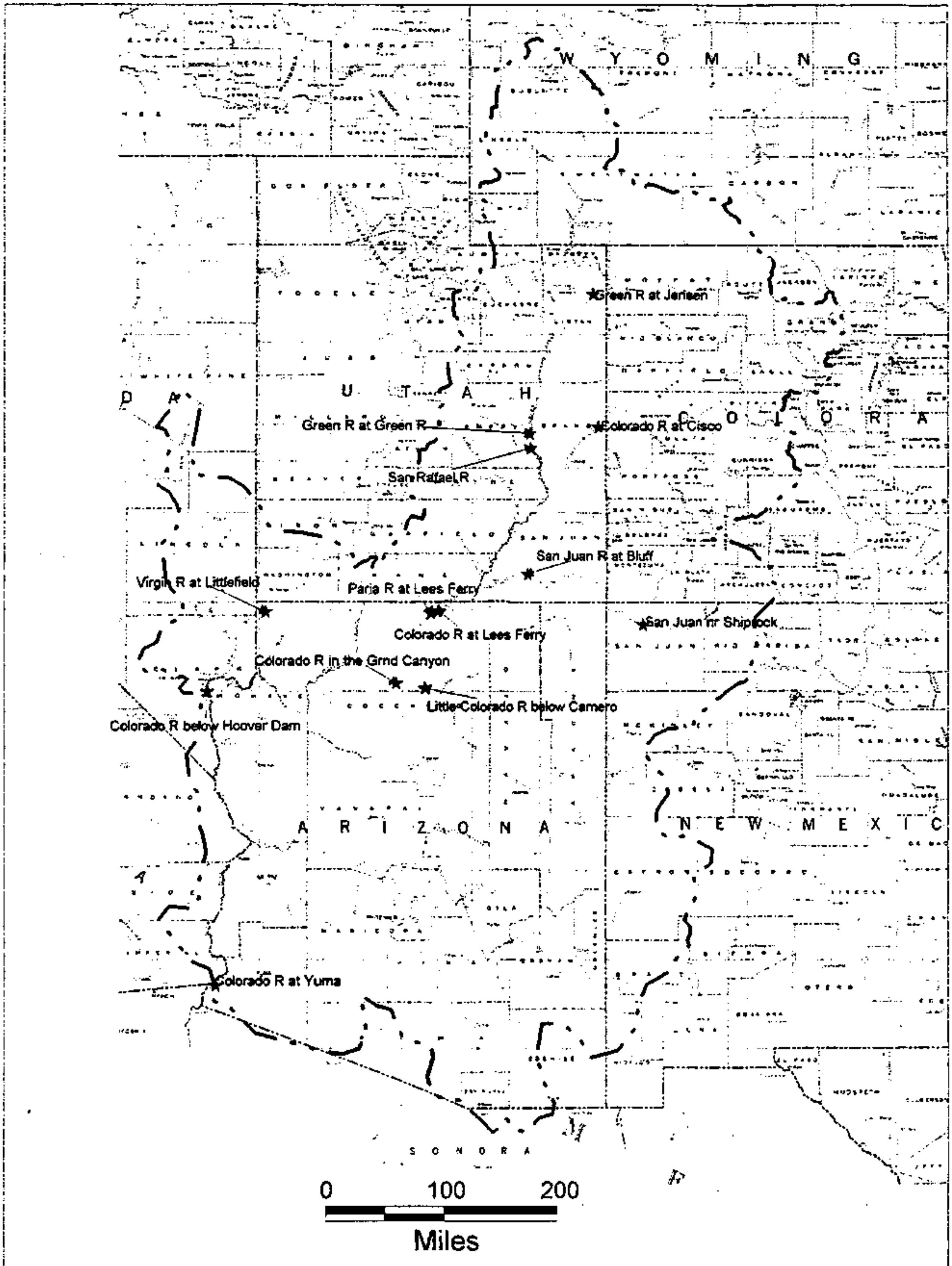


Figure 1: Colorado River basin and gaging stations.

Hydrology

Glen Canyon before dam construction experienced extremely variable inflows. Three main rivers, the Colorado, Green and San Juan, contribute to flow through the canyon. Smaller rivers such as the Dirty Devil and Escalante and myriad side canyons also contributed flow. The larger rivers flooded during the spring snowmelt season while smaller rivers and side canyons flooded during the summer thunderstorm season.

Annual flows for three mainstem river gages and their summation are extremely variable (Figures 2). The coefficient of variation, standard deviation divided by the mean, is a good measure of variability. Representing less than 15% of total mainstem flow, the San Juan River is the most variable inflow river because of the higher variability of southwestern climate and the smaller watershed size. The Colorado River accounts for just less than half of the inflow (Table 1). The Green River has about 85% as much flow as the Colorado River (Table 1). Construction of Flaming Gorge Reservoir had little impact on annual flows on the Green River (Figure 2) because its volume is only about 60% of the average river flow. Seasonal flows have become less variable and daily peaks essentially eliminated.

Table 1: Flow Statistics on Mainstem Rivers **and Glen Canyon and Local Inflow**

Gage	Years	Mean (af/y)	Std Dev (af/y)	CV %	upper (af/y)	lower (af/y)
Colorado R at Cisco	23-96	5266000	1971000	37	11081000	1660000
Green River at Green River	06-96	4498000	1613000	36	8826000	1214000
San Juan River at Bluff	29-96	1645000	851000	52	4898000	129000
Glen Canyon inflow	29-96	10870000	3923000	36	20939000	3835000
Colorado R at Lees Ferry	23-62	12036000	3851000	32	19590000	20374000
Colorado R at Lees Ferry	63-96	9689000	3909000	40	3948000	1384000
Glen Canyon local inflow	29-62	519000	292000	56	1283000	80000
Glen Canyon local inflow	63-96	-1067000	2367000	221	2873000	-5979000
Colorado R at Grd Canyon	23-62	12267000	391800	32	19853000	4185000
Colorado R at Grd Canyon	63-96	10058000	3893000	39	20602000	1629000
Grd Canyon local inflow	23-96	349000	191000	55	1030000	15800

CV is coefficient of variation, the standard deviation divided by the mean expresses as a percent.

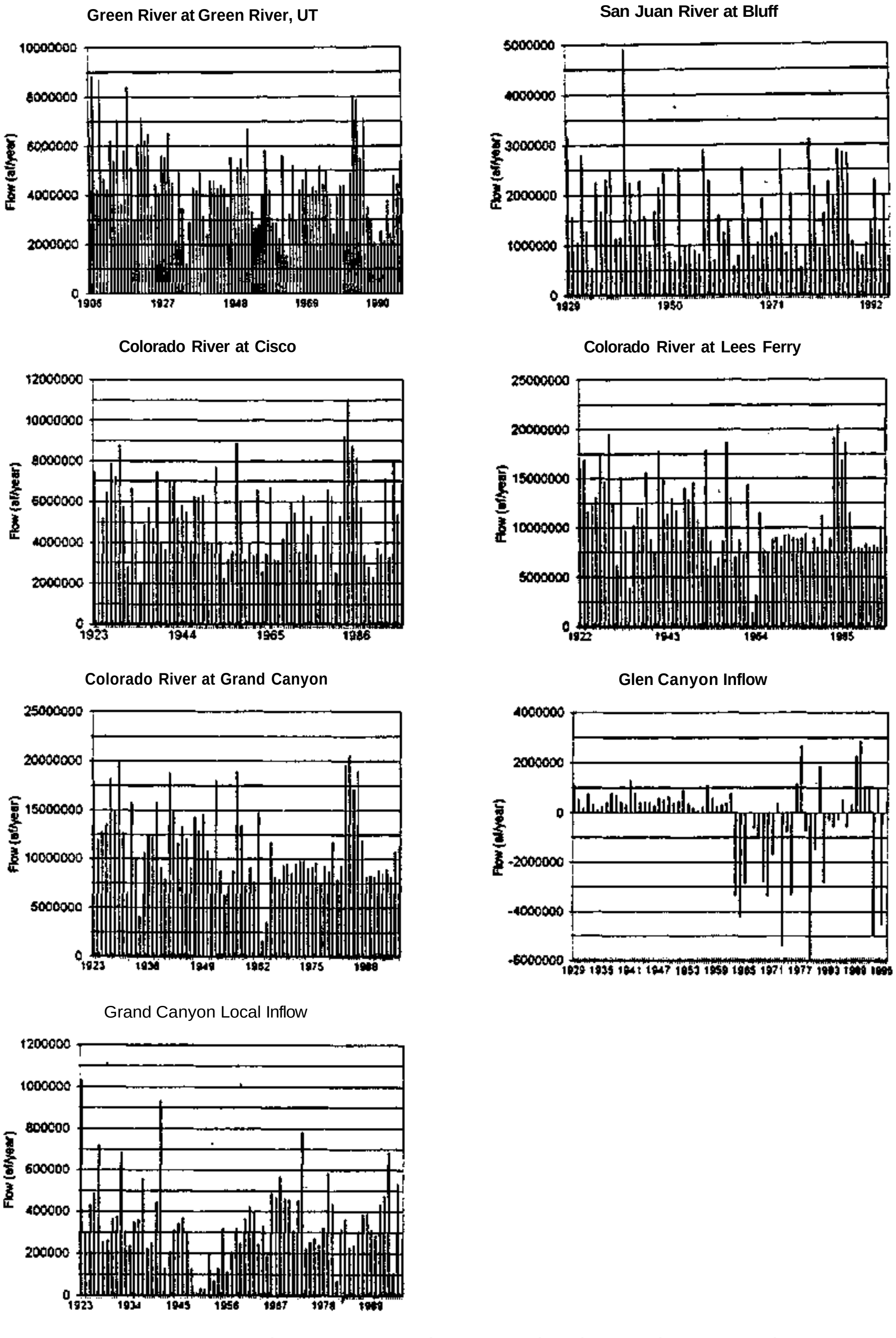


Figure 2: Annual flows at various gages on the Colorado River and calculated local inflow into Glen Canyon and the Grand Canyon.

Comparison of annual flow among stations is useful only if the period of record is consistent among stations. Dams that change the flow substantially also render the comparison less useful. The best period here is 1929 to 1962. Flow at Lee's Ferry equaled 11.50 maf/y while the flow at the Colorado R at Cisco, the Green River and the San Juan R at Bluff was 5.17, 4.07 and 1.74 maf/y, respectively. About 0.52 maf/y entered the river within Glen Canyon.

Flow at Lees Ferry became very constant after dam construction (Figure 2). The coefficient of variation is greater since dam construction primarily due to the skewness caused by flooding in 1983 and 84 (Table 1). The fact that the CV is lower prior to 1963 reflects the statistical principle of the central limit theorem. Essentially, the variability of the upstream gages cancels each other when the runoff from each watersheds is independent. While Lake Powell was filling, 1963 through 1980, the outflow, and flow at Lees Ferry, was very consistent. The initial low flows after closure occurred because the water level had to reach the penstock.

The difference between flows at Lees Ferry and the inflow to Glen Canyon prior to dam construction is local Glen Canyon inflow. Local inflow to Glen Canyon from 1929 through 1962 averaged 519,000 af/y (Table 1). After 1962, the difference represents the difference between local inflow and water lost to reservoir storage, evaporation and bank storage. Years with high negative flows are years that water was being added to reservoir storage.

Hydrology of the Bureau of Reclamation and the Compact: Flows at Lees Ferry were used to divide the river's flow between Upper and Lower Basins. Quoting LaRue (1925), Dawdy (1992) wrote: "[t]he average annual run-off available for storage at the Colorado-San Juan reservoir site is about 15,000,000 acre-feet." LaRue had estimated flows from 1895 through 1922 to equal 16.8 million af/y. The measured flow from 1923 through 62 equaled 12,036,000 af/y. This is 22.4% less than LaRue's prediction and illustrates current problems with the distribution and availability of basinwide flows.

That the Compact overestimated flows on the river is well documented. Considering all possible ten-year moving average flows at Lees Ferry, the highest estimate was in 1931 and equaled 14,050,000 af/y. Because Lees Ferry flows equal the sum of river flows plus local Glen Canyon inflows, summing the means in Table 1 suggests that total flow at Lees Ferry, based on the period 1929-96, equals about 11,389,000 af/y.

Dawdy (1992) emphasized the uncertainty inherent in Colorado River flow statistics. When annual flows are autocorrelated, the mean value is less certain than when annual flows are perfectly random.

> The message was that autocorrelation of streamflows (the tendency for high years to follow high years and for low years to follow low years) reduces the information concerning the mean flow of the river. An example of this is the fact that the last three years of runoff from the upper basin have been below normal...Thus, more years are required to determine the water availability with a given level of reliability than would be the case if the water volumes that flowed in each year were completely random and unrelated...Uncertainty in the average inflow results in uncertainty in the average yield... (Dawdy, 1992, page 42-43)

Dawdy (1992) also raises questions about the USBR's use of reconstituted inflows to the reservoir. Using different time periods, Dawdy (1992, page 46-47) wrote:

> The data available at the time of the compact gave a mean discharge slightly greater than the 16 million acre-feet divided under the compact. The average after the compact is just over 14 million acre-feet, ending with and including the high water year of 1983. For the period 1923-1956, the current USER estimates are about 500,000 acre-feet greater than the values provided Leopold (14.35 million versus 13.85 million)....The source of the difference of 500,000 acre-feet should be determined, and its validity should be assessed. Once, again, releases may be determined by the accuracy of that determination.

He is clearly suggesting that incorrect inflow estimates may be affecting the way the USER manages the river system.

Ferrari (1988) estimated inflow to Glen Canyon as 11.550 maf/y for the 23.5 years prior to 1987. He based his estimates on the sum of the three primary river inflows. A notation on his table suggested that the inflow values represented about 90% of all inflow which implies that local inflow equaled 1,283,000 af/y or more than twice estimates herein.

Sediment Inflow

Various sources of information about sediment inflow to Glen Canyon tend to be divided into time periods. After the end of dam construction, most long-term gages were dismantled so that trend analysis of a long-term, natural flow record is impossible. This section will examine sediment transport for three periods, 1925 though 1941, 1941 through 1957, and from 1960 through 1997. Then the section will examine sediment survey data in Lakes Mead and Powell and then conclude with an estimate of sediment inflow to Lake Powell.

1925-41: Howard (1947) reported on sediment flow data collected at various points on the Colorado River. These included gages near Cisco, Utah, Lees Ferry, AZ, Grand Canyon, AZ, Willow Beach, AZ, Topock, AZ, and Yuma, AZ[i] (Figure 1). He also reported on gages an the Green River at Green River, UT and the San Juan River near Bluff, UT. The period of record varies but primarily spans much of the 1930s decade.

Data collection was with an integrated sampler over the depth from river bottom to top. The basic method was to lower a bottle to the river bottom, open it and raise it to the surface at a rate that the bottle is not full when it reaches the top. This method is inaccurate in that the rate of inflow to the bottle is higher at the bottom than at the top. Concentrations were reported as a percent by weight. The daily load (t/d) equals mean concentration (percent by weight) x mean daily discharge (cfs) x 27.

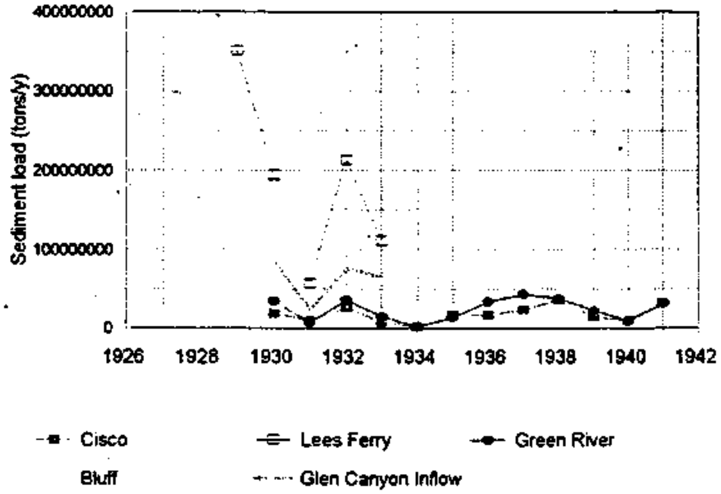
[i] The gage at Yuma was maintained by the Bureau of Reclamation while all others were maintained by the Geological Survey.

Suspended sediment samples do not include bedload. Bedload includes material that moves along the river bottom, usually rolling and stopping. One particle may move while an identical particle nearby does not move. In some rivers, bedload is a major portion of the sediment load. In the Colorado River, suspended sediment ranges from sand through clay sizes. Gravel may be suspended in turbulent reaches, but it will soon settle in pools only to be suspended by high flows. As far as reservoir inflow is concerned, bedload settles at the very upstream end. Most beaches and riparian vegetation depend on the smaller, suspended sediment. Also, USER (1995) indicates that the load through the Grand Canyon is "predominately" silt and clay. The lack of bedload information in sediment loads reported here is likely a minor error.

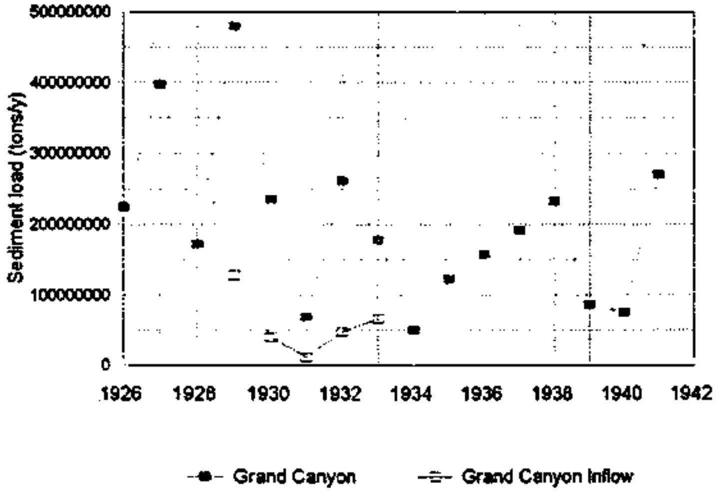
Howard (1947) identifies many sources of potential error in any relation between sediment and water flow rate. Considerable variation in sediment concentration exists through both the day and the cross-section. Sediment concentration would be much higher after heavy rains over portions of the desert. There was no relationship between concentration and flow discharge. This suggests that, even prior to dam construction, sediment loads were supply limited. The river could have carried more sediment and did so when tributaries delivered high loads.

The load at Lees Ferry substantially exceeds the sum of the loads at Cisco, Bluff and Green River (Figure 3). Side canyons and other rivers contribute 35 to 58% of the total load at Lees Ferry in the four years that measurements were available at all gages. The Escalante and Dirty Devil are the primary perennial side canyon tributaries, but, there are also many additional slot canyons in this reach.

Upper Basin



Grand Canyon Reach



Lower River

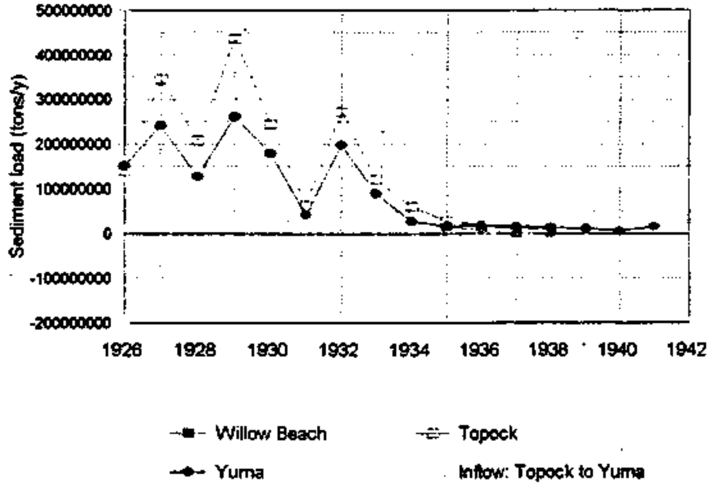


Figure 3: Sediment loading along the river from 1926 to 1941. Data from Howard (1947)

The gages at Cisco and Lees Ferry illustrate the variability between suspended sediment loads and flow rates and the dependence on source area. At Cisco, in 1937, total load was almost 23,560,000 tons, but almost 7% of the load (1,630,000 tons) occurred on one day. That day's mean discharge was 12,910 cfs, while in 1933 and 1938, the peak loads of 324,000 and 879,000 t/d occurred when the mean discharge was 28,600 and 37,400 cfs, respectively. The high one day load in 1937 probably resulted from high erosion rates in one portion of the basin. This explains why Howard (1947) did not find a relation between sediment load and discharge.

1941-1957: EA Andrews (1991) states: "the decrease in mean annual sediment loads in the Colorado River near Grand Canyon after 1941 is quite large, nearly 100 million tons/year,..." (90,718,000 English t/y). This period also has the best sediment gaging. The average load at Lees Ferry dropped to less than 60,000,000 t/y from a five-year average of 186,000,000 t/y[2]. The average load at Cisco is 8,000,000 t/y, a drop of 10,000,000 t/y from the 1930 to 41 average. The average load at Bluff became 18,000,000 t/y while the previous average had been 44,000,000 t/y. The average load at Green River became 15,000,000 t/y while the average from 1930 to 1941 had been 24,000,000 t/y. By far the San Juan River at Bluff had the largest decrease.

Most runoff from the San Juan River originates in the headwaters while most sediment erodes from the lower reaches (Figure 4). Sediment transport increases by almost 80% while flow increases only 10% from Shiprock to Bluff. Similar results are seen on the Colorado River. Sediment loads in the Colorado River are 2.5 times higher than at Jensen while flows are only 20% higher. For their flow, the Little Colorado and Paria River contribute much more sediment than any other portion of the watershed. This is clear evidence that upper watersheds contribute most of the water flow while watersheds on the Colorado Plateau contribute mostly sediment.

Many sources document the development of arroyos in the Southwest beginning about 1880 (Webb, 1985; Leopold, 1946; Bryan, 1925; Bull, 1992). By 1941, many of the arroyos

---

[2] From 1928-33.

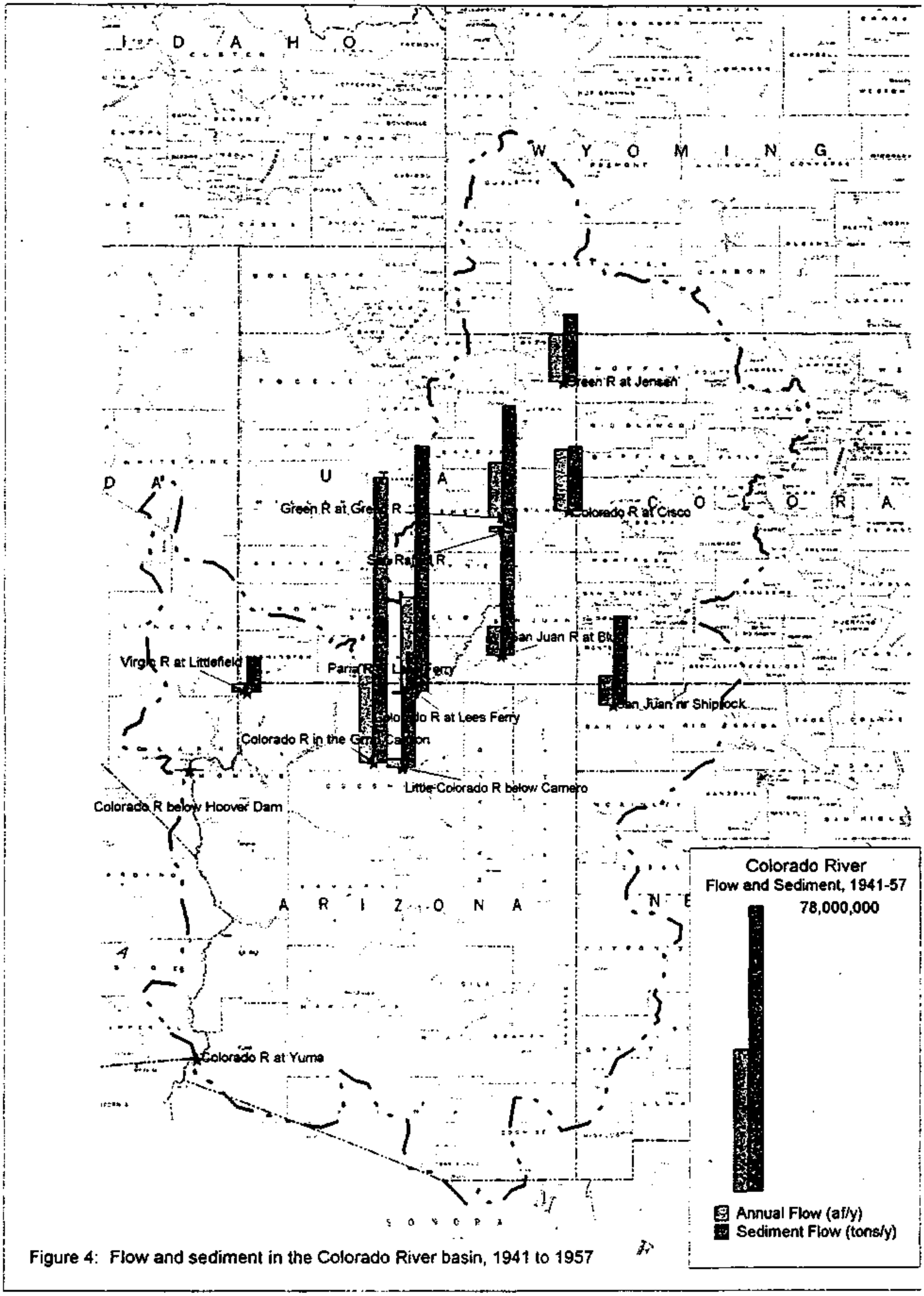


Figure 4: Flow and sediment in the Colorado River basin, 1941 to 1957

were completely developed. The cause of the arroyo development is open to question. Webb (1985) and Andrews (1991) argue that climate change causing drought and extreme floods caused headcutting and massive erosion. However, thirty years before he wrote his landmark book of essays, A Sand County Almanac, Aldo Leopold (1946) was blaming cattle grazing for causing massive arroyo development. Geomorphologist Bull (1992) suggests that a little of both was probably the cause.

A dry period beginning about 1880 coincides with the second or third decade of cattle grazing in the northern part of the Southwest[3]. Both decreases the vegetative cover of watersheds and lead to increased runoff and upland sediment production. There were also various flood events during the last two decades of the 19th century and the first two decades of the 20th century. Flooding exacerbates erosion leading to headcutting and arroyo development, Andrews (1991) provides evidence from the Paria River showing that flood flows were much higher during the period 1924-41 than 1942-86. The ten-year flood calculated for the early period is almost twice as high at 11,500 cfs rather than 5600 cfs.

During this period about 17.8 million t/y entered Glen Canyon from tributaries downstream from the three main river gages (Andrews, 1991). This is 29.6% of the difference between the upstream gages and the outflow at Lees Ferry. The calculation assumes the sediment balance in Glen Canyon is in equilibrium[4]. If this period actually did have few flood flows, it is likely that aggradation occurred in the low gradient Glen Canyon. Thus, inflow from tributaries is probably higher than just estimated.

1960- 1997: Many sediment gaging stations were eliminated after 1960 (Andrews, 1991). Gages at the Green River at Green River, San Juan at Bluff and Colorado River at Cisco were sampled on an infrequent basis after 1960, Flow and sediment data from these gages are available

---

[3] Much of New Mexico and southeast Arizona had been grazed for much longer than this.

[4] Inflow=outflow with no accumulation.

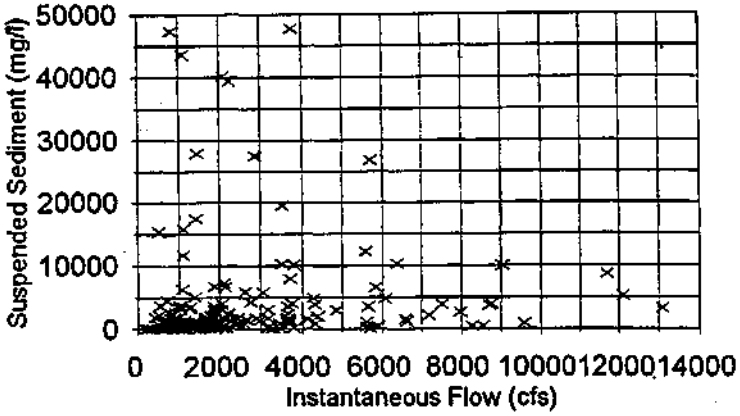
from an EPA water quality WEB page (www.epa.gov). Sediment measurement were made on about a monthly basis. Because of the daily variation in load, there is insufficient data to estimate monthly or annual loads.

Sediment concentrations at Green River and Cisco are variable (Figure 5). Many, but not all of the highest concentrations, coincide with high river flows. All three stations have a linear relation of sediment concentration with flow. Each have high outliers probably associated with large tributary sediment inflows. The range in sediment concentrations at a given flow rate reflects the source regions of the flow. Many of the highest flow rates had low concentrations reflecting their source in snowmelt runoff. Low sediment concentrations occur when the river flows are primarily from the river headwaters which do not produce high quantities of sediment. The river bed upstream from Moab, Utah, primarily consists of cobble that does not produce much suspended sediment.

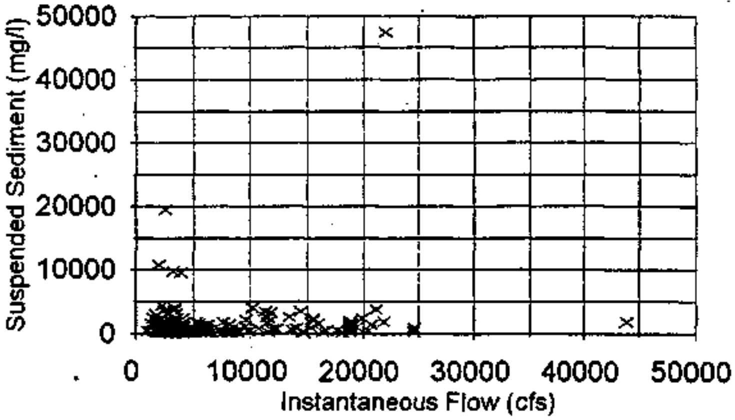
Relatively low flows with high concentrations probably coincide with large side channel inflows. Andrews (1991) reproduced an average annual sediment hydrograph for the Paria River showing that the maximum sediment inflow occurs during July and August during monsoonal storm runoff.

After the construction of Flaming Gorge reservoir, decreased river flows decreased mean annual sediment discharge at three different gages by a range from 48 to 56% (Andrews, 1991). Between 1941 and 57, almost 80% of the sediment load was produced below the reservoir. The decreased transport since dam construction far exceeds the amount of sediment trapped in the reservoir. The reservoir decreased the flow variability and high flows that are most responsible

San Juan River, Bluff
1973-95



Green River at Green River
1973-95



Colorado River at Cisco
1973-95

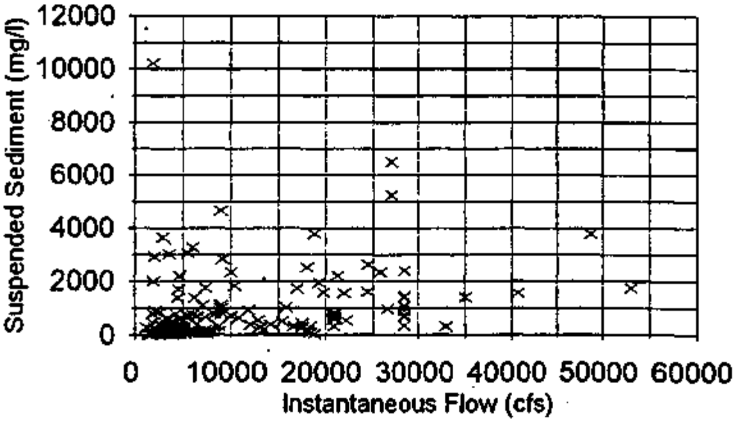


Figure 5: Suspended sediment as a function of instantaneous flo

for transporting sediment. Tributary flows deposit sediment which is leading to aggradation. This may be seen in the increased numbers and area of mid-channel bars in the Green River downstream from the Yampa River. Also, the decreased flows have allowed tamarisk to impinge on the active channel of the Green River thereby stabilizing previously mobile sediment.

Sediment Inflow to Lake Powell: Two watershed changes have combined to decrease sediment inflow to Glen Canyon. These are the construction of Flaming Gorge Reservoir in 1962[5] and other reservoirs that have decreased and controlled the variability of river flows. The second is the decrease in flood flows observed since 1940 that has caused tributaries to erode less than during the previous 60 years (discussed above). The effects of the first are likely to last for the effective life of Flaming Gorge Reservoir. But the period which decreased flood flows will last are less clear.

Future sediment inflows could be much higher than current inflows. Webb (1985) found that large floods on the Escalante River occurred most frequently between 1200 and 900 years BP, 600 and 400 years BP and the past 100 years. His methods would not allow the data to be broken into shorter, decadal periods. Possibly, the period of larger floods has not ended as suggested by large floods in the early 1980s and 1990s. If this occurs, it is likely that the sediment inflow rate to the reservoir will increase.

The trap efficiency of Lake Powell is almost 1.0, meaning that most sediment inflow is trapped in the reservoir. The best estimate of reservoir sediment inflow is a measure of the accumulated volume. The most recent survey of sediment in Lake Powell occurred in 1986 (Ron Ferrari, personal communication, US Bureau of Reclamation). Ferrari (1988) estimated that

---

[5] Flaming Gorge reservoir was created in 1962 by impoundment of the Green River behind Flaming Gorge Dam. Located in northeast Utah and southwest Wyoming, the reservoir is 91 miles long and covers 42,000 acres

sediment accumulated at the rate of 36,946 af/y from March 1963 through September, 1986 which suggests that about 3% of the reservoir capacity was lost by 1986.

All of the sediment flow rates discussed above used weight as the load measure. To convert into volume in the reservoir, it is necessary to estimate the unit weight of the sediment. Ferrari (1988) did not estimate the sediment unit weight. The only estimate I have been able to locate is from a letter from Floyd Dominny to the Congress[6] in which he assumed the sediment to weight 65 lbs/ft^3.

Table 2 shows measured specific weights for reservoir deposits reported by Morris and Fan (1998). Lake Powell fluctuates 20 to 30 feet annually and more than 100 feet in a decade and may not qualify as a fully aerated reservoir (Table 1), but it is certainly not always submerged. The average sediment flow at Bluff, Cisco and Green River for 1963 though the early 80's (depending upon gage discontinuation) is 37.6 million t/y. Andrews (1991) estimates that tributaries below the three gages contribute 29.6 % of additional sediment to the average inflow to 48.8 million t/y. Using Ferrari's estimate of inflow gives 1318 t/af or 60 lbs/ft^3. If 60 lbs/ft^3 is accurate, Table 2 suggests there is a substantial amount of silt in the sediment. This corresponds to the statement in USER (1995) that the load is primarily silt and clay. From this we infer that beach sand must be a small part of the load.

---

[6] This letter was attached to an article by David Brower (1968) published in

Table 2: Typical Specific Weights (lbs/ft^3) for Reservoir Deposits (after Morris and Fan (1998))

	Reservoir operation	
Dominant grain size	Always submerged	Aerated
Clay	40-60	60-80
Silt	55-75	75-85
Clay-silt mixture	40-65	65-85
Sand-silt mixture	75-95	95-110
Clay-silt-sand mixture	50-80	80-100
Sand	85-100	85-100
Gravel	85-125	85-125
Poorly sorted sand and gravel	95-130	95-130

Prior to 1941, the Lees Ferry gage provides the best estimate for sediment inflow to Glen Canyon. Inflow below the other gages is not well related to flows at those gages, therefore regression based record extension is not likely to provide an accurate estimate. Using the five years of record at Lees Ferry, the average inflow to Glen Canyon was 142,000 af/y, or 3.8 times the average inflow since dam construction. The average inflow based on the 1941 to 1957 record was 45,900 af/y. Since construction, the rate has been 36,900 af/y.

How Long Before the Reservoir is Full?

Reservoir Deposits: Ferrari (1988) measured 868,231 af of sediment in the reservoir below the 3700 foot level. The location of the deposits is complicated because of multiple inflow points and the fact that the reservoir took 17 years to fill. The sediment deposits are a mixture of delta deposits on the major inflow rivers and tributaries and wedge deposits near the dam (Morris and Fan, 1998). Approximately 472,000 af of sediment occurred in the Colorado River area, 281,000 af occurred in the San Juan River area and about 115,000 af occurred in the remaining tributaries. These are not accurate measures of specific tributary load because sediment from side canyons could be moved by dynamic currents into the main channel. Also, sediment from the main channel may circulate into side channels.

The location and depth of sediment within the reservoir depends on source loads, sediment gradation, reservoir operations, and flow velocities. As the reservoir was filling, deposition occurred wherever the flowing river met the stagnant reservoir pool. Most sediment deposition occurs in a delta on each of the major tributaries. Deltas have a "pivot point" above which their slope is very flat and below which they drop rapidly to the original river level. Delta pivot points usually form at an elevation corresponding to the average pool elevation. The location of the toe depends on the sediment gradation.

On the Colorado River arm, the delta forms at elevation 3400 and rises to a pivot point at 3670 feet. This level is below the mean operating pool of 3685 because the Colorado River arm has high velocity due to the narrow canyon. The delta forms at 3300 feet in the San Juan and rises to a pivot point at 3690 feet. This is higher than the Colorado River arm because of slow velocities and higher sediment concentration. Although Ferrari does not discuss it, the different delta shapes could reflect different sediment size distributions. The lower delta "toe" in the San Juan arm probably indicates finer sediment being transported further into the reservoir. T

The cross-sections throughout the deltas have a flat deposition surface. This tendency to accumulate in the deepest portion of the cross-section (the thalweg) reflects the turbid density currents and the logarithmic vertical concentration profile which causes higher concentrations at the deepest points (Morris and Fan, 1998).

Dead storage occurs between 3120 and 3370 and inactive storage occurs between 3370 and 3490. Because the delta volumes are predominately above this point, most of the lost volume is from active conservation (3490 to 3700) and active flood control (3700 to 3711).

Side canyons below the reservoir water levels are also inundated, but the depth of sediment varies in relation to the sediment producing capabilities of each drainage area and the frequency of high flows. Ferrari (1988) provides profile plots of numerous side canyons. Sediment depth varies from 30 to 50 feet in the downstream 27 miles of the Escalante River. The

Dirty Devil River has over 100 feet of sediment at its mouth and 80 feet at the delta pivot point 9 miles above the mouth. The upper end of the delta is 20 miles upstream from the mouth. Profiles in Rainbow Bridge canyon show about 25 feet of sediment just below the arch. Profiles of Antelope, Aztec Creek, Bullfrog Creek, Cedar Canyon, Farley Canyon, Gunsight Canyon, Halls Creek, Hansen Creek, Iceberg Canyon, Kane Creek, Knowles Canyon, Lake Canyon, Last Chance Canyon, Little Valley Canyon, Moke Canyon, Navajo Canyon, Red Canyon, Rock Creek, Wahweap Canyon, Warm Creek, West Canyon, and White Canyon suggest that an average depth of sediment in side canyons ranges from 30 to 50 feet.

Rate of Accumulation: Ferrari estimated that 36,946 af/y of sediment deposited in Lake Powell between 1963 and 1986 and that the reservoir had more than 700 years before it was full to the 3700 foot elevation. Because of normal variability in flooding and sediment production, the inflow rate could increase substantially as during previous periods. This section considers compaction and inflow and provides a range of estimates for the time for the reservoir to fill.

Coarse sediment deposits in deltas with very fine material depositing near the dam. Ferrari's (1988) profile plots show about 40 feet of accumulation at the dam that extends for about 40 miles above the dam. The canyon at this point is about 450 feet wide. Based on several assumptions, we estimate that 7.9% of the sediment inflow deposited in the canyon just above the dam. This deposition will eventually impinge on dam operations. The canyon rises approximately 70 more feet before it widens substantially to about 1000 feet. The lower intake to the penstock is at elevation 3470 and the minimum level for power generation is 3490 (Ferrari, 1988). Accounting for canyon shape and assuming the same rate of deposition at the dam and at the delta, the intake will be reached in 422 years. Total reservoir volume below 3490 is about 6,200,000 af. It is important not to assume that when the sediment volume reaches 6,200,000 af that the penstocks will be inoperable. Currently, 65.8% of the sediment volume occurs above this elevation, primarily in deltas. The reservoir will be almost full before the deltas reach the canyon just upstream from the dam.

Delta deposits grow by extending the toe farther into the reservoir. The coarsest sediment settles first in the deltas which have a lot of room to grow. Almost 13,000,000 af of reservoir volume exists above elevation 3600 and 33% of the sediment volume currently is above this elevation. Of course, much of that is in the wider portion of the reservoir. That will be the last of the reservoir to fill.

Life of the Reservoir: Reservoir lives should be measured in half lives because the sediment trapping efficiency decreases as the remaining volume decreases and because of sediment compaction (Morris and Fan, 1998). The current trapping efficiency is currently near 1.0 which means that most sediment inflow is captured, although it is probable that a few percent of the finest material which reaches the dam is discharged. (Only 7.9% of total inflow reaches the dam; a few percent of that means that only about 0.2% of total sediment inflow does not deposit in the reservoir or that 99.8% of the inflow is trapped.) Once the capacity is reduced to only about 70% of the average inflow, the trapping efficiency will begin to decrease. With annual runoff near 12,000,000 af/y, the reservoir volume must decrease to about 9,000,000 af before trapping efficiency significantly decreases. Thus, trapping efficiency is not important for estimating the life of Lake Powell.

Compaction, or consolidation of the deposits, occurs because of the weight of deposits. Smaller particles compact more because they begin loosely packed because of their shape and molecular charges. Large particles tend to rest directly against each other preventing much additional compaction. Yang (1996) recommends use of the following equation for estimating sediment density after T years of operations:

$$W_T = W_0 + 0.4343\ K\ \left(\frac{T}{T-1}\ \ln T\ -\ 1\right)$$

W_0 is the original specific weight (determined above to be 60 lb/ft^3), T is time in years, and K is a constant based on the type of reservoir operation and sediment size. The three types of reservoir operation are (1) sediment always submerged, (2) moderate to considerable drawdown and (3) reservoir normally empty. With decadal ranges more than 100 feet but annual ranges of less than .30 feet, Lake Powell probably is somewhere between type 1 and 2. Ferrari (1988) found that a Type I curve best described Lake Powell, but his figure shows substantial variation. Assuming silt[7], K will be about 3.8. The unit weight increases to about 69 lb/ft^3 after 700 years (Figure 6).

At the current sediment inflow rate and considering compaction, Lake Powell will require about 800 years to reach 26 million af (Figure 7). If sediment inflow increases to rates seen prior to 1941, the same volume will fill in less than 200 years. Other scenarios could result in intermediate predictions. Because most watersheds experience threshold dynamics (Richards, 1982), the inflow rate will probably fluctuate so that the time until Lake Powell fills with sediment is probably between 200 and 800 years.

Impacts of Draining Glen Canyon Reservoir

Rate of Canyon Recovery: Canyon recovery will vary between the two main river, the two main tributary rivers, and the numerous small canyons and slot canyons.

Sediment deposits currently inundate the upper ends of the main Colorado River and San Juan River channels. The rate that sediment will erode from the channel so that some semblance of previous channel reforms is relatively constant because there are annual snowmelt floods. Erosion will eventually reestablish the profile that existed before the dam. The rate of sediment removal depends on the depth of sediment, its erodibility, the establishment of riparian vegetation, and the duration and shear stress of the river inflows. If the critical shear stress is exceeded for a substantial duration, the rate of erosion will probably be quite high. Delta deposits span the river from canyon wall to canyon wall. The river will begin to cut a new channel immediately. Its'

---

[7] This assumption is based on the small amount of sediment that reaches the dam. That is likely to be the clay portion. However, 60 ft^3/lb as calculated for the inflow is too low to have much sand. It is at the low end of the silt range.

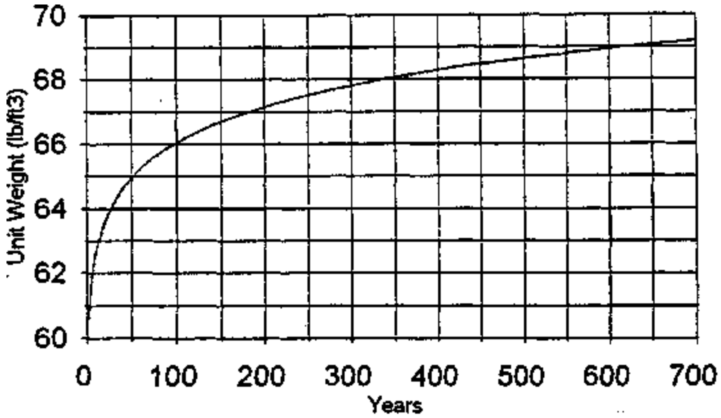

Sediment Unit Weight

Figure 6: Decrease of sediment unit weight with time.

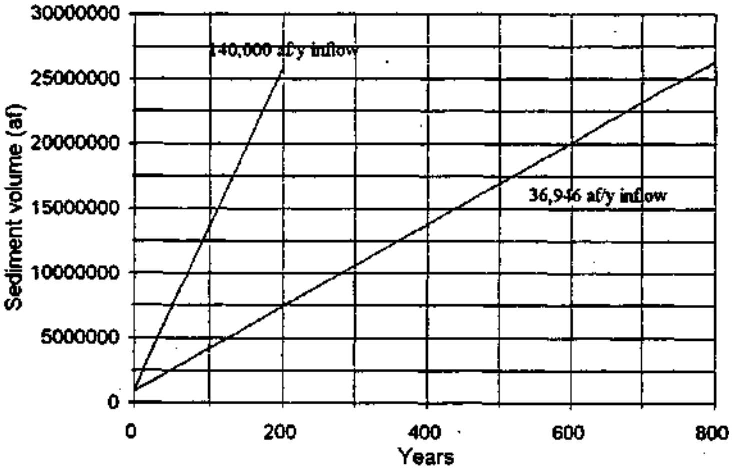

Lake Powell
Sediment Fill Curve

Figure 7: Lake Powell sediment volume with time for two sediment inflow rates.

shape will be determined by the flow rate, gradient and size and cohesiveness of the sediment. Initially, the channel will probably have vertical side walls into which erosion will cut. A floodplain will form by cantilever failures and slumping which will widen the channel. There will be terraces of sediment above the forming channel and floodplain. These will erode by wind and rain and may be stabilized by vegetation. If vegetation stabilization occurs, there will probably be more sediment in the recovered canyon than in the original Glen Canyon. The amount of remaining sediment will vary with canyon width and the rate at which the reservoir is drawn down.

Ferrari's (1988) range profiles allow estimates of the amount of sediment that needs to erode from portions of the canyon to clear it out. For example, at a wide spot two miles below the Dirty Devil River there is a maximum sediment depth of 75 feet and a maximum width of more than 700 feet[8]. The water depth, when the reservoir is at 3700, is 180 feet. The depth just upstream from the Dirty Devil River decreases to 145 feet with 95 feet of sediment and similar width. Moving upstream through Cataract Canyon, the sediment thickness increases to a maximum of 180 feet just downstream from Dark Canyon. Water depth at this point is just 25 feet while width is just 350 feet.

However, substantial portions of the river channel are essentially free of sediment. Deltas formed upstream from these reaches and finer sediment moved through the reaches on density currents. From above Good Hope Bay to Rainbow Bridge the river profile has not changed. The downstream 5 miles of the San Juan also appears to be free of sediment. Any plan to drain Lake Powell should consider whether sediment should be transported through this reach to avoid the sediment impacts.

There are two analyses performed herein to estimate the time for canyons to recover. First, we performed a water surface profile analysis to determine the flow velocity and shear stress

[8] Note that most range profiles show a flat sediment surface.

for representative channel shapes for both major rivers and slot canyons. This analysis provides information on how long the river or side canyon flow exceeds a critical velocity needed to initiate sediment movement. Considering typical hydrographs, it is possible to determine the length of time that erosion will remove sediment and form a new active channel (Richards, 1982). Second, we performed a regional flood frequency analysis on gaging stations in southern Utah based on drainage area. This will estimate the frequency and magnitude of flood flows in Glen Canyon tributary slot canyons.

Shear Stress Analysis: At the Lees Ferry gage prior to the building of the dam, sediment concentrations were as high as 3.33 %. The highest concentrations occurred during the late summer due to tributary flows from monsoonal storms. This supports a conclusion that concentrations are supply limited. This means that the river flow could transport more sediment if it was available. Most of the reservoir deposits are fine grained. When the critical velocity is exceeded, an ample supply of sediment will be mobilized and sediment transport will be close to sediment carrying capacity. For this analysis, we assume that concentrations in the river when it is cutting into reservoir sediment deposits will be 3%.

The American Society of Civil Engineers Sedimentation Task Committee (Vanoni, 1977) published a graph of critical water velocities necessary for initiating sediment movement. The upper velocity range for eroding fine silt to fine sand is between 3.5 to 1.2 fps, respectively. For simplicity, this analysis uses 3 fps for incipient motion. Flows that cause channel velocities to exceed 3 fps initiate erosion and the resulting sediment concentration will approximate 3%.

The HECRAS (Hydrologic Engineering Center River Analysis System) water surface profile model was used to estimate flow velocities for an assumed river cross-section. The assumption was for a B-channel type cross-sectional shape (Rosgen, 1993). The B-channel shape has a width/depth ratio of about 12, sinuosity from 1.2 to 1.4, and is moderately entrenched. Side channel slopes are 3:1. Multiple profile runs of a range of flows were run for the assumed shape and measured profile slopes (Ferrari, 1988). Various slopes were imposed on the profile.

Mannings roughness coefficients were 0.05 and 0.03 for overbanks and channel bottoms, respectively. The higher overbank values reflect new vegetation and rougher sediment bedforms.

For the Colorado River, 15 profiles with Q equal to 1000, 2000, 4000, 6000, 8000, 10000, 15000, 20000, 25000, 30000, 35000, 40000, 45000, 50000, 60000 and 70000 resulted in channel velocities exceeding 3 fps for most slopes (Figure 8). Thus, flows greater than 1000 cfs would initiate sediment movement and transport sediment at a 3% concentration.

For the San Juan River, 15 profiles with Q equal to 200, 400, 600, 800, 1000, 1500, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000 and 10000 cfs had fewer velocities exceeding 3 fps (Figure 9). For further analysis, the threshold for sediment transport was 800 cfs, therefore all flows over 800 cfs were assumed to transport sediment at a 3% concentration.

Almost all flows exceed 1000 cfs at the Colorado River at Cisco gage (Figure 10) while about 18% of all flows are less than 800 cfs at the San Juan River at Bluff gage (Figure 11). This means that the Colorado River always flows at rates sufficient to erode the deposits. The San Juan River flows at rates sufficient to erode deposits for about 82% of the time.

In order to consider how long it will take sediment deposits to be removed, we analyzed annual hydrographs for 1973 and 1974, representative wet and dry years, for both rivers. We calculated daily load based on mean flow rate and 3% sediment concentration. Using the appropriate specific weight, we then converted it to volume in acre-feet.

During the dry and wet year, respectively, almost 340,000 af and 480,000 af is removed from the Colorado River (Figure 12). Corresponding values on the San Juan River are 60,000 af and 220,000 af (Figure 13). Ferrari (1988) indicated that 472,000 and 281,000 af of sediment deposited in the Colorado and San Juan River segments, respectively. This suggests that all

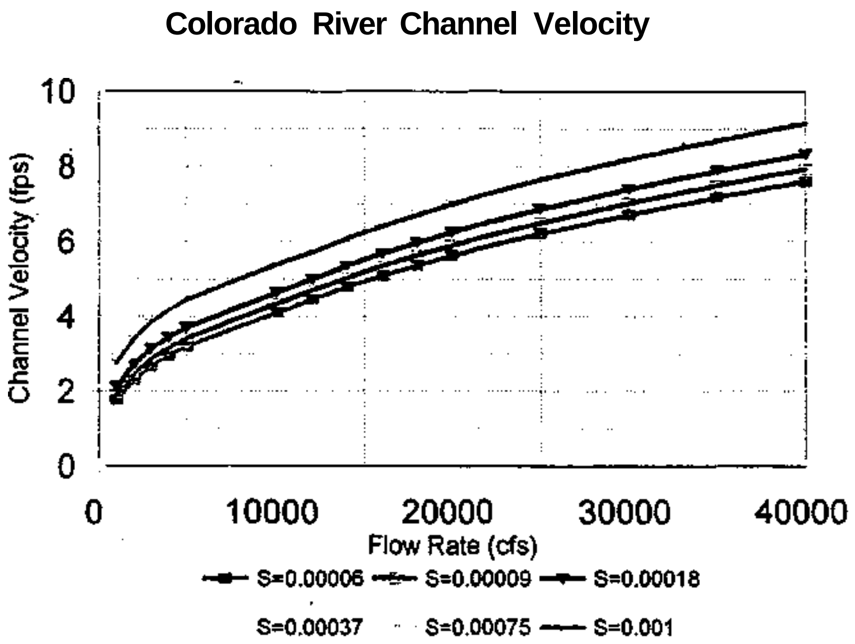


Figure 8: Channel velocity as a function of flow rate for the Colorado River a recovering Glen Canyon.

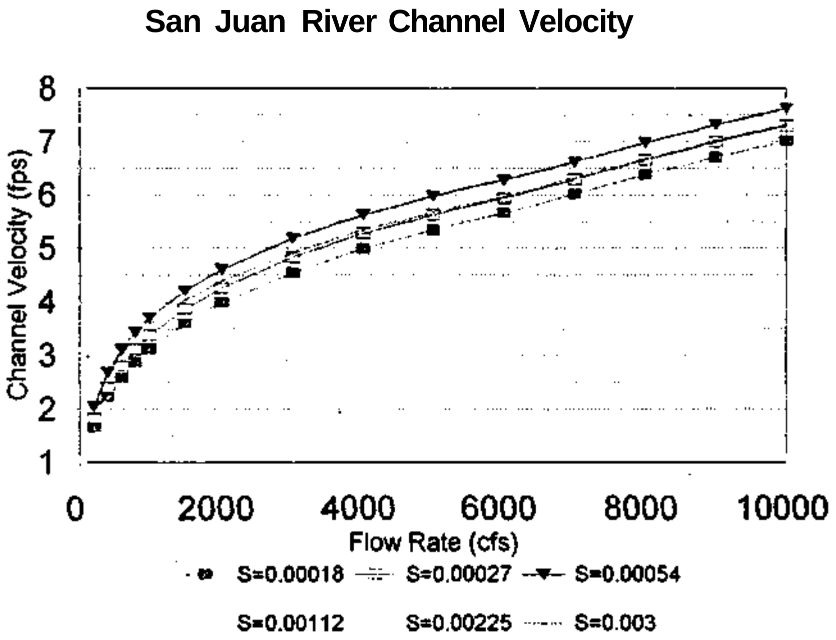


Figure 9: Channel velocity as a function of flow rate for the San Juan River a recovering river channel.

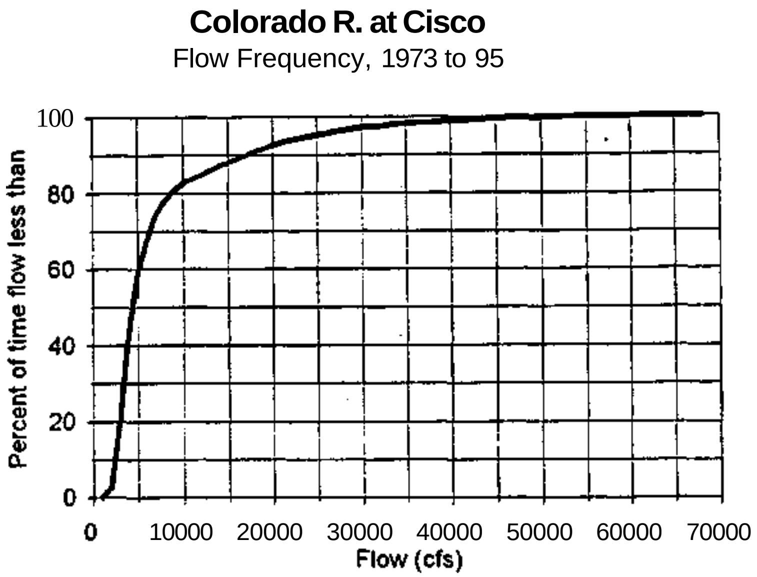


Figure 10: Flow frequency on the Colorado River above Glen Canyon.

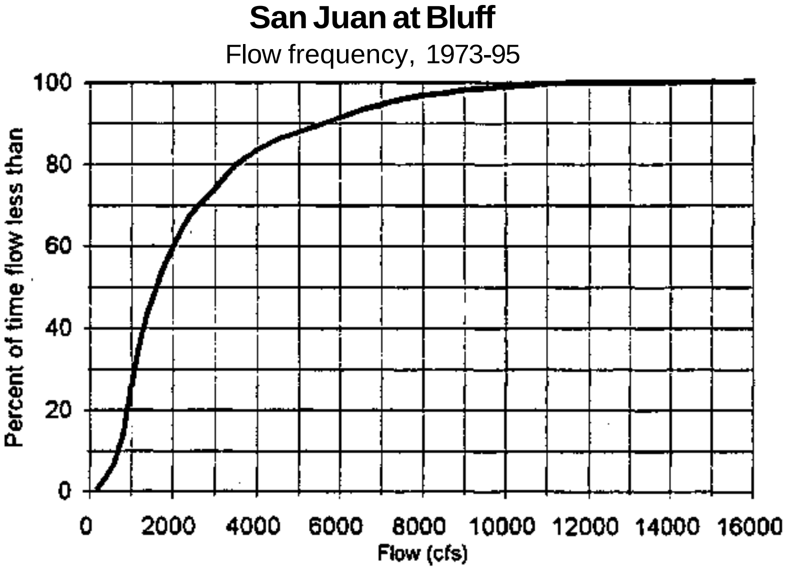


Figure 11: Flow frequency on the San Juan River above Glen Canyon.

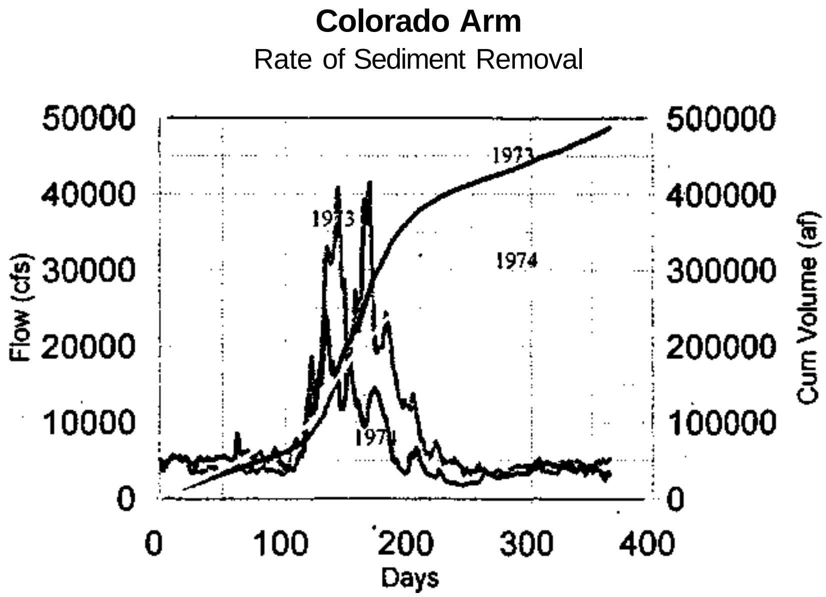


Figure 12: Hydrographs and cum. sediment removal for the Colorado River in Glen Canyon.

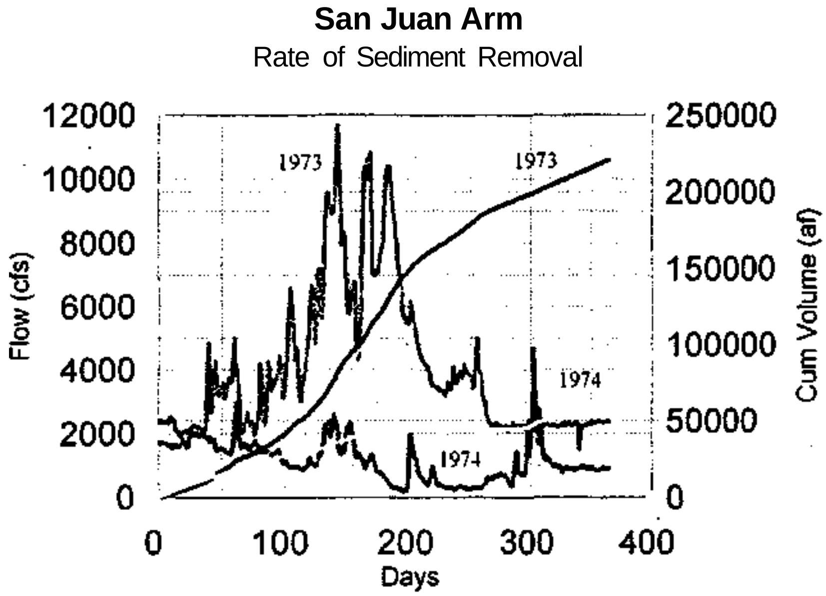


Figure 13: Hydrographs and cum. sediment removal for the San Juan River in Glen Canyon.

sediment could be removed from the Colorado River in 1 to 2 years. It will require from 2 to about 6 years to remove all sediment from the San Juan River. As discussed above, the river will probably incise and leave terraces above the flowing water. The capacity for the river to move sediment indicates that the final channel will have formed within just a few years. Because of a river's tendency to meander at wavelengths dependent on the flow rate (Richards, 1982), there may be a tendency for the river to move around on the former delta eroding the terraces.

Tributaries such as the Escalante River and Dirty Devil River probably will mimic the main rivers. The Escalante was filled with no more than 40 feet of sediment and the canyon often expanded from 200 feet to 400 feet from the bottom to the top of the sediment. Over about 27 miles, the Escalante has about 39,000 af. The Dirty Devil is about 200 feet wide and 100 feet deep for about 16 miles. This volume is also about 39,000 af.

Flows in slot canyons almost always have sufficient velocity to remove the sediment. It is more important to consider how often sufficient flows occur rather than the velocity. In most instances, this coincides with canyon flooding frequency. A flow of 1000 cfs for a day removes about 150 af.

These results indicate that there is great flexibility in designing sediment removal strategy. The final channel and terrace shapes will reflect the rate that the reservoir is drained. There is 13,000,000 af of water in the top 100 feet and 7,000,000 af in the next 100 feet. The reservoir will be 10/13ths empty before the level has dropped 200 feet. Rapid drainage will allow channel incision to occur and cause high, dry terraces. Sediment will be transported into the currently clean mid reservoir channel reaches. Slow drainage will allow sediment to be slowly transported from the higher levels of the delta downstream toward the toes. This would allow an active channel, floodplain and terraces to form. The terraces could become vegetated before water levels are lowered, thereby partially stabilizing them. Then, rapid drainage through the mid levels could move the sediment through the clean channel reaches quickly.

Regional Flood Frequency Analysis: The analysis above suggests that most flows will exceed the critical velocity for incipient motion. Many tributaries have only a few feet of sediment in large lengths of their canyon (Ferrari, 1988). All that is required is for the washes to experience flows and most of the sediment will be removed. This analysis focuses on the magnitude of low return interval floods.

A regional flood frequency analysis provides a basis for estimating flood flows and their return intervals for basins that do not have gages. For this analysis, all gages with more than 15 years of record in the upper Lake Powell, upper Colorado River, Kane Springs, lower Lake Powell, lower San Juan, lower Green, Colorado headwaters Plateau, Dirty Devil and Escalante regions of Utah were used for the analysis. The log-Pearson type III frequency curve as implemented in Bulletin 17b (WRC, 1982) and programed in the USGS program PEAKFQ was used for determining flood flows and frequencies. Table 3 presents estimated flood flows for the 2-, 5-, 10- and 25- year flood and drainage area for the analyzed gages.

Table 3: Flood Peak Flows for Washes in the Regional Flood Frequency Analysis

Station	Area (mi^2)	Q2	Q5	Q10	Q25
09187000	115	394	1274	2308	4297
09316000	75	1816	3763	5402	7829
09182000	7.58	9.5	19.1	26.6	37.0
09183000	162	2142	4635	7005	10960
09185500	378	501	1221	1955	3241
09185800	2.48	Regulated, not calculated			
09186500	31.2	Regulated, not calculated			
09185200	17.8	534	843	1060	1341
09184000	74.9	658	1724	2843	4839
09334000	136	1187	3073	4993	8304
09315500	180	2467	4768	6654	9413
09182600	3.9	281	727	1167	1900
09334500	276	2202	4257	5973	8532

Table 3 (continued)

List of Gaging Stations

Station-09187000	COTTONWOOD CREEK NEAR MONTICELLO, UTAH
Station-09182000	CASTLE CREEK ABOVE DIVERSIONS, NEAR MOAB, UTAH
Station-09183000	COURTHOUSE WASH NEAR MOAB, UTAH
Station-09183000	COURTHOUSE WASH NEAR MOAB, UTAH
Station-09185500	HATCH WASH NEAR LA SAL, UTAH
Station-09185800	INDIAN CREEK TUNNEL NEAR MONTICELLO, UTAH
Station-09186500	INDIAN C AB COTTONWOOD CREEK, NR MONTICELLO, UT
Station-09184000	MILL CREEK NEAR MOAB, UT
Station-09185200	KANE SPRINGS CANYON NEAR MOAB, UTAH
Station - 09334000	NORTH WASH NEAR HANKSVILLE (KITE), UTAH
Station-09315500	SALERATUS WASH AT GREEN RIVER, UTAH
Station-09182600	SALT WASH NEAR THOMPSON, UTAH
Station - 09334500	WHITE CANYON NEAR HANKSVILLE UTAH

Following Stedinger et al (1982), we fit the four presented return interval flows to the following equation using ordinary least squares regression[9]:

$$Q_i = \alpha + \beta_1 \log(area)$$

Qi is the flow for return interval I. Table 4 presents the coefficients and coefficient of determination for this analysis.

Table 4: Results of Regional Frequency Regression Analysis

Return Interval	α	β	R^2
2	-407	827	0.36
5	-817	1752	0.42
10	-1180	2599	0.46
25	-1761	3974	0.49

---

[9] This type of regression analysis could utilize other geomorphic parameters such as basin slope, relief, drainage density, etc. For the purpose of this analysis, the easily available area probably provides accurate enough results.

Due to the negative intercept, the second term of the relation must exceed the value of the intercept to make the equation positive, and meaningful. The minimum area for these relations is 3.1, 2.9, 2.8, and 2.8 mi^2, respectively, which corresponds with the point where the straight lines in Figure 14 intersect the x-axis.

The coefficient of determination increases with return interval suggesting that watershed area explains more variance for larger floods. This implies that storms cause large floods when centered over a larger proportion of the watershed. This explains why not all heavy showers produce large floods. The location of the storm is as important as the rain intensity. There is more variability for small areas. The two smallest basins have extremely different frequency curves (Table 4), Smaller areas are influenced more by small anomalies such as the centering of the storms over steep impervious areas.

Another important point about these stations is that floods occurred in most years, even in the smallest basins. This suggests that most tributaries to Glen Canyon have flooding in most years which will cause rapid removal of sediment from slot canyons.

Summary of Canyon Recovery: The uncontrolled mainstem river experiences flows sufficient to move sand, silt and clay for many months even in dry years. It is apparent that the river will downcut through and form an active channel within existing sediment deposits with high terraces forming above (100 to 200 feet) the channel. Migrating rivers will rework the beaches and terraces in places; in other places, rapid vegetation growth will stabilize the sand.

The rate that small drainages and side canyons clean will be vary depending on drainage area and characteristics. Sediment depths in the lower end of small drainages is very poorly known. A 10 foot wide slot buried in 10 feet of sediment for five miles has 60 af of sediment to be removed. A 1000 cfs flow for 24 hours was shown above to remove 150 af. Clearly, this will remove the majority of sediment from the slot just described. However, floods on slot canyons frequently are very short in duration, therefore the 24 hour-assumption may be inappropriate.

@ *

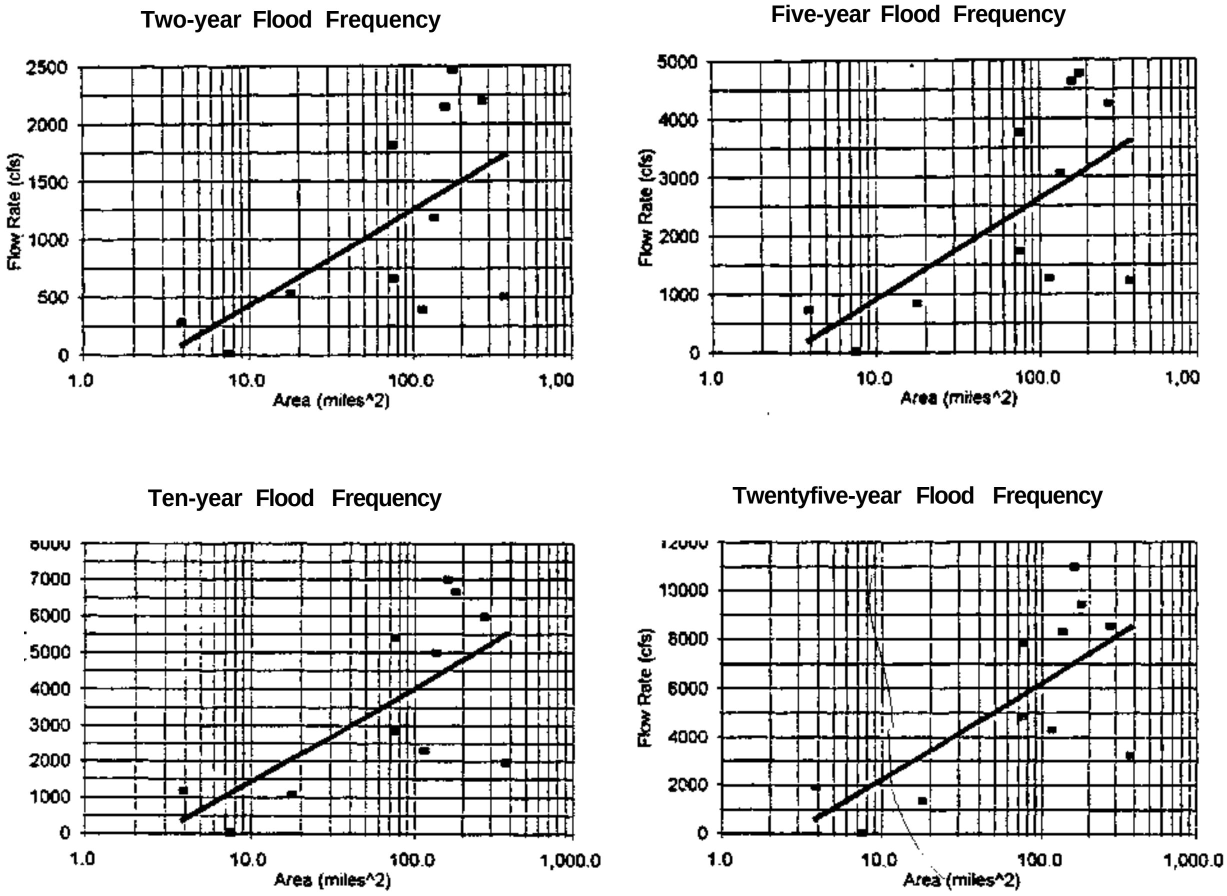


Figure 14: Flow rate versus drainage area relationships for two-, five-, ten- and twenty-five-year return interval flood flows for small gages in southern Utah and northern Arizona. The record lengths are too short to have sufficient accuracy in the estimation of higher return period flood flows.

Also, there is a wide scatter around the predictions of flood runoff with area. The following table provides duration times necessary to remove 60 af of sediment for various flow rates. Based on these calculations, it is obvious that the time for sediment removal from small slots is variable. However, the flood frequency analysis suggests that most canyons experience eroding flows most years. Therefore, Table 5 provides an indication the time required to clean out the canyons. .

Table 5: Time for 60 AF of Sediment Removal from a 10-foot Slot

Flow Rate (cfs)	Sediment Removed (af) For 24-hour Duration	Time (hr) to Remove 60 Af of Sediment
100	15	96
1000	150	9.6
5000	750	1.9
25000	3750	0.4

Grand Canyon

> *To make imposing canyons you need a considerable river canying a large amount of abrasive material But that river must flow through an arid country where the breaking down and widening of the sides will take place more slowly in proportion to the downward cut than it does in regions of normal rainfall Because the rainfall in the West is so much less than in most other parts of the United States, the West is a country of canyons, great and small, as the East is a country of valleys. And because all the conditions for canyon-making were realized more extravagantly by the Colorado River and the region through which it ran than anywhere else on the globe, its canyon is the most triumphant example of what a river can do. There was the rising land; the swift, sand-filled river; and the arid country.* (Krutch, 1989)

The hydrology and sediment relations of the Grand Canyon were adequately considered in the Glen Canyon environmental studies. This report excerpts a points and adds a few previously unconsidered points.

Hydrology

The hydrology of the Grand Canyon prior to Glen Canyon Dam resembled that of Glen Canyon described above. The variability of the Grand Canyon gage is the same as the Lees Ferry gage (Table 1, Figure 2). Local inflow between Lees Ferry and the Grand Canyon gages averages 349,000 af/y and is as variable as Glen Canyon inflow (Figure 2). It results primarily from the Paria and Little Colorado Rivers. For example, local inflows during 1949 through 1951 were very low while river flows were normal (Figure 2). Neither flows on the San Juan River nor Glen Canyon local inflows had similar low flows.

After 1963, Grand Canyon flows changed due to Glen Canyon Dam. With the exception of floods in the early 1980s, annual flows through the Grand Canyon have been essentially constant because of the requirement to release 7.5 maf/y for the lower basin and 0.83 maf/y for Mexico[10]. The four high flow years, 1983-86, caused the high average in Table 1.

Reservoir management also decreases day-to-day and seasonal variability. Plotting two years with very similar annual runoff at the Grand Canyon, 1946 with 9,119,000 af/y and 1993 with 8,932,000 af/y, Figure 15 shows how the dam modified the annual flow distribution throughout the year. As described by the BOR:

> Predam flows were characterized by large year-to-year and seasonal variability... Melting of the mountain snowpack typically produced high runoff of long duration during the late spring and early summer. Spring flows often were characterized by double peaks. Annual maximum daily flows greater than 80,000 cfs were not uncommon; in some years they exceeded 100,000 cfs. In contrast, flows less than 3,000 cfs were typical throughout late summer, fall, and winter. (USER, 1995, page 77)

Based on Figure III-7 in USBR (1995), powerplant capacity flows of 33,200 cfs has been exceed just 2% of the time since 1963.

---

[10] The Law of the River requires that 75,000,000 af be released in any 10-year period for the Lower Basin and 830,000 af/y for Mexico. The dividing line is Lees Ferry, above the Paria River. The tributary flow is effectively Lower Basin water under current interpretation of the Law.

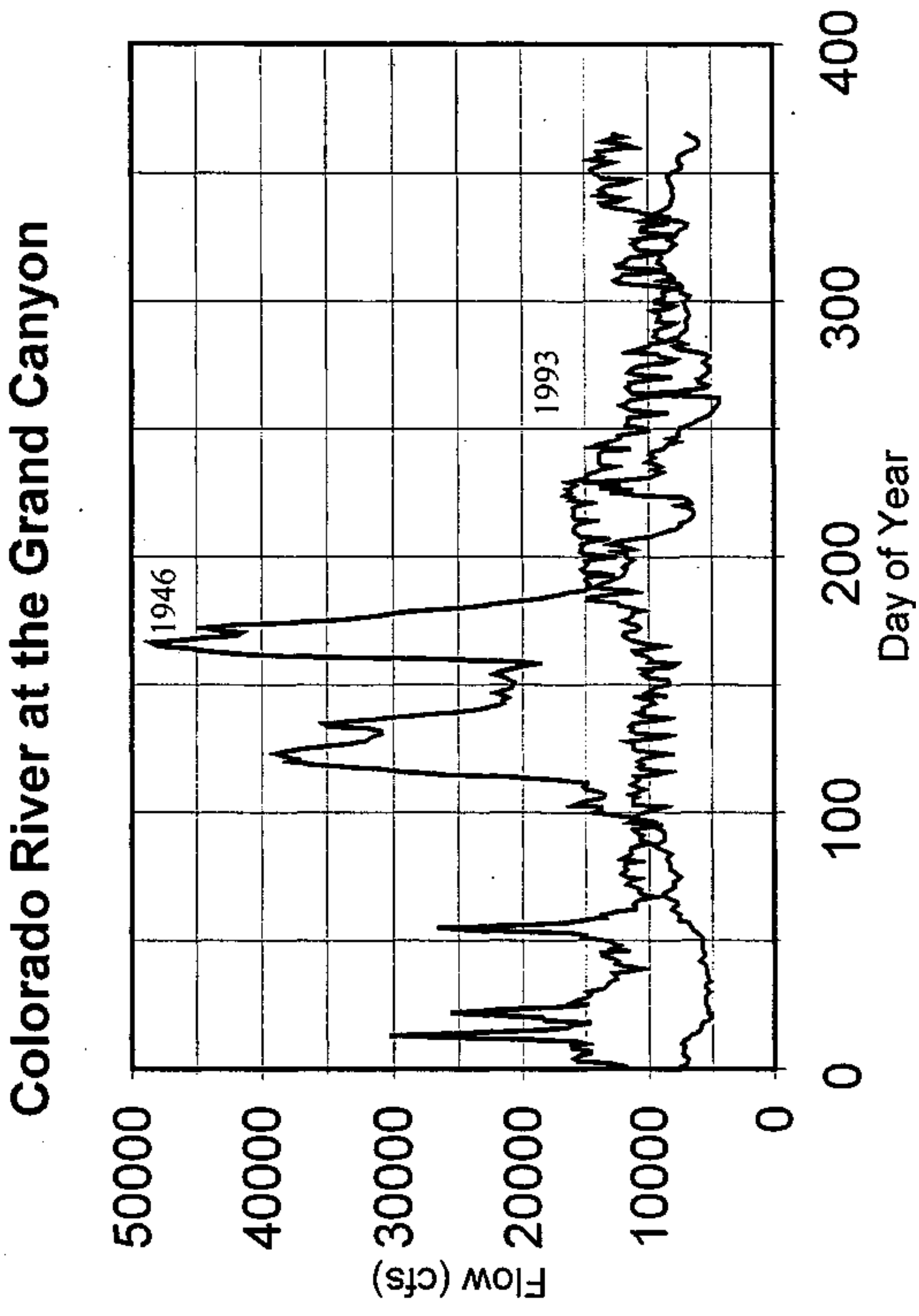


Figure 15: Daily hydrographs for the Colorado River at the Grand Canyon for 1946 and 1993 illustrating the change in seasonal variability since the closure of Glen Canyon.

Hourly flows are extremely variable in contrast to predam flows due to hydroelectric production. With 27.1% of daily minimum releases between 1000 and 2900 cfs, the daily low flows are lower than occurred prior to 1963. In contrast, 31% of the daily maximum releases exceeded 25,000 cfs. Over 15% of all days had fluctuations that exceed 20,000 cfs and 43.4% have fluctuations that range from 12,100 to 20,000 cfs. To exactly meet the requirements for the lower basin, the average release would be 11,506 cfs.

The variability is caused by ramping, the rapid increase or decrease in flow through the turbines to meet daily power demands. Ramp up rates, the rate of increase, and ramp down rates exceeded 8000 cfs/hour over 11% and 7% of the time, respectively. Decreasing these ramping rates is one of the primary objectives of the Glen Canyon Dam Environmental Impact Statement because they cause much of the damage to riparian and aquatic ecosystems in the Grand Canyon.

Sediment Inflow

Prior to the closure of Glen Canyon Dam, sediment flow at Lees Ferry was the primary sediment source for the Grand Canyon. The average load at Lees Ferry dropped to less than 60,000,000 t/y from 1941 to 1957 after a five-year average, 1928 to 1933, of 186,000,000 t/y (Figure 3). The Paria and Little Colorado River contributed 18.6%, or about 12,000,000 t/y, of the Lee's Ferry load between 1941 and 1957. USSR reported that since dam construction, the load at the Grand Canyon has been 11,000,000 t/y and that 70% comes from the Paria and Little Colorado Rivers. They also reported that 700,000 t/y were added from the side tributaries in the Grand Canyon. Some of this input is included in the Grand Canyon estimate.

Hereford (1986) reconstructed channel changes in the Paria River for the past 100 years. Arroyo cutting began in 1883 and widened to a maximum around 1940 after which it narrowed and became vegetated. Aggradation in the lower part of the river between 1939 and 1964 indicates that 2 meters (7 feet) of sediment had deposited. Over a ten mile reach, fifty feet wide, this an accumulation of 424 acre-feet or 785,000 t (specific weight of 85lb/ft3). Compared with the 1941-57 average sediment inflow of 2.74 million t/y from the Paria, this accumulation of 30,000 t/y is trivial. This suggests that tributary sediment inflow has remained relatively constant.

Sediment Transport

Water released from Glen Canyon is clean, or "hungry" which means that it is carrying little load and has a high capacity to carry sediment. However, low flows leaving the dam have little transport capacity for large sediment. Limited supply and reduced transport capacity combine to cause the existing problems of sediment transport in the Grand Canyon. Transport capacities vary throughout the canyon based on localized gradient, river width and flow rate. Silt and clay still reach Lake Mead. Much of the following discussion is from USER (1995).

Sand is the primary sediment of concern to Grand Canyon ecology. Sand predominates on the beaches on which riparian vegetation grows and recreationists camp. The river's sand transport capacity is extremely variable depending on location and flow rate and depends on ramping of the reservoir releases. Clean water releases have decreased sand storage between Glen Canyon and the Little Colorado River while there has been a net increase of sand storage below the LCR. The average reservoir releases are capable of transporting the annual load from the Paria River, thus the reach above the LCR is likely to continue to erode and armor the bed.

Narrow, steep reaches of the river in the Grand Canyon account for 90% of the total drop through the canyon over 10% of the length. Sand transports easily through these reaches and is stored temporarily in the intervening low gradient reaches. Sand is temporarily stored in the bed, in the eddies and along the margins of the river.

Almost 27,000,000 tons of sand accumulated between Lees Ferry and Phantom Ranch by 1983, but the high flows decreased the accumulation to almost 4,000,000 tons by 1988. The majority of the eroded sand has been transported to the delta in Lake Mead.

Reservoir operations impact sandbars in the Grand Canyon by undercutting high beaches and terraces. Some lower beaches and terraces aggrade as the constant flows are incapable of transporting the sand. The dam eliminated high natural annual snowmelt peaks that usually deposit sand on high beaches. The lower flows that do transport sand deposit it on lower beaches. Eventually, lower flows erode the base of higher beaches causing sloughing into the river and onto the lower beaches. A good example of this occurred in 1993. "Floods in the LCR during January-February 1993 added much sand to the system and substantially aggraded many sandbars downstream; however, ... erosion removed much of the newly deposited sand from higher to lower elevations." (USER, 1995, page 97-98)

Constant regulated flows allow riparian vegetation to develop on certain previously barren beaches. Many productive fluvial marshes developed along the river in the Grand Canyon as a result of the controlled flows (Stevens et al, 1995). Pre-dam floods often removed or drowned nascent vegetation which traps sand making it is less available for transport in the future.

Effects of Reoperating Lake Powell

Because of the negative effects that Lake Powell operations have had on the river in the Grand Canyon, the USER performed an environmental analysis of various river operations scenarios (USER, 1995). The selected alternative, Modified Fluctuating Flow, would reduce the daily flow fluctuations described above, but the annual and seasonal flows would be essentially the same as previously existed.

The selected alternative would set minimum flows at now less than 800 cfs between 7 am and 7 pm and 5000 cfs at night. The maximum release would be 25,000 cfs. Ramp rates would be limited to 4000 cfs/h and 1500 cfs/h for increases and decreasing flows, respectively. Daily fluctuations would be limited to 5000, 6000 or 8000 cfs depending on the monthly release volume.

There would also be two types of environmental flows with this alternative. Habitat ' maintenance flows, steady high releases within the powerplant's capacity for 1 to 2 weeks in the spring, would rejuvenate backwater channels and maintain sandbars. These would occur when the reservoir volume is low. When the reservoir is high, beach/habitat-building flows would be released to rebuild high elevation sandbars, deposit nutrient, and restore backwater channels. The flows would exceed the powerplant's capacity for short durations. Apparently these flows will occur only during years that the reservoir must be lowered for flood control reasons.

The alternative was selected because it balanced power needs with the environmental needs. This alternative provided for long-term sand storage within the Grand Canyon. Models of the No Action alternative, existing conditions, suggested that all sand would eventually be removed from the canyon.

Impacts of Draining Lake Powell

Sand accumulation on lower beaches and in the river invert has been the focus of controlled floods by the USER. The primary objective of a 1996 controlled flood was to mobilize the sediments from the bottom of the Colorado River channel and to redeposit it in the eddies and near-shore areas along the river corridor. Secondary objectives included restoration and rejuvenation of near-shore habitats for native fish, avifauna and insects.

The following discussion was drawn from the report of the Glen Canyon Environmental Studies group (1996) in Flagstaff, AZ on the artificial flooding. It provides results that might be expected as close-to natural flows are restored to the river. However, these flows are much lower than natural flows through the canyon.

The artificial floods mobilized sediment from lower beaches to upper beaches. Sand bar volumes increased by an average of 53%. There was only a slight increase in planimetric area from 5% to 7% which suggests that sand was redistributed to higher elevations on bars.

Erosion rates are dictated by the range and duration of flows. Evolution of sand bar . topography during the flood was faster than anticipated in that sand storage, especially in the lateral separation eddies, aggraded and degraded by as much as 18 feet within less than 24 hours. Lower beach erosion occurred as subaqueous mass failures of steep portions of sand bars.

Most of the total sediment erosion occurs during the rising limb of the hydrograph as sediment-transport capacity is increasing. Massive scour during the beach habitat building flow was probably caused by rapid changes in eddy circulation. In most eddies that were examined, deposits at the eddy separation and reattachment points grew and were subsequently eroded from the channel and along the outer margin of the eddy. Local changes in sand storage depend upon local channel geometry and sand supply. Sand scoured from the deepest part of the channel and eddies were redeposited along the channel margins. Sand transport rates initially were increased by a factor often which then dropped off rapidly to the levels predicted by the sediment rating curves. The large pulse of sand in suspension contributed to rapid deposition rates observed during the early parts of the flood. Average velocity during the flood was 7 ft./s with a range from 5.5 to 7.2 ft/s. There was a net average deposition of 1.7 to 7 ft. of sand at the eddy reattachment points. The flood essentially scoured the eddies clean.

Since the last dam release of magnitude similar to the 1996 controlled flood occurred in 1986, 25 debris fans were aggraded by debris flows. Significant changes occurred at Lava Falls and Crystal Rapids, increasing the navigational severity of the two largest rapids in the Grand Canyon. Most of the debris fan reworking occurred during the rising hydrograph, particularly between 28,000 to 45,000 ft^3/s. The Lava Falls constriction widened from 34% to 42% and the aggraded area was reduced by 23%. Of 16 aggraded debris fans expected to be reworked during the controlled flood, 8 decreased 10% or more in size. Four debris fans had 67,000 m^3 or more eroded by the controlled flood. Velocities through rapids after the flood either remained the same or, in the case of Lava Falls Rapid decreased by 50% as a result of the controlled flood. Both Lava Falls and Crystal Rapids became significantly easier for navigation as did most of the rapids involved. As the interval between debris flows and reworking floods increases, aggraded debris fans are more difficult to rework because smaller dam releases cause particle suturing and interlocking. Debris fans should be reworked no more than 5 years after the debris flow if flood discharges are similar to the 1996 controlled flood. In general, debris fans where stream power in the Colorado River is highest, changed more than other debris fans adjacent to riffles.

New backwater habitats along the channel margins were created due to changes in shape and extent of reattachment bars. Backwaters depend on the degree to which reattachment bars are created, the amount of deposition in the channel, and the volume of water that flows through a river system. The flood scoured out return flow channels with sand floored channels and concomitantly rejuvenated the adjacent backwater habitats. Backwater numbers increased by 20% immediately after the test flows and subsequently declined in numbers during the high releases during the summer of water year 1996 as they refilled with sediment.

In summary, it is possible for flows from Glen Canyon Dam to temporarily improve conditions within the Grand Canyon. The positive impacts of artificial floods can be undone by periods of high dam releases. Wegner (1998, personal communication) indicated that flood control releases after these experimental high floods removed much of the sediment that had been deposited on the high beaches.

Only the draining of Lake Powell will allow the natural flow and sediment transport to resume. Controlled floods cannot reach the 80,000 to 120,000 cfs that were common in predam conditions. Only this type of flooding will allow the large extent of riparian vegetation to be thinned to pre-dam levels.

Below Lake Mead

> *For months at a time the river -would run low, a slack, sluggish ooze gulfward; but with the spring thawing of the mountain snowpack or -with a torrential summer storm, the sediment-carrying river would become a chaotic avalanche. Entire boulders would tumble along in the churning current. Then the river, overloaded with rock, dirt, and water, would slop over its banks onto the surrounding floodplain and lay down some of its burden.* (Worster, 1985)

Sediment Transport

Prior to reservoir development, the lower Colorado River transported substantial quantities of sediment. Seasonal flows varied from 100,000 cfs during snowmelt runoff in May and June to less than 5000 cfs during the late fall. Hydrology was very similar to that described for the Grand Canyon. Sediment loads averaged more than 200 million t/y during 1925 through 1935 leaving the Grand Canyon, but only 140 million tons made it as far as Yuma, Arizona. This indicates that the Lower Colorado River aggraded during this period (BOR, 1996). The river bottom braided as sediment deposited and constantly changed as oxbow lakes and backwaters formed (Minckley 1979).

Braiding occurs when the river flow no longer is sufficient to transport the sediment load (Richards, 1982). That the river aggraded during this period is evidence of abnormally high sediment production from the watershed. The high sediment load was the cause of the canal breach that formed the Salton Sea. The Colorado River blocked the Alamo Canal with sediment in 1904. The temporary diversion constructed to serve the Imperial Valley failed during a local flood on the Gila River in October 1905 diverting the entire flow of the Colorado River into the Salton Sink (BOR, 1996).

Reservoir development in the Lower Colorado Region effectively eliminated sediment movement along the river from upstream (Ohmart et al, 1988). Reservoir management eliminated much of the seasonal flow variability. Bedload movement is essentially nonexistant between Hoover and Imperial Dams (Ohmart et al, 1988).

Sources of Sediment

Suspended load often reflects sediment erosion from the uplands. When reservoirs trap suspended sediment, there will be a suspended load only if alternative sources exist. In the lower Colorado River, these sources include bank erosion and tributary floods.

Bank erosion has been reduced by the Bureau's channelization and riprapping program in the lower Colorado region. Reclamation maintains the channel, banklines, levee systems, and control structures along the lower Colorado River (BOR, 1996). Included are 168 miles of stabilized banklines, 114 miles of levees and 75 associated river structures including jetties and training structures (BOR, 1996). Because of this maintenance, most sediment in the river below Imperial Dam is from the Gila River. The following section documents the low sediment transport rates and the amount of sediment from the Gila River during a major flood event in early 1993.

Colorado River Sediment Transport Data: Suspended sediment concentrations were measured infrequently from 1979 to 1995 at Morales Dam. Figure 16 shows the relation between suspended sediment concentration and instantaneous flow rate. The outliers from 1993 above the average relation resulted from high sediment loading due to flooding in the Gila River. These points indicate that transport on the lower river is supply, limited. Flows after the flooding had concentrations two orders of magnitude higher than before the flooding for similar flow rates indicating that flood deposition provided sediment that the river moved for several months. Stork (personal communication, BOR) indicated that sediment from this flooding substantially decreased the capacity of the Colorado River channel through Yuma.

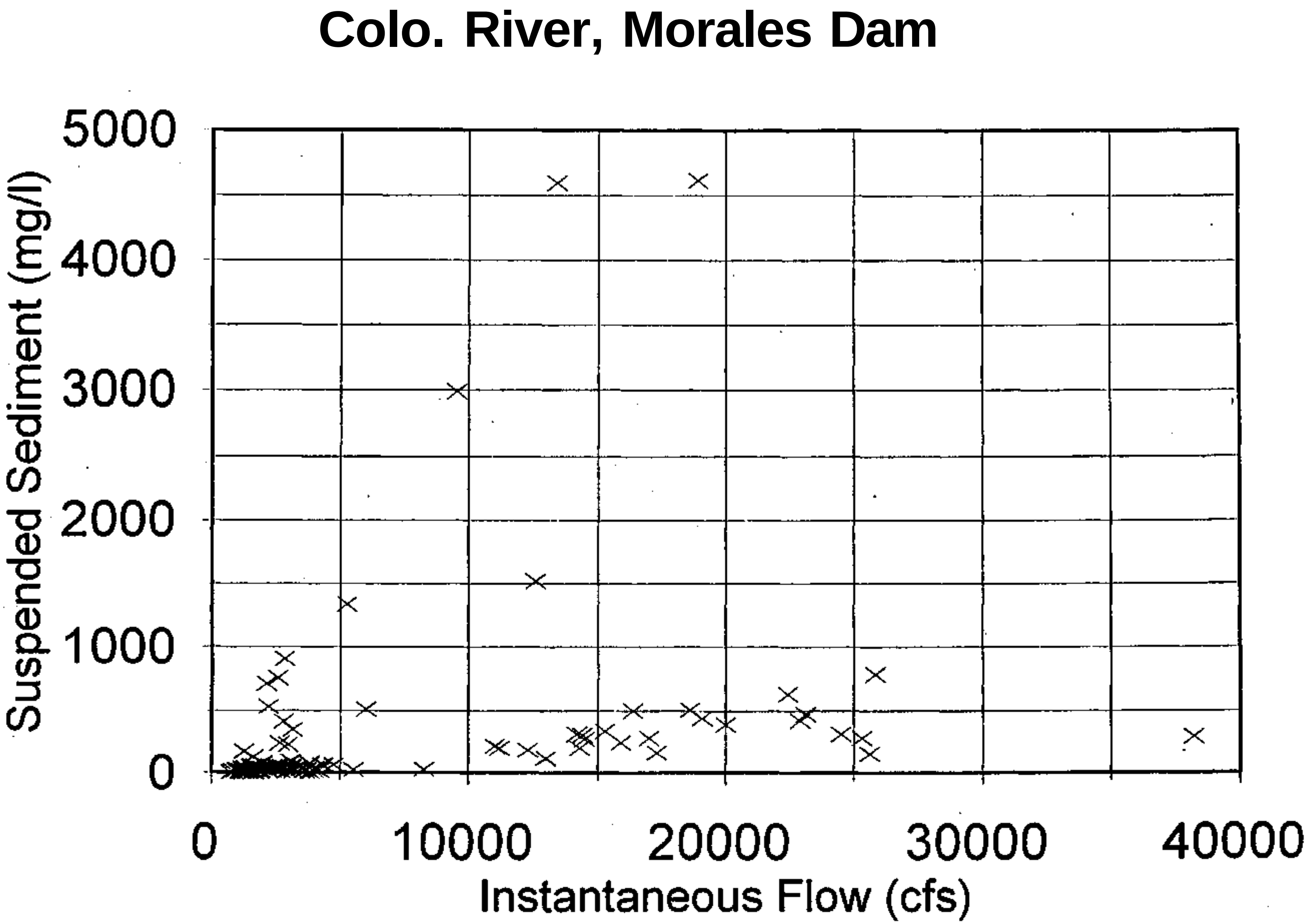


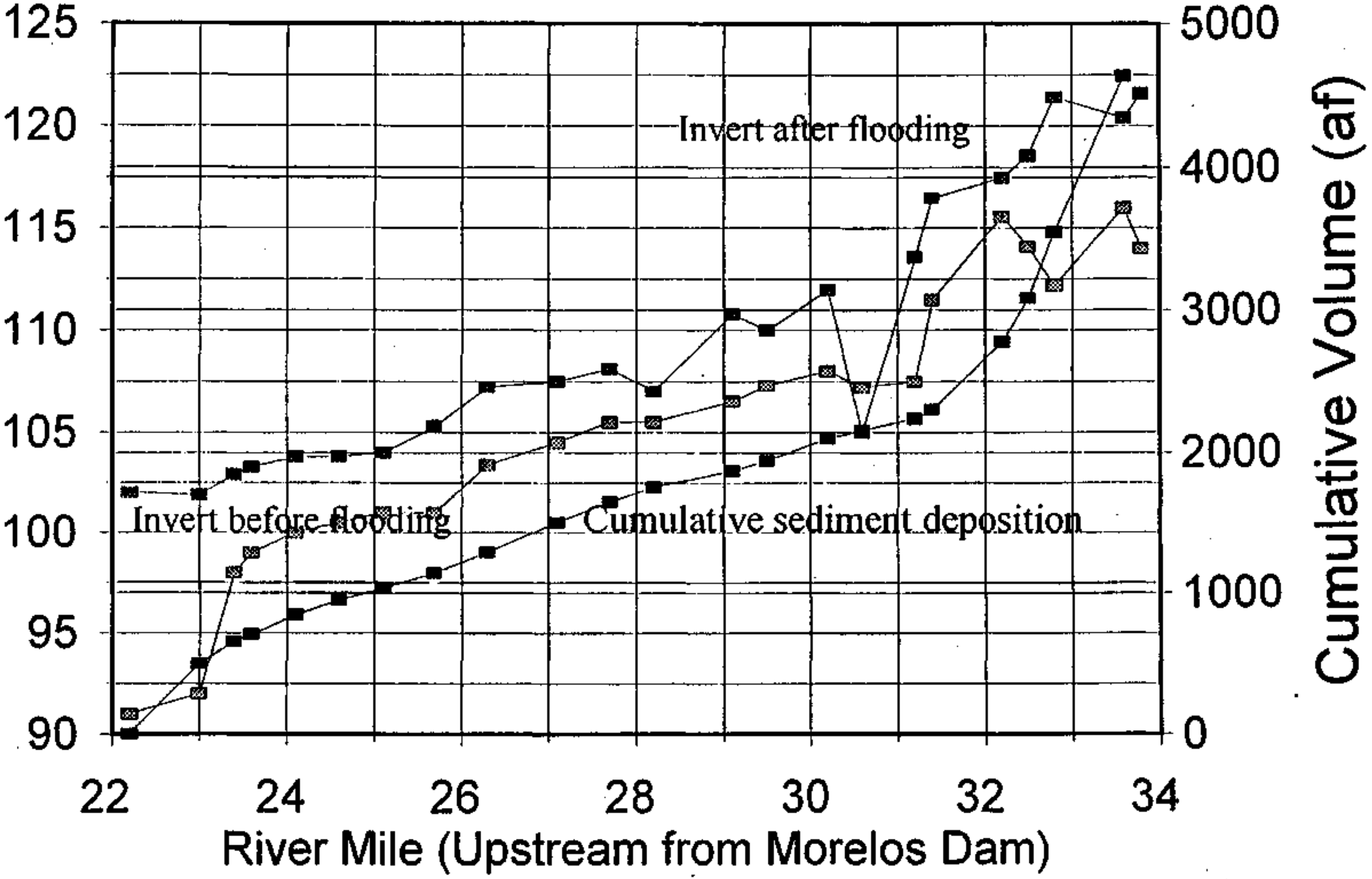
Figure 16: Sediment concentrations and flow rates for the Colorado River at Morales Dam.

To better assess changes in sediment transport and cross-sections in the Lower Colorado River, we obtained a series of cross-sections for the river from the Yuma Projects Office[11]. These included cross-sections from the Morelos Dam upstream to several miles upstream from the Gila River inflow for the time periods 1985 through 1988, after the 1993 floods, and in 1998 after completion of the dredging.

During the floods, the river bottom raised an average of 4.3 feet between the Gila River and Morales Dam. Depths near the dam and confluence frequently exceeded 10 feet while in the middle of the reach sediment depths ranged from 2 to 5 feet (Figure 17). Increased deposition near Morales Dam is due to the dam backwater. (Morales Dam diverts the remains of the Colorado River into canals to Mexico and has essentially no storage.) Sediment depths tended to be higher on the banks due to the river reworking sediments in the invert while the banks were dry. Near the confluence, the river invert moved west about 1600 feet because of the sediment that deposited in the river near the confluence and the erosive action of the flows emanating from the Gila River and impinging on the western banks.

Sediment deposition was about 4700 af with the majority resulting from major flooding on the Gila River. The highest average daily flow at Dome was almost 28,000 cfs. Based on Colorado River at Morales Dam flows, the Gila River contributed most of the Colorado River flow for several months in 1993 (Figure 18). If the sediment concentration is 4000 mg/1 as measured in the Colorado River during 1993, the cumulative sediment flow from the Gila River during 1993 was just over 16,000 af. This is likely an overestimate because as Painted Rock Reservoir was draining, the sediment concentration was probably very low. This suggests that most of the sediment from the flooding was captured upstream of Morales Dam.

[11] Ms. Janet Stork, personal communication. U.S. Bureau of Reclamation, Yuma, AZ.



Sediment Deposition

Morelos Dam to the Gila River

Figure 17: Profile of the Colorado River between Morelos Dam and the Gila River and sediment deposition upstream from Morelos.

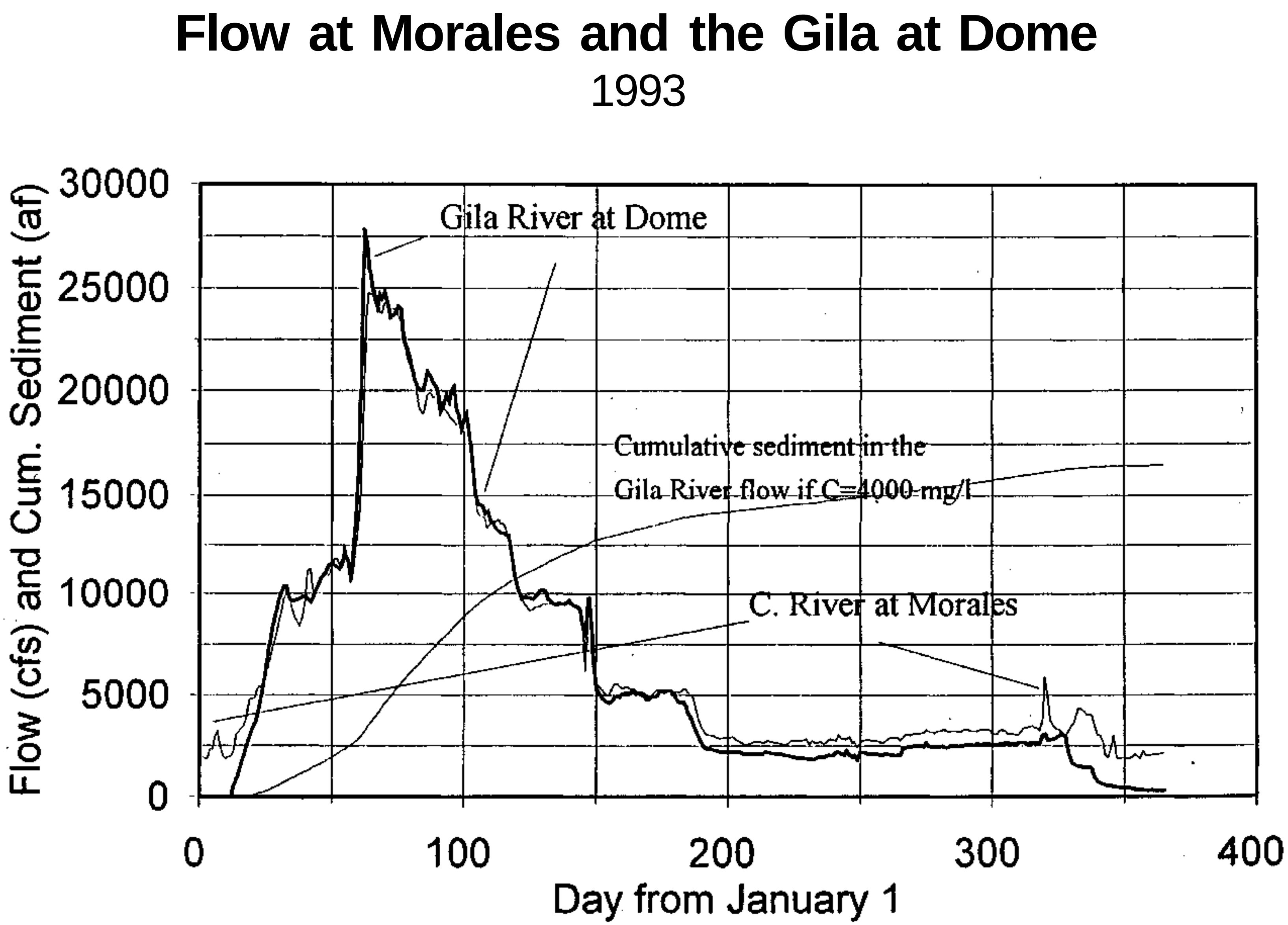


Figure 18: Daily flow for water 1993forthe Gila R at Dome and the Colorado R at Morales and cumulative sediment movement.

The estimate does not include the sediment deposition in the Gila River below Painted Rock Dam. The Gila River is usually dry except for drainage from Wellton-Mohawk and the channel capacity has probably decreased since the closing of Painted Rock Dam. Because of these conditions, much of the flow occurred in the vegetated floodplain where much sediment would have deposited. The Gila River will probably be a source of sediment to the lower Colorado River until this sediment is removed.

Changes Expected from a Drained Lake Powell

Because of the lack of sediment sources affected by mainstem river flows, the primary effect of draining Lake Powell will be on the flows in the lower Colorado River. Rosencrans (1997) analyzed impacts of draining Glen Canyon on river flows by comparing the normal hydrology using current criteria with a *Drain Lake Powell* scenario. The *Drain Lake Powell* scenario only changes two model parameters. First, the initial and target elevations for Lake Powell are set equal to 3370 feet, the bottom of the dam. Second, the sediment accumulation in Lake Mead is adjusted to account for the extra sediment draining from Glen Canyon. The analysis did not account for any alternative storage such as water banking.

Under current criteria, the Lower Basin Consumptive Use is 7,926,000 af/y which exceeds requirements by 426,000 af/y. The *Drain Lake Powell* scenario reduced the Lower Basin Consumptive Use to 7,835,000 af/y, or 1.15%, which still exceeds requirements by 4.5%. Flows to Mexico exceeded requirements (1,515,000 *af/y)* in 35% of the years as opposed to 22% of the years under current operations (Rosencrans, 1997). In other words, 22 years each century will have "excess" or flood flows to Mexico[12]. Draining Glen Canyon will increase that to 35 years. Under current criteria, 61,000,000 af per century or 2,772,000 af/flood year currently flows to Mexico. With a drained Glen Canyon, this flow will increase to 105,300,000 af per century or 3,008,000 af/flood year. This 8.5% increase in flood flow during flood years is not likely to significantly alter sediment movement in the lower basin.

[12] Many of these excess flows are diverted to irrigation; only true flood flows reach the delta region.

With just one major reservoir, floods may pass quicker and have higher peaks. If 3,008,000 af is spread over 60 days, the flood flow will be about 25,000 cfs. Spread over longer periods, the rate reduces proportionately.

Comparison of flood years with nonflood years illustrates the differences without Glen Canyon Dam. Flooding during 1983 and 1984 resulted in 36,000,000 af of water while in the normal years of 1990 and 1991 only 12,000,000 af bypassed Imperial Dam. Hydrographs for the later years show that current flows vary from around 3000 cfs to 12,000 cfs (Figure 19) while peaks in 1983 exceeded 40,000 cfs. The 1984 flood flows were primarily less than 30,000 cfs because neither upstream reservoir spilled. This two years of flooding were and will be extreme even with a drained Lake Powell. If the operating criteria of Lake Mead was not adjusted to provide more flood control space, it is possible that peak flows on the lower Colorado River will be slightly higher. The definition of a new 100-year floodplain through Parker and Yuma should be a part of future studies for implementing the drainage of Lake Powell.

With respect to sediment, these floods will all pass through Lakes Mead, Mojave and Havasu and will have very clean water. Higher floods due to draining Glen Canyon may cause further degradation and armoring of the river channel.

Colorado River at Imperial

Example Hydrographs

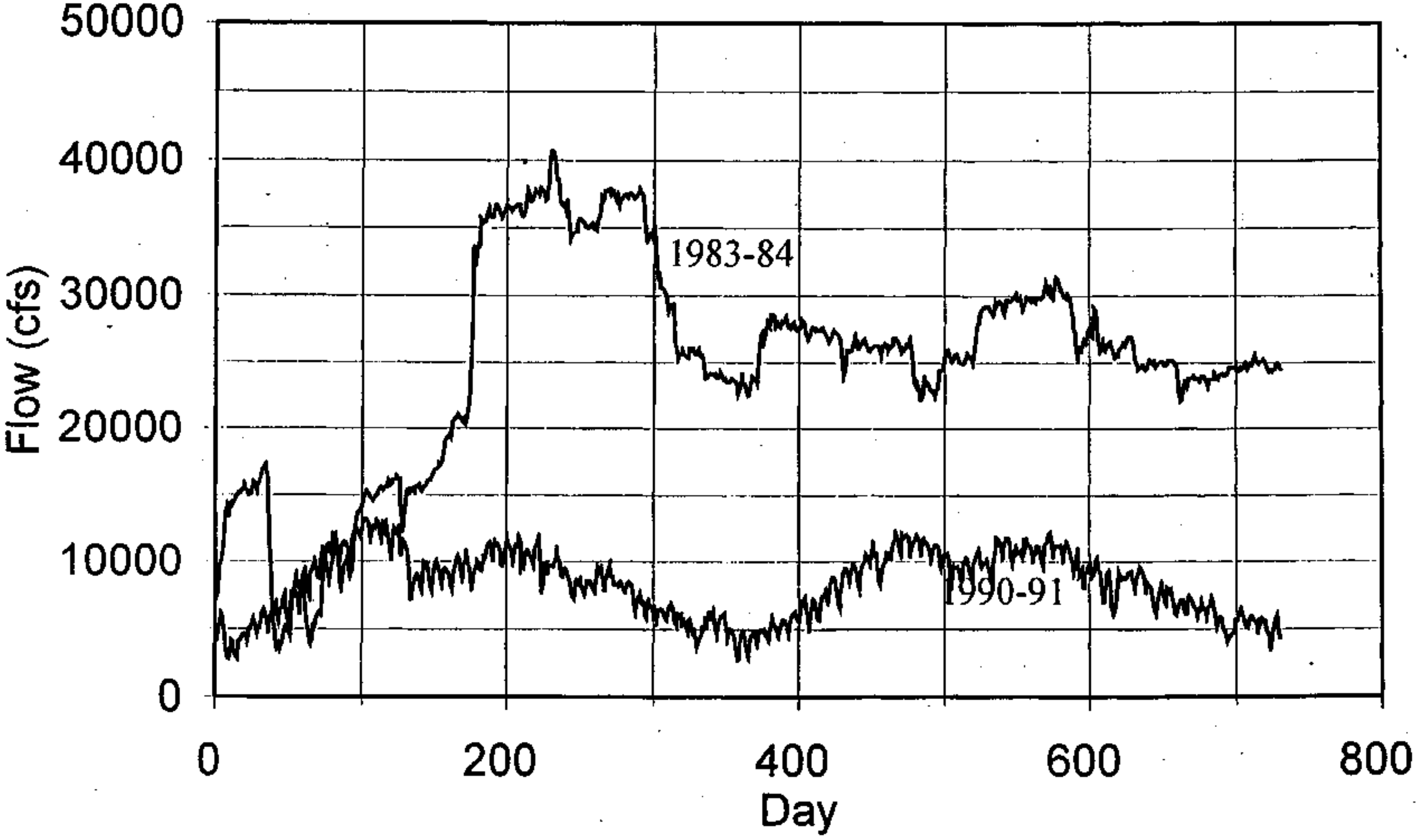


Figure 19: Example daily hydrographs for the Colorado River at Imperial Dam for the 1983 floods-and normal years from 1990-91

Conceptual Sediment Model for the Colorado River Basin

The classic conceptual model for rivers is that the headwaters are a source region for both water and sediment, intermediate reaches are transport zones where the river's sediment load is in a quasiequilibrium state, and the lower reaches are braided (Schumm, 1975). The headwaters are characterized by steep, narrow river and tributary channels. The middle reaches are typified by meandering reaches where deposition and erosion both occur in equal volumes. In the lower reaches a delta forms where the gradient is slight and the river can no longer carry its sediment load. As deposition occurs, braiding occurs and form multiple channels.

The Colorado River has atypical zones and reaches. While the headwaters of all three upstream major rivers are in the Colorado and Wyoming Rocky Mountains, there are large tributaries in the middle reach, from about Grand Junction to Imperial Dam[13], that supply large sediment loads. Below Imperial Dam lies the upstream end of the Colorado River delta.

To understand a conceptual model, it is essential to understand the equilibrium of alluvial river channels. There are three types of equilibrium in a river: steady state, dynamic and dynamic metastable. A steady state river has sediment inflow equal to outflow. The channel form remains roughly constant on average with time, but short-term random changes in annual flow and weather cause changing width and bedforms. Dynamic equilibrium occurs in reaches undergoing change. Sediment flows may be in equilibrium over the short-term, but over the long-term the river is adjusting to changes in the watershed. Canyons are still being cut in the Colorado River system as the plateau rises with geologic time. Dynamic, metastable equilibrium occurs when a dynamic river surpasses a threshold. This occurred in the late 1800s and early 1900s on many

[13] I am aware of no research that has defined quantitatively the different reaches of the Colorado River. At Grand Junction, the river leaves the mountainous canyons of its headwaters; there are intermittent canyons and meandering reaches between Grand Junction and Imperial Dam. Below Imperial, an obvious delta forms. Throughout geologic time, the main Colorado River channel has changed plan significantly, sometimes even diverting into the current Salton Sea.

Colorado River tributaries when climate changes and livestock grazing combined to increase watershed sediment yield, remove river stabilizing vegetation and initiate headcutting.

While the mainstem may have relatively well-defined zones in its natural condition, the tributaries confuse the situation. Debris torrents from tributaries in the Grand Canyon cause localized regions of high sediment transport capacity and turbulent flow. Rivers like the LCR, Paria and Virgin add high sediment loads at times of the year when the mainstem flows at low velocities. This provides temporary sediment storage until snowmelt the following spring removes the sediment. This is a dynamic equilibrium.

The Glen Canyon reach has substantial sediment inflow from the tributaries. The system was in dynamic metastable equilibrium in early years when the river loads were three times current loads. Negative feedback in the tributaries caused the system to return to regular dynamic equilibrium. The channels adjusted to reflect the new watershed conditions. New conditions led to new hydraulic geometry relations (Leopold et al, 1964) and the amount of sediment issuing from the tributaries substantially decreased. Dynamic metastable equilibrium sediment production rates are not sustainable, therefore sediment inflows to Glen Canyon should not approach values seen in the early 1900s for a long time.

Most of the extra load passed through the Grand Canyon as it should in the intermittent reach. Below Boulder Canyon, Minckley (1979) reported that aggradation occurred throughout the system, especially in the delta region. Aggradation, combined with irrigation engineering mismanagement, may have caused the river to divert into the Salton Sea in 1904 (USBR, 1996).

The combined effects of regulated flow and sediment traps result in the river observed today. Grand Canyon flow reflects annual delivery requirements and daily power production needs. Sediment has been stored (temporarily) in Lake Powell. The river does not adequately transport its current load through the Grand Canyon and the river aggrades at low levels (but the high beaches are eroding). Lake Mead just downstream from the Grand Canyon captures all sediment that emerges from the Grand Canyon. While Lake Mead releases primarily respond to water delivery needs from the lower basin states, there are also substantial daily ramping effects. Lake Mojave primarily reregulates Lake Mead releases. Diversions to California and Arizona occur from Lake Havasu. Then, flows below Lake Havasu primarily reflect the demands of the Imperial Irrigation District and Mexico. There are no daily ramping effects. Summer flows are only a tenth and winter flows are about three times historic flows. Upstream releases contain essentially no sediment, therefore the only sources of sediment to current flows are the tributaries since most banks have been armored with riprap.

The removal or drainage of Lake Powell would cause immediate change's to the hydrology and sediment relations within the Grand Canyon. The river would carry the sediment load provided it. The seasonal dynamic equilibrium would be restored where aggradation occurs in later summer and erosion occurs during snowmelt. High floods would replenish the sand on high beaches.

Because of the amount of sediment to be removed from Glen Canyon, there could be an initial influx of sediment which could initiate a dynamic metastable equilibrium in the Grand Canyon. Sediment availability could exceed transport capacity. Bedrock controls the channel width and profile in some locations and the channel would be unable to adjust. Some of the eddies and low velocity backwaters may be inundated with silt and clay. For these reasons, the drawdown of Glen Canyon must be appropriately timed with annual and seasonal hydrologic inputs. Drowning the eddies in mud would have negative ecologic impacts.

Below Lake Mead, the impacts on sediment movement would be minimal because of the lack of sediment in the system. Hoover, Davis, and Parker Dam would continue to control the flows during most years. Lake Mead would still be a sink for sediment passing through the Grand Canyon. The clean water caused degradation throughout the reach. Because the flow rates on the overbanks are low, it is unlikely that erosion of the upper beaches and riparian areas in the Imperial and Cibola Wildlife refuges would occur with a drained Lake Powell.

Toxic Metals in the Sediment

As sediments accumulate, metals that are adsorbed on the particles also accumulate. Neither Ferrari (1988) nor USER (1995) discuss contaminants in the sediment, but Stanford and Ward (1992) discuss heavy metal inflow and accumulation in the sediments. Most of this discussion is based on their literature review.

Mercury and selenium are the only heavy metals reaching the reservoir in sufficient concentrations to affect the food web. The total mercury load reaching the reservoir is 2200 kg/y, 40% of which results from natural erosion of the Chinle and Morrison formation in the upper Colorado River basin. Concentrations in the sediments ranged from 5 to 53 and averaged 30 ppb. Mercury concentrations in water approached 6 ppb. Concentrations in fish flesh, including threadfin shad, walleye, largemouth bass, and rainbow trout, ranged from 5 to 700 ppb which suggested a 43-fold increase relative to average concentrations in the catchment substrata (Potter et al., 1975). The largest, oldest fish had the largest concentration because they had the longest time to bioaccumulate.

The superfund site on the Carson River east of Reno, NV has sediment mercury concentrations from 200 to 14000 ppb. These exceeded concentrations in the sediment of a reservoir thirty miles downstream by 6.6 to 467 times (Miller, G.C, 1997, personal communication with UNR Env.Chem professor). Erosion of the river sediments during high flows caused concentrations in fish flesh, including walleye, trout and bass, downstream in Lake Lahontan to equal 10 ppm which is 10 times the allowable concentration in fish.

By the end of 1997, sediment had been accumulating in Lake Powell for 33.5 years which would result in 1,238,000 af of sediment, using Ferrari's (1988) estimate and 73,700 kg of mercury which is 50 ppb of sediment. These calculations indicate that estimates just provided are accurate and within reasonable limits.

As sediments erode from a drained reservoir, mercury will migrate downstream. Davis et al (1993) indicate that metal ions are strongly adsorbed soil particles although the reactivity depends on water chemistry and particle size. Most of the sediments are in the silt/clay size; the smaller the particles the stronger the diffuse double layer in which metal ions are electrostatically attracted. Certain salts at certain pH levels could cause dissolution of heavy metals. Substantial quantities of organic ligands could also form complex ligands with the mercury which would detach the molecule from the sediment particle. Prior to draining Lake Powell, a test using river water, sediments and turbulence to predict the final state of mercury in the water flowing downstream. Dissolved mercury could pass through Lake Mead; bound mercury will be deposited in Lake Mead.

The observed bioaccumulation in the reservoir and downstream on the Carson River indicates that disturbed sediments do cause bioaccumulation. Assuming that mercury is evenly distributed, sediment concentrations of 30,000 mg/1, levels easily reached by flows on drying reservoir sediments, mercury concentration in the flow will be 0.0015 mg/1. Assuming flow at Lees Ferry to be 12,000,000 af/y, draining Lake Powell will deliver approximately 22,200 kg/y. The actual flow mercury delivery will depend on the rate the reservoir is drained. This estimate is probably too high.. Similar calculations on the Carson River using sediment concentrations at 1000 ppb would result in 0.3 mg/1 Hg in the flow. During the floods in 1995 that caused the problem, average flows were 2000 cfs for about 3 months. This would be about 357,000 af and 132,000 kg of mercury reaching Lahontan Reservoir which has about 400,000 af of capacity. If the reservoir was full, the concentration would be 0.27 mg/1. This resulted in fish flesh concentrations of 10 ppm. If Lake Mead is full, the inflow from draining Glen Canyon will result in mercury concentrations of 0.000692 mg/1 which is 390 times less than Lahontan Reservoir.

These calculations suggest that draining Glen Canyon will not result in substantial mercury concentrations in Lake Mead. However, if mercury is not evenly distributed, it is possible that localized problem zones could result. A hydrodynamic study of Lake Mead should be undertaken to identify locations that sediment concentrations could lead to elevated mercury levels.

Selenium is the other heavy metal suggested to potentially impact the food web in Glen Canyon. However, there are no available measurement in the sediments or water column of Lake Powell. Ohmart et al (1988) identify selenium as the primary heavy metal .problem in the lower river. They suggest that selenium concentrations approach the threshold of reproductive failure in fish. They also found that a liver sample on a sampled Yuma clapper rail at Mittry Lake contained double the normal levels of selenium. This was similar to values found in livers collected at Kesterson Wildlife Refuge in California where selenium has caused major avian reproductive problems.

These concentrations suggest that additional selenium loadings could cause problems in the lower river. Assuming that selenium remains bound to sediment, most will be trapped in Lake Mead. Of course, sediment and selenium deposited in Lake Mead sediments even before Glen Canyon was dammed. Research into selenium concentrations in delta deposits in both Lake Mead and Lake Powell should be conducted to determine whether concentrations are high enough to bioaccumulate in fish and riparian vegetation.

Conclusion

' The Colorado River currently transports little sediment downstream from Lee's Ferry because reservoirs act as sediment traps and because river flows are controlled to levels that will not transport sediment. This has caused degradation of channel bottoms in the Grand Canyon and along the lower river in Topock, Cibola and Imperial reaches. There is very little replenishment of sand on upper beach levels any where in the river. Controlled flows have allowed riparian vegetation to encroach on the channel in many locations.

Draining or removing Glen Canyon Dam will allow the Grand Canyon to return to its predam state eventually, although there could be a period where the sediment supply to the Grand Canyon exceeds the river's ability to transport it. Reservoir releases should be timed so as not to cause major flooding, erosion or deposition. Lake Mead will receive up to 800,000 af of sediment and then begin to fill at rate of near 40,000 af/y.

Glen Canyon will recover quickly from the 860,000 af of sediment that buries the mainstem and side channels. Flows in the mainstem rivers and side channels all exceed critical velocities for incipient motion. Many of the ungaged tributaries flood most years which will quickly clean them. Slot canyons do not likely have more than a few feet of sediment unless they are immediately adjacent to a delta. There is no evidence from any of the sediment survey range lines that reservoir currents will move sediment up the slots.

Most sediment from the mainstem rivers accumulated in deltas with little accumulation at the base of the dam. The midreaches of Glen Canyon more than 60 miles upstream of the dam and below the toe of the delta at about 3400' MSL have very little sediment. As the reservoir lowers, the delta will be eroded and sediment transported and deposited further down in the reservoir. The river will cut a channel leaving high terraces. The migrating river will undercut these terraces. Not all of the current 850,000 af of sediment will be removed.

The current sediment inflow to Glen Canyon is about 36,000 af/y. However, sediment transport into Glen Canyon prior to 1941 was about four times as high due to high tributary sediment production. At the current rate and considering compaction and lost trap efficiency, Lake Powell will be totally full of sediment in about 800 years. If the rates observed prior to 1940 return, the reservoir will fill in less than 200 years. The actual life will probably be somewhere in between. The powerplant intake may be reached in about 400 years.

Sediment flow in the lower Colorado River below Hoover Dam will not be affected very much unless high river flows coincide with high sediment producing tributary flows, especially from the Gila River. The USSR's current dredging operations removes most sediment from the river and armors the banks thereby decreasing bank erosion. Flooding may further degrade the river. Overbank flooding will not likely contain, enough sediment to replenish and nourish overbank areas.

Heavy metals, including mercury and selenium, exist in the sediments in Glen Canyon. Mercury concentrations are not high enough to cause significant bioaccumulation problems. Selenium levels in the Colorado lower river are very high and currently cause avian reproductive problems. Draining Glen Canyon should not affect this as long as sediments are captured in Lake Mead and most selenium remains bound to sediment particles.

Recommendations

This report briefly analyzed Colorado River sediment flow before and after the commencement of reservoir management. It raised many questions, some of which lead to recommendations for future study.

1. As Lake Powell drains, large amounts of sediment may be released to the Grand Canyon. Sediment will also be redistributed within the draining reservoir and may accumulate in places that are currently clean. The rate of drainage at different reservoir levels will control the release and the redistribution of sediment. For example, half of the water and about 60% of the reservoir sediment is in the top 100 feet of the reservoir. As that water is released, some of the sediment deposits will be redistributed to lower levels in the reservoir. The proportions depend on the rate of water release which controls the rate at which sediment is exposed.

As a part of the Glen Canyon EA, the Glen Canyon Institute should perform a detailed reservoir release analysis. This will allow the institute to propose a release scenario that will protect existing resources in the Grand Canyon and allow the canyons currently inundated by Lake Powell to be cleansed.

2. The potential for heavy metal release is a significant concern. The institute should obtain updated sediment quality data especially including mercury and selenium. In addition to analyzing content, the tests should include analysis of the release of metals to the water as sediment flows through turbulent rapids. Also, the analysis should include fish flesh in Lake Powell, the Grand Canyon, and Lake Mead.

3. More detailed analyses of flow in the river without Lake Powell should be performed. Monthly predictions would be useful and could be accomplished with the annual operations model CRSSEZ by superimposing normalized annual hydrographs on the annual flows produced by the model. The removal of Lake Powell will free about 500,000 af of water annually for environmental uses. The analysis should consider release scenarios that will maximize the environmental benefits from these releases. This should include estimates of how flows could be used to move sediment in the lower Colorado River and into the delta region of Mexico.

Acknowledgments

The author gratefully acknowledges data and reports provided by Mr. Randy Peterson, Mr. Ron Ferrari and Ms. Janet Stork of the Bureau of Reclamation. He also appreciates the funding provided by the Sierra Club to the Glen Canyon Institute for the study.

References

Abbey, E., 1968. Desert Solitaire: A Season in the Wilderness. Ballantine, New York.

Andrews, E. A., 1986. Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah: Geological Society of America Bulletin 97:1012-1023.

Andrews, E. A., 1991. Sediment transport in the Colorado River basin. Page 54-75 in Colorado River Ecology and Dam Management: Proceedings of a Symposium, May 24-25, 1990, Santa Fe, New Mexico. National Academy Press, Washington.

Bryan, K, 1925. Date of channel trenching in the arid southwest. Science 62:338-344.

Davis, J.A., D.B. Kent, B.A. Rea, A.S. Maest, and S.P. Garabedian, 1993. Influence of redox environment and aqueous speciation on metal transport in groundwater: Preliminary results of trace injection studies, in Allen, H.E., E.M. Perdue, and D.S. Brown, 1993, Metals in Groundwater. Lewis Publishers, Boca Raton.

General Accounting Office (GAO), 1996. Bureau of Reclamation: As Assessment of the Environmental Impact Statement on the Operations of the Glen Canyon Dam, Report GAO/RCED-97-12. Washington.

Glen Canyon Environmental Studies (GCES), 1997. Grand Canyon Artificial Flooding. Flagstaff, AZ.

Hereford, R., 1986. Modern alluvial history of the Paria River drainage basin, southern Utah. Quaternary Research 25:293-311.

Howard, C.S., 1947. Suspended Sediment in the Colorado River: 1925-41. U.S. Geological Survey Water-Supply Paper 998. Washington.

Krutch, J.W., 1989. Grand Canyon: today and All Its Yesterdays. University of Arizona, Tucson, AZ.

Leopold, A., 1946. Erosion as a menace to the social and economic future of the Southwest. J of Forestry 44:627-633.

Leopold, L.B., M.G. Wolman, and J.P. Miller, 1964. Fluvial Processes in Geomorphology. W.H. Freeman, San Francisco.

Morris, G.L, and J. Fan, 1998. Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use. McGraw-Hill, New York.

Pontius, D., 1997. Colorado River Basin Study, Report to the Western Water Policy Review Advisory Commission. SWCA, Inc., Tucson, AZ.

Richards, K., 1982. Rivers: Form and Process in Alluvial Channels. Methuen, London and New York.

Schumm, S.A., 1977. The Fluvial System. Wiley-Interscience, New York.

Stedinger, J.R., R.M. Vogel and E. Foufoula-Georgiou, 1992. Frequency analysis of extreme events. Chapter 18 in Maidment, D.R. (Editor in chief), Handbook of Hydrology. McGraw-Hill, New York.

Stevens, L.E., J.C. Schmidt, T.J. Ayers,and B.T. Brown, 1995. Flow regulation, geomorphology, and the Colorado River marsh development in the Grand Canyon, Arizona. Ecological Applications 5:1025-1039.

U.S. Bureau of Reclamation (BOR), 1995. Operation of Glen Canyon Dam: Final Environmental Impact Statement. U.S. Dept. Of the Interior, Bureau of Reclamation.

U.S. Bureau of Reclamation (BOR), 1996. Biological Assessment: Lower Colorado River. U.S. Dept. Of the Interior, Bureau of Reclamation.

Webb, R.H., 1985. Late Holocene flooding on the Escalante River, south central Utah: Doctoral Dissertation, University of Arizona, 204 p.

Worster, D., 1985. River of Empire: Water, Aridity, arid the Growth of the American West. Oxford, New York.

Appendix 1: Flood Frequency Analysis for Region Around Glen Canyon

```
                         U. S. GEOLOGICAL SURVEY
                   ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                   Following Bulletin. 17-B Guidelines
                             Program peakfq
                        (Version 2.4, Apr, 1998)


                      ____PROCESSING DATE/TIME ___

                          1998 SEP 8 13:53:34

                       ____PROCESSING OPTIONS ___

                    Plot option         = None
                    Basin char output   = None
                    Print option        = Yes
                    Debug print         = No
                    Input peaks listing = Long
                    Input peaks format  = WATSTORE peak file



                         U. S. GEOLOGICAL SURVEY
                   ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                   Following Bulletin 17-B Guidelines
                             Program peakfq
                        (Version 2.4, Apr, 1998)



   Station - 09187000            COTTONWOOD CREEK NEAR MONTICELLO, UTAH
                          1998 SEP 8 13:53:34


                     I N P U T   D A T A   S U M M A R Y

              Number of peaks in record           =       17
              Peaks not used in analysis          =        0
              Systematic peaks in analysis        =       17
              Historic peaks in analysis          =        0
              Years of historic record            =        0
              Generalized skew        '           =   -0.111
              Standard error of generalized skew  =    0.550
              Skew option                         =   WEIGHTED
              Gage base discharge                 =      0.0
              User supplied high outlier threshold =
              User supplied low outlier criterion  =
              Plotting position parameter         =     0.00



           NOTICE  --  Preliminary machine computations.
           User responsible for assessment and interpretation.

   WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                 0.0
   WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.           14.5
   WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.   10123.9
1


   Station - 09187000            COTTONWOOD CREEK NEAR MONTICELLO, UTAH
                          1998 SEP 8 13:53:34


        ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                      FLOOD BASE                LOGARITHMIC
                 ---------------------------------------------------
                           EXCEEDANCE                STANDARD
                  DISCHARGE  PROBABILITY    MEAN     DEVIATION    SKEW
                 ---------------------------------------------------

 SYSTEMATIC RECORD      0.0      1.0000     2.5830     0.6160     -0.151
```

```
BULL.17B  ESTIMATE        0.0      1.0000      2.5830      0.6160      -0.131


   ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

     ANNUAL                                     'EXPECTED    95-PCT CONFIDENCE LIMITS
   EXCEEDANCE       BULL.17B      SYSTEMATIC  PROBABILITY'    FOR BULL.  17B ESTIMATES
   PROBABILITY      ESTIMATE        RECORD       ESTIMATE         LOWER          UPPER

      0.9950             8.3           8.1            4.2           1.5           22.6
      0.9900            12.3          12.1            7.3           2.6           31.1
      0.9500            35.3          35.0           27.9          10.8           74.0
      0.9000            61.0          60.9           52.9          22.4          118.2
      0.8000           117.2         117.4          109.2          52.1          211.8
      0.5000           394.9         396.7          394.9         219.2          715.6
      0.2000          1274.0        1275.0         1359.0         703.8         2877.0
      0.1000          2308.0        2301.0         2617.0        1198.0         6200.0
      0.0400          4297.0        4254.0         5389.0        2038.0        14170.0
      0.0200          6374.0        6277.0         8757.0        2831.0        24130.0
      0.0100          9045.0        8859.0        13780.0        3775.0        38870.0
      0.0050         12410.0       12090.0        21240.0        4887.0        59950.0
      0.0020         18120.0       17520.0        36760.0        6638.0       100900.0


     Station - 09187000            COTTONWOOD CREEK NEAR MONTICELLO, UTAH
                          1998 SEP 8 13:53:34


                      I N P U T   D A T A   L I S T I N G


    WATER  YEAR     DISCHARGE    CODES      WATER YEAR    DISCHARGE   CODES

       1950            30.0                    1961         1680.0
       1951          1520.0                    1962          290.0
       1952           112.0                    1963         2200.0
       1953          2140.0                    1964         1950.0
       1954            78.0                    1965          100.0
       1955           167.0                    1966          275.0
       1956           236.0                    1967          450.0
       1957           766.0                    1968         1830.0
       1960            67.0

       Explanation  of  peak  discharge  qualification  codes

      PEAKFQ  WATSTORE
       CODE     CODE    DEFINITION

         D        3     Dam failure,  non-recurrent flow anomaly
         G        8     Discharge greater than stated value
         X       3+8    Both of the above
         L        4     Discharge less than stated value
         K     6 OR C   Known effect of regulation or urbanization
         H        7     Historic peak

     Station - 09187000            COTTONWOOD CREEK NEAR MONTICELLO, UTAH
                          1998 SEP 8 13:53:34


   EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

     WATER          RANKED        SYSTEMATIC       BULL.17B
      YEAR        DISCHARGE         RECORD         ESTIMATE

      1963          2200.0          0.0556          0.0556
      1953          2140.0          0.1111          0.1111
      1964          1950.0          0.1667          0.1667
      1968          1830.0          0.2222          0.2222
      1961          1680.0          0.2778          0.2778
      1951          1520.0          0.3333          0.3333
      1957           766.0          0.3889          0.3889
      1967           450.0          0.4444          0.4444
      1962           290.0          0.5000          0.5000
```

```
     1966          275.0         0.5556         0.5556
     1956          236.0         0.6111         0.6111
     1955          167.0         0.6667         0.6667
     1952          112.0         0.7222         0.7222
     1965          100.0         0.7778         0.7778
     1954           78.0         0.8333         0.8333
     1960           67.0         0.8889         0.8889
     1950           30.0         0.9444         0.9444


                        U. S. GEOLOGICAL SURVEY
                   ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                    Following Bulletin 17-B Guidelines
                            Program peakfq
                       (Version 2.4, Apr, 1998)

     Station - 09316000               BROWNS WASH NEAR GREEN RIVER, UTAH
                         1998 SEP 8 13:53:34

                    I N P U T   D A T A   S U M M A R Y

                Number of peaks in record           =      19
                Peaks not used in analysis          =       0
                Systematic peaks in analysis        =      19
                Historic peaks in analysis          -       0
                Years of historic record            =       0
                Generalized skew                    =   -0.213
                Standard error of generalized skew  =    0.550
                Skew option                         =   WEIGHTED
                Gage base discharge                 =     0.0
                User supplied high outlier threshold =
                User supplied low outlier criterion  =
                Plotting position parameter         =     0.00

             NOTICE  --  Preliminary machine computations.
             User responsible for assessment and interpretation.

    WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                   0.0
    WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.            210.4
    WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.     14599.0

     Station - 09316000               BROWNS WASH NEAR GREEN RIVER, UTAH
                         1998 SEP 8 13:53:34


         ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                       FLOOD BASE                 LOGARITHMIC
                  ------------------------------------------------------
                           EXCEEDANCE                 STANDARD
                  DISCHARGE PROBABILITY      MEAN     DEVIATION     SKEW
                  ------------------------------------------------------
 SYSTEMATIC RECORD       0.0      1.0000      3.2437     0.3899     -0.257
BULL.17B  ESTIMATE       0.0      1.0000      3.2437     0.3899     -0.236

    ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

     ANNUAL                                 'EXPECTED   95-PCT CONFIDENCE LIMITS
   EXCEEDANCE      BULL.17B     SYSTEMATIC  PROBABILITY'  FOR BULL. 17B ESTIMATES
   PROBABILITY     ESTIMATE        RECORD     ESTIMATE        LOWER         UPPER

     0.9950         142.3          139.8         93.9          50.9         264.4
     0.9900         186.1          183.5      , 135.6          73.0         329.1
     0.9500         377.8          376.0        329.2         187.6         593.0
     0.9000         543.5          542.7        499.8         301.3         810.4
     0.8000         833.3          834.4        799.6         517.7        1189.0
     0.5000        1816.0         1821.0       1816.0        1280.0        2590.0
     0.2000        3763.0         3765.0       3897.0        2634.0        6088.0
     0.1000        5402.0         5389.0       5774.0        3644.0        9618.0
     0.0400        7829.0         7774.0       8810.0        5017.0       15580.0
     0.0200        9872.0         9768,.0     11620.0        6100.0       21160.0
     0.0100       12100.0        11930.0      14970.0        7225.0       27730.0
     0.0050       14510.0        14260.0      18970.0        8396.0       35370.0
     0.0020       17990.0        17590.0      25430.0       10020.0       47200.0
```

```
     Station - 09316000               BROWNS WASH NEAR GREEN RIVER, UTAH
                               1998 SEP 8 13:53:34


                        I N P U T   D A T A   L I S T I N G


    WATER YEAR     DISCHARGE    CODES       WATER YEAR     DISCHARGE    CODES

       1949          2400.0                    1959          5620.0
       1950           738.0                    1961          4460.0
       1951          2120.0                    1962          1700.0
       1952          2710.0                    1963           767.0
       1953           816.0                    1964          1680.0
       1954          2880.0                    1965           470.0
       1955          5100.0                    1966          1160.0
       1956           531.0                    1967          2070.0
       1957          5500.0                    1968          5500.0
       1958           352.0


       Explanation of peak discharge qualification codes

      PEAKFQ   WATSTORE
       CODE      CODE    DEFINITION

         D         3     Dam failure, non-recurrent flow anomaly
         G         8     Discharge greater than stated value
         X        3+8    Both of the above
         L         4     Discharge less than stated value
         K       6 OR C  Known effect of regulation or urbanization
         H         7     Historic peak

     Station - 09316000               BROWNS WASH NEAR GREEN RIVER, UTAH
                               1998 SEP 8 13:53:34

   EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

      WATER          RANKED        SYSTEMATIC       BULL.17B
       YEAR        DISCHARGE         RECORD         ESTIMATE

       1959          5620.0          0.0500          0.0500
       1957          5500.0          0.1000          0.1000
       1968          5500.0          0.1500          0.1500
       1955          5100.0          0.2000          0.2000
       1961          4460.0          0.2500          0.2500
       1954          2880.0          0.3000          0.3000
       1952          2710.0          0.3500          0.3500
       1949          2400.0          0.4000          0.4000
       1951          2120.0          0.4500          0.4500
       1967          2070.0          0.5000          0.5000
       1962          1700.0          0.5500          0.5500
       1964          1680.0          0.6000          0.6000
       1966          1160.0          0.6500          0.6500
       1953           816.0          0.7000          0.7000
       1963           767.0          0.7500          0.7500
       1950           738.0          0.8000          0.8000
       1956           531.0          0.8500          0.8500
       1965           470.0          0.9000          0.9000
       1958           352.0          0.9500          0.9500
1

                                U. S. GEOLOGICAL SURVEY
                         ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                          Following Bulletin 17-B Guidelines
                                    Program peakfq
                               (Version 2.4, Apr, 1998)

     Station - 09182000    CASTLE CREEK ABOVE DIVERSIONS, NEAR MOAB, UTAH
                               1998 SEP 8 13:53:34

                        I N P U T   D A T A   S U M M A R Y

               Number of peaks in record            =       24
```

```
              Peaks not used in analysis          =       0
              Systematic peaks in analysis        =      24
              Historic peaks in analysis          =       0
              Years of historic record            =       0
              Generalized skew                    =   -0.193
              Standard error of generalized skew  =    0.550
              Skew option                         =   WEIGHTED
              Gage base discharge                 =      0.0
              User supplied high outlier threshold =
              User supplied low outlier criterion  =
              Plotting position parameter"        =     0.00

           NOTICE  --  Preliminary machine computations.
           User responsible for assessment and interpretation.

   WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                   0.0
   WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.              1.0
   WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.        80.1

     Station - 09182000    CASTLE CREEK ABOVE DIVERSIONS, NEAR MOAB, UTAH
                           1998 SEP 8 13:53:34


          ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                    FLOOD BASE                     LOGARITHMIC
                ------------------------------------------------------
                           EXCEEDANCE                STANDARD
                 DISCHARGE PROBABILITY      MEAN     DEVIATION      SKEW
                ------------------------------------------------------
  SYSTEMATIC RECORD      0.0     1.0000     0.9509     0.3861      -0.608
  BULL.17B ESTIMATE      0.0     1.0000     0.9509     0.3861      -0.415

   ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

     ANNUAL                                   'EXPECTED   95-PCT CONFIDENCE LIMITS
   EXCEEDANCE     BULL.17B     SYSTEMATIC  PROBABILITY¹   FOR BULL.  17B ESTIMATES
   PROBABILITY    ESTIMATE       RECORD       ESTIMATE        LOWER         UPPER

     0.9950          0.6           0.5           0.4          0.3           1.1
     0.9900          0.9           0.8           0.7          0.4           1.5
     0.9500          1.9           1.8           1.7          1.0           2.8
     0.9000          2.8           2.7           2.6          1.7           4.0
     0.8000          4.3           4.4           4.2          2.9           5.9
     0.5000          9.5           9.8           9.5          7.0          13.0
     0.2000         19.1          19.1          19.6         13.9          28.9
     0.1000         26.6          25.9          27.9         18.8          43.3
     0.0400         37.0          34.7          40.1         25.1          65.4
     0.0200         45.3          41.1          50.3         29.8          84.2
     0.0100         53.7          47.3          61.6         34.5         104.8
     0.0050         62.4          53.3          73.7         39.2         126.9
     0.0020         74.2          60.9          91.4         45.3         158.6

     Station - 09182000    CASTLE CREEK ABOVE DIVERSIONS, NEAR MOAB, UTAH
                           1998 SEP 8 13:53:34

                         I N P U T   D A T A   L I S T I N G

    WATER YEAR     DISCHARGE    CODES       WATER YEAR     DISCHARGE    CODES

       1951           3.0                      1964           17.0
       1952          23.0                      1965           26.0
       1953          20.0                      1966            9.0
       1954           5.0                      1967           27.0
       1955          10.0                      1968           24.0
       1957          19.0                      1969            7.0
       1958          18.0                      1970           11.0
       1959           1.0                      1971            4.0
       1960           3.0                      1972            6.9
       1961           4.0                      1973           19.0
       1962           8.0                      1974         .  4.7
       1963           3.0                      1975           20.0


       Explanation of peak discharge qualification codes
```

```
   PEAKFQ  WATSTORE
    CODE     CODE   DEFINITION

     D        3     Dam failure, non-recurrent flow anomaly
     G        8     Discharge greater than stated value
     X       3+8    Both of the above
     L        4     Discharge less than stated value
     K     6 OR C   Known effect of regulation or urbanization
     H        7     Historic peak

  Station - 09182000    CASTLE CREEK ABOVE DIVERSIONS, NEAR MOAB, UTAH
                        1998 SEP 8 13:53:34

EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

  WATER       RANKED       SYSTEMATIC      BULL.17B
   YEAR      DISCHARGE       RECORD        ESTIMATE

   1967         .27.0        0.0400         0.0400
   1965         26.0         0.0800         0.0800
   1968         24.0         0.1200         0.1200
   1952         23.0         0.1600         0.1600
   1953         20.0         0.2000         0.2000
   1975         20.0         0.2400         0.2400
   1957         19.0         0.2800         0.2800
   1973         19.0         0.3200         0.3200
   1958         18.0         0.3600         0.3600
   1964         17.0         0.4000         0.4000
   1970         11.0         0.4400         0.4400
   1955         10.0         0.4800         0.4800
   1966          9.0         0.5200         0.5200
   1962          8.0         0.5600         0.5600
   1969          7.0         0.6000         0.6000
   1972          6.9         0.6400         0.6400
   1954          5.0         0.6800         0.6800
   1974          4.7         0.7200         0.7200
   1961          4.0         0.7600         0.7600
   1971          4.0         0.8000         0.8000
   1951          3.0         0.8400         0.8400
   1960          3.0         0.8800         0.8800
   1963          3.0         0.9200         0.9200
   1959          1.0         0.9600         0.9600


                       U. S. GEOLOGICAL SURVEY
                  ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                   Following Bulletin 17-B Guidelines
                           Program peakfq
                        (Version 2.4, Apr, 1998)

  Station - 09183000                 COURTHOUSE WASH NEAR MOAB, UTAH
                        1998 SEP 8 13:53:34


                  I N P U T   D A T A   S U M M A R Y

          Number of peaks in record          =      31
          Peaks not used in analysis        =        0
          Systematic peaks in analysis       =      31
          Historic peaks in analysis         =       0
          Years of historic record           =       0
          Generalized skew                   =   -0.185
          Standard error of generalized skew  =    0.550
          Skew option                         =  WEIGHTED
          Gage base discharge                =      0.0
          User supplied high outlier threshold = --
          User supplied low outlier criterion   = --
          Plotting position parameter         =     0.00

       NOTICE -- Preliminary machine computations.
       User responsible for assessment and interpretation.

 WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                 0.0
 WCF198I-LOW OUTLIERS BELOW FLOOD BASE WERE DROPPED.              98.4
 WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.   21987.2
```

```
     Station - 09183000                COURTHOUSE WASH NEAR MOAB, UTAH
                           1998 SEP 8 13:53:34

          ANNUAL FREQUENCY CURVE PARAMETERS — LOG-PEARSON TYPE III

                         FLOOD BASE                  LOGARITHMIC
                    ---------------------------------------------------------
                                EXCEEDANCE                STANDARD
                     DISCHARGE PROBABILITY      MEAN      DEVIATION      SKEW
                    ---------------------------------------------------------
 SYSTEMATIC RECORD        0.0      1.0000      3.2952      0.5054      -1.268
 BULL.17B ESTIMATE       98.4      0.9677      3.3380      0.3925       0.111

   ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

     ANNUAL                      'EXPECTED                95-PCT CONFIDENCE LIMITS
   EXCEEDANCE     BULL.17B    SYSTEMATIC  PROBABILITY'  FOR BULL. 17B ESTIMATES
   PROBABILITY    ESTIMATE       RECORD     ESTIMATE         LOWER        UPPER

     0.9950          --            26.1         --            --           --
     0.9900          --            48.1         --            --           --
     0.9500        507.1          211.3       473.7         309.8        723.3
     0.9000        691.7          415.1       662.7         450.9        952.3
     0.8000       1013.0          850.1       991,.2        708.4       1349.0
     0.5000       2142.0         2506.0      2142.0        1628.0       2813.0
     0.2000       4635.0         5245.0      4747.0        3485.0       6619.0
     0.1000       7005.0         6864.0      7348.0        5077.0      10790.0
     0.0400      10960.0         8488.0     11970.0        7531.0      18580.0
     0.0200      14690.0         9403.0     16660,.0       9705.0      26640.0
     0.0100      19180.0        10110.0     22700,.0      12190.0      37050.0
     0.0050      24530.0        10650.0     30500,.0      15030.0      50310.0
     0.0020      33140.0        11170.0     44380..0      19400.0      73250.0

     Station - 09183000                COURTHOUSE WASH NEAR MOAB, UTAH
                           1998 SEP 8 13:53:34


                      I N P U T   D A T A   L I S T I N G

    WATER YEAR     DISCHARGE    CODES      WATER YEAR    DISCHARGE    CODES

       1950          1810.0                   1975 .       1510.0
       1951           902.0                   1976         2100.0
       1952           630.0                   1977         2160.0
       1953          3140.0                   1978         2170.0
       1954          2420.0                   1979          782.0
       1955          1700.0                   1980         7430.0
       1957         12300.0                   1981         9500.0
       1966          2740.0                   1982         4000.0
       1967          7430.0                   1983         7690.0
       1968          3720.0                   1984         8020.0
       1969          2650.0                   1985         1170.0
       1970          1100.0                   1986          973.0
       1971           643.0                   1987         6480.0
       1972           782.0                   1988          759.0
       1973          2130.0                   1989           31.0
       1974          1040.0


      Explanation of peak discharge qualification codes

     PEAKFQ  WATSTORE
      CODE     CODE    DEFINITION

        D        3     Dam failure, non-recurrent flow anomaly
        G        8     Discharge greater than stated value
        X       3+8    Both of the above
        L        4     Discharge less than stated value
        K      6 OR C  Known effect of regulation or urbanization
        H        7     Historic peak
```

```
   Station - 09183000                    COURTHOUSE WASH NEAR MOAB, UTAH
                               1998 SEP 8 13:53:34


 EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

   WATER         RANKED        SYSTEMATIC       BULL.17B
    YEAR        DISCHARGE        RECORD         ESTIMATE

    1957         12300.0         0.0313          0.0313
    1981          9500.0         0.0625          0.0625
    1984          8020.0         0.0938          0.0938
    1983          7690.0         0.1250            .1250
    1967          7430.0         0.1563            .1563
    1980          7430.0         0.1875            .1875
    1987          6480.0         0.2188            .2188
    1982          4000.0       .  0.2500           ,2500
    1968          3720.0         0.2813            .2813
    1953          3140.0         0.3125            .3125
    1966          2740.0         0.3438            .3438
    1969          2650.0         0.3750          0.3750
    1954          2420.0         0.4063          0.4063
    1978          2170.0         0.4375          0.4375
    1977          2160.0         0.4688          0.4688
    1973          2130.0         0.5000          0.5000
    1976          2100.0         0.5313          0.5313
    1950          1810.0         0.5625          0.5625
    1955          1700.0         0.5938          0.5938
    1975          1510.0         0.6250          0.6250
    1985          1170.0         0.6563          0.6563
    1970          1100.0         0.6875          0.6875
    1974          1040.0         0.7188          0.7188
    1986           973.0         0.7500          0.7500
    1951           902.0         0.7813          0.7813
    1972           782.0         0.8125          0.8125
    1979           782 .0        0.8438          0.8438
    1988           759.0         0.8750          0.8750
    1971           643 .0        0.9063          0.9063
    1952           630.0         0.9375          0.9375
    1989            31.0         0.9688          0.9688

                          U. S. GEOLOGICAL SURVEY
                     ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                      Following Bulletin 17-B Guidelines
                              Program peakfq
                         (Version 2.4, Apr, 1998)

   Station - 09185500                     HATCH WASH NEAR LA SAL, UTAH
                               1998 SEP 8 13:53:34

                      I N P U T   D A T A   S U M M A R Y

            Number of peaks in record           =      22
            Peaks not used in analysis          =       0
            Systematic peaks in analysis        =      22
            Historic peaks in analysis          =       0
            Years of historic record            -       0
            Generalized skew                    =   -0.140
            Standard error of generalized skew  =    0.550
            Skew option                         =   WEIGHTED
            Gage base discharge                 =      0.0
            User supplied high outlier threshold =
            User supplied low outlier criterion  =
            Plotting position parameter         =     0.00

         NOTICE  --  Preliminary machine computations.
         User responsible for assessment and interpretation.

 WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                   0.0
 WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.             39.2
 WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.      6506.2

   Station - 09185500                     HATCH WASH NEAR LA SAL, UTAH
                               1998 SEP 8 13:53:34
```

```
          ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                         FLOOD BASE               LOGARITHMIC
                    -------------------------------------------------------
                                EXCEEDANCE              STANDARD
                     DISCHARGE  PROBABILITY     MEAN    DEVIATION     SKEW
                    -------------------------------------------------------

 SYSTEMATIC RECORD        0.0      1.0000     2.7031     0.4571      0.196
 BULL.17B  ESTIMATE       0.0      1.0000     2.7031     0.4571      0.047

    ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

      ANNUAL                                   'EXPECTED   95-PCT CONFIDENCE LIMITS
    EXCEEDANCE      BULL.17B      SYSTEMATIC  PROBABILITY'  FOR BULL. 17B ESTIMATES
    PROBABILITY     ESTIMATE        RECORD      ESTIMATE         LOWER          UPPER

       0..9950         35 .2          40 .7         25 .5         12 .9          66 .3
       0..9900         45 .3          50 .8         35 .2         18 .0          81 .8
       0,.9500         90 .7          95 .0         80 .6         44 .1         147 .1
       0..9000        131 .7         134 .2        122 .4         70 .9         203 .6
       0..8000        207 .7         206 .4        200 .0        124 .4         306 .8
       0..5000        500 .7         487 .8        500 .7        341 .6         732 .9
       0..2000       1221 .0        1210 .0       1270 .0        826 .8        2036 .0
       0..1000       1955 .0        1984 .0       2112 .0       1264 .0        3645 .0
       0..0400       3241 .0        3414 .0       3736 .0       1957 .0        6935 .0
       0..0200       4501 .0        4887 .0       5511 .0       2584 .0       10600 .0
       0..0100       6056 .0        6787 .0       7949 .0       3312 .0       15600 .0
       0..0050       7955 .0        9210 .0      11300 .0       4153 .0       22280 .0
       0..0020      11090 .0       13410 .0      17750 .0       5460 .0       34450 .0

       Station - 09185500                     HATCH WASH NEAR LA SAL, UTAH
                               1998 SEP 8 13:53:34
```

```
                           I N P U T   D A T A   L I S T I N G

      WATER YEAR    DISCHARGE    CODES       WATER YEAR    DISCHARGE    CODES

         1950          728.0                    1961          139.0
         1951          574.0                    1962          215.0
         1952         1100.0                    1963          961.0
         1953          157.0                    1964         1160.0
         1954           61.0                    1965          160.0
         1955          574 .0                   1966          424.0
         1956          253.0                    1967          760.0
         1957          640.0                    1968          196.0
         1958          497.0                    1969          337.0
         1959         3210.0                    1970         4650.0
         1960          462.0                    1971         1850.0

         Explanation of peak discharge qualification codes

        PEAKFQ   WATSTORE
         CODE      CODE    DEFINITION

          D         3      Dam failure, non-recurrent flow anomaly
          G         8      Discharge greater than stated value
          X        3+8     Both of the above
          L         4      Discharge less than stated value
          K       6 OR C   Known effect of regulation or urbanization
          H         7      Historic peak

       Station - 09185500                     HATCH WASH NEAR LA SAL, UTAH
                               1998 SEP 8 13:53:34
```

```
    EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

       WATER         RANKED        SYSTEMATIC      BULL.17B
        YEAR        DISCHARGE        RECORD        ESTIMATE

        1970         4650.0          0.0435         0.0435
        1959         3210.0          0.0870         0.0870
        1971         1850.0          0.1304         0.1304
        1964         1160.0          0.1739         0.1739
```

```
      1952        1100.0         0.2174         0.2174
      1963         961.0         0.2609         0.2609
      1967         760.0         0.3043         0.3043
      1950         728.0         0.3478         0.3478
      1957         640.0         0.3913         0.3913
      1951         574.0           4348         0.4348
      1955         574.0           4783         0.4783
      1958         497.0           5217         0.5217
      1960         462.0           5652         0.5652
      1966         424.0         0.6087         0.6087
      1969         337.0         0.6522         0.6522
      1956         253.0         0.6957         0.6957
      1962         215.0         0-.7391        0.7391
      1968         196.0         0.7826         0.7826
      1965         160.0         0.8261         0.8261
      1953         157           0.8696         0.8696
      1961         139           0.9130         0.9130
      1954          61.0         0.9565         0.9565

                          U. S. GEOLOGICAL SURVEY
                    ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                    Following Bulletin 17-B Guidelines
                              Program peakfq
                         (Version 2.4, Apr, 1998)

     Station - 09185800         INDIAN CREEK TUNNEL NEAR MONTICELLO, UTAH
                           1998 SEP 8 13:53:34


                    I N P U T   D A T A   S U M M A R Y

               Number of peaks in record            =       19
               Peaks not used in analysis           =       17
               Systematic peaks in analysis         =        2
               Historic peaks in analysis           =        0
               Years of historic record             =        0
               Generalized skew                     =   -0.097
               Standard error of generalized skew   =    0.550
               Skew option                          =   WEIGHTED
               Gage base discharge                  =      0.0
               User supplied high outlier threshold=--
               User supplied low outlier criterion=--
               Plotting position parameter          =     0.00



            NOTICE  --  Preliminary machine computations.
            User responsible for assessment-and interpretation.

 **WCF109W-PEAKS WITH MINUS-FLAGGED DISCHARGES WERE BYPASSED.      17
 **WCF113W-NUMBER OF SYSTEMATIC PEAKS HAS BEEN REDUCED TO NSYS      2
 **WCF118W-SYSTEMATIC RECORD SHORTER THAN WRC SPEC.     2
   WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                     0.0
***WCF141E-SAMPLE SIZE TOO SMALL TO CALC STATS.  SYS  -   2.0
          NSYS,NBGB,NLWOUT,NHIOUT,NHISTN,HISTPN
            2    0    0    0    0     2.0
***WCF003E-CALCS ABORTED.    RETURN CODE =  3






******  AFTER  CALC  ABORT  --
     Station -  09185800         INDIAN CREEK TUNNEL NEAR MONTICELLO, UTAH
                           1998 SEP 8 13:53:34


                      I N P U T   D A T A   L I S T I N G


    WATER YEAR    DISCHARGE    CODES      WATER YEAR    DISCHARGE    CODES

       1958          -17.0                   1968          -18.0      K
       1959           -4.0                   1969          -14.0      K
```

```
        1960           -11,0       K          1970        -10.0
        1961            -9.0       K          1971         -6.0
        1962           -15.0       K          1972        -12.0
        1963            -6.0       K          1975        -10.0
        1964            -6.0       K          1976        -15.0
        1965           -13.0       K          1977          4.0
        1966           -11.0       K          1978         15.0
        1967            -9.0       K


        Explanation of peak discharge qualification codes

       PEAKFQ   WATSTORE
        CODE     CODE  ' DEFINITION

          D        3    Dam failure, non-recurrent flow anomaly
          G        8    Discharge greater than stated value
          X       3+8   Both of the above
          L        4    Discharge less than stated value
          K     6 OR C  Known effect of regulation or urbanization
          H        7    Historic peak

                              U. S. GEOLOGICAL SURVEY
                        ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                        Following Bulletin 17-B Guidelines
                                  Program peakfq
                              (Version 2.4, Apr, 1998)

      Station - 09186500   INDIAN C AB COTTONWOOD CREEK, NR MONTICELLO, UT
                             1998 SEP 8 13:53:34

                        I N P U T   D A T A   S U M M A R Y

                  Number of peaks in record           =       26
                  Peaks not used in analysis          =       26
                  Systematic peaks in analysis        =        0
                  Historic peaks in analysis          =        0
                  Years of historic record            =        0
                  Generalized skew                    =   -0.103
                  Standard error of generalized skew  =    0.550
                  Skew option                         =   WEIGHTED
                  Gage base discharge                 =      0.0
                  User supplied high outlier threshold=--
                  User supplied low outlier criterion=--
                  Plotting position parameter         =     0.00


               NOTICE  --  Preliminary machine computations.
               User responsible for assessment and interpretation.

   **WCF109W-PEAKS WITH MINUS-FLAGGED DISCHARGES WERE BYPASSED.      26
   **WCF113W-NUMBER OF SYSTEMATIC PEAKS HAS BEEN REDUCED TO NSYS =     0
  ***WCF117E-NO DATA IN 'SYSTEMATIC RECORD.   NSYS,NPK,NHIST,NMISS=
                                          0       26        0       26
  ***WCF003E-CALCS ABORTED.    RETURN CODE =  3

       **   AFTER   CALC   ABORT   --
      Station - 09186500   INDIAN C AB COTTONWOOD CREEK, NR MONTICELLO, UT
                             1998 SEP 8 13:53:34

                         I N P U T   D A T A   L I S T I N G

     WATER YEAR    DISCHARGE    CODES      WATER YEAR    DISCHARGE    CODES

        1950          -90.0       K          1963        -240.0
        1951         -179.0       K          1964         -31.0
        1952         -293.0       K          1965         -86.0
        1953          -63.0       K          1966         -53.0
        1954          -53.0       K          1967        -709.0
        1955         -582.0       K          1968        -709.0
        1956         -107.0       K          1969        -134.0
        1957         -138.0       K          1970        -652.0
        1958         -108.0       K          1971       -2330.0
        1959          -18.0       K          1988        -205.0
        1960          -62.0       K          1989        -108.0
```

```
    1961          -55.0                    1990         -47.0
    1962          -86.0                    1991         -17.0

    Explanation of peak discharge qualification codes

   PEAKFQ  WATSTORE
    CODE     CODE   DEFINITION

      D        3    Dam failure, non-recurrent flow anomaly
      G        8     Discharge greater than stated value
      X       3+8   Both of the above
      L        4    Discharge less than stated value
      K     6 OR C  Known effect of regulation or urbanization
      H        7    Historic peak

                    U. S. GEOLOGICAL SURVEY
                ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                Following Bulletin 17-B Guidelines
                        Program peakfq
                   (Version 2.4, Apr, 1998)

  Station - 09185200              KANE SPRINGS CANYON NEAR MOAB, UTAH
                       1998 SEP 8 13:53:34

                  I N P U T   D A T A   S U M M A R Y
           Number of peaks in record            =       15
           Peaks not used in analysis           =        0
           Systematic peaks in analysis         =       15
           Historic peaks in analysis           =        0
           Years of historic record             =        0
           Generalized skew                     =   -0.161
           Standard error of generalized skew   =    0.550
           Skew option                          =   WEIGHTED
           Gage base discharge                  =      0.0
           User supplied high outlier threshold =
           User supplied low outlier criterion  =
           Plotting position parameter          =     0.00

         NOTICE  --  Preliminary machine computations.
         User responsible for assessment and interpretation.

 WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                 0.0
 WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.          149.6
 WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.    1841.6



  Station - 09185200              KANE SPRINGS CANYON NEAR MOAB, UTAH
                       1998 SEP 8 13:53:34

        ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                     FLOOD BASE                 LOGARITHMIC
                 ------------------------------------------------------
                             EXCEEDANCE             STANDARD
                  DISCHARGE  PROBABILITY    MEAN    DEVIATION     SKEW
                 ------------------------------------------------------
SYSTEMATIC RECORD       0.0     1.0000     2.7200     0.2426     -0.251
BULL.17B ESTIMATE       0.0     1.0000     2.7200     0.2426     -0.203

   ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

    ANNUAL                            'EXPECTED   95-PCT CONFIDENCE LIMITS
  EXCEEDANCE    BULL.17B   SYSTEMATIC PROBABILITY'  FOR BULL. 17B ESTIMATES
  PROBABILITY   ESTIMATE     RECORD     ESTIMATE        LOWER        UPPER

    0.9950        111.9       109.2        80.2         52.7         170.7
    0.9900        131.7       129.2       102.3         66.4         194.4
    0.9500        203.0       201.5       181.9        121.5         276.6
    0.9000        253.7       253.1       237.4        164.8         334.2
    0.8000        330.0       330.6       319.4        233.5         422.4
    0.5000        534.8       537.2       534.8        417.4         687.9
    0.2000        843.8       844.5       868.0        658.7        1197.0
    0.1000       1060.0      1056.0      1119.0        807.0        1618.0
    0.0400       1341.0      1328.0      1478.0        985.6        2230.0
```

```
   0.0200       1554.0       1532.0       1781.0       1114.0       2737.0
   0.0100       1770.0       1735.0       2117.0       1239.0       3282.0
   0.0050       1990.0       1940.0       2497.0       1361.0       3868.0
   0.0020       2285.0       2213.0       3074.0       1521.0       4705.0


   Station - 09185200              KANE SPRINGS CANYON NEAR MOAB, UTAH
                      1998 SEP 8 13:53:34

                     I N P U T   D A T A   L I S T I N G

  WATER YEAR    DISCHARGE    CODES       WATER YEAR    DISCHARGE    CODES

     1959          168.0                    1968           530.0
     1961          435.0                    1969           650.0
     1962          270.0                    1970          1290.0
     1963          480.0                    1971           320.0
     1964          850.0                    1972           720.0
     1965          405.0                    1973           335.0
     1966          544.0                    1974           960.0
     1967         1080.0


     Explanation of peak discharge qualification codes

    PEAKFQ  WATSTORE
     CODE     CODE    DEFINITION

       D        3     Dam failure, non-recurrent flow anomaly
       G        8     Discharge greater than stated value
       X       3+8    Both of the above
       L        4     Discharge less than stated value
       K       OR C   Known effect of regulation or urbanization
       H        7     Historic peak

   Station - 09185200              KANE SPRINGS CANYON NEAR MOAB, UTAH
                      1998 SEP 8 13:53:34

 EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

   WATER         RANKED       SYSTEMATIC      BULL.17B
    YEAR        DISCHARGE       RECORD        ESTIMATE

    1970          1290.0        0.0625         0.0625
    1967          1080.0        0.1250         0.1250
    1974           960.0        0.1875         0.1875
    1964           850.0        0.2500         0.2500
    1972           720.0        0.3125         0.3125
    1969           650.0        0.3750         0.3750
    1966           544.0        0.4375         0.4375
    1968           S30.0        0.5000         0.5000
    1963           480.0        0.5625         0.5625
    1961           435.0        0.6250         0.6250
    1965           405.0        0.6875         0.6875
    1973           335.0        0.7500         0.7500
    1971           320.0        0.8125         0.8125
    1962           270.0        0.8750         0.8750
    1959           168.0        0.9375         0.9375


                          U. S. GEOLOGICAL SURVEY
                     ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                     Following Bulletin 17-B Guidelines
                               Program peakfq
                          (Version 2.4, Apr, 1998)



   Station - 09184000                          MILL CREEK NEAR MOAB, UT
                      1998 SEP 8 13:53:34


                    I N P U T   D A T A   S U M M A R Y
```

```
              Number of peaks in record           =      47
              Peaks not used in analysis          =       0
              Systematic peaks in analysis        =      47
              Historic peaks in analysis          =       0
              Years of historic record            =       0
              Generalized skew        -           =   -0.180
              Standard error of generalized skew  =    0.550
              Skew option                         =   WEIGHTED
              Gage base discharge                 =      0.0
              User supplied high outlier threshold=--
              User supplied low outlier criterion  =   --
              Plotting position parameter         =     0.00


           NOTICE  --  Preliminary machine computations.
           User responsible for assessment and interpretation.

      WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                 0.0
      WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.           28.2
      WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.   15241.6


       Station - 09184000                          MILL CREEK NEAR MOAB, UT
                           1998 SEP 8 13:53:34


          ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                            FLOOD BASE                 LOGARITHMIC
                       ------------------------------------------------------
                                   EXCEEDANCE             STANDARD
                        DISCHARGE  PROBABILITY     MEAN   DEVIATION     SKEW
                       ------------------------------------------------------
    SYSTEMATIC RECORD        0.0      1.0000     2.8169     0.4979     0.037
    BULL.17B ESTIMATE        0.0      1.0000     2.8169     0.4979    -0.022


      ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

        ANNUAL                                'EXPECTED   95-PCT CONFIDENCE LIMITS
      EXCEEDANCE     BULL.17B    SYSTEMATIC PROBABILITY'  FOR BULL. 17B ESTIMATES
      PROBABILITY    ESTIMATE      RECORD     ESTIMATE         LOWER         UPPER

        0.9950          33.5          35.6        28.4          16.9          55.4
        0.9900          44.8          47.0        39.3          23.8          71.5
        0.9500          98.8         100.8        93.0          60.4         144.3
        0.9000         150.6         151.7       145.0          98.3         210.9
        0.8000         250.3         249.5       245.6         175.3         337.1
        0.5000         658.7         651.4       658.7         498.3         871.0
        0.2000        1724.0        1718.0      1756.0        1279.0        2462.0
        0.1000        2843.0        2863.0      2951.0        2031.0        4350.0
        0.0400        4839.0        4952.0      5175.0        3278.0        8065.0
        0.0200        6817.0        7067.0      7488.0        4443.0       12060.0
        0.0100        9272.0        9741.0     10500.0        5825.0       17330.0
        0.0050       12280.0       13080.0     14380.0        7452.0       24170.0
        0.0020       17250.0       18710.0     21230.0       10030.0       36180.0
       Station - 09184000                          MILL CREEK NEAR MOAB, UT
                           1998 SEP 8 13:53:34


                     I N P U T   D A T A   L I S T I N G


       WATER YEAR     DISCHARGE    CODES      WATER YEAR     DISCHARGE    CODES

          1915           220.0                   1970           194.0
          1916           235.0                   1971           322.0
          1917           450.0                   1973           790.0
          1949           163.0                   1974          3450.0
          1950           255.0                   1975           106.0
          1951          2940.0                   1976          3160.0
```

```
 1952          202.0                   1977          375.0
 1953         5110.0                   1978         2080.0
 1954         2080.0                   1979          600.0
 1955          163.0                   1980          768.0
 1956          257.0                   1981          685.0
 1957         4450.0                   1982          665.0
 1958         1060.0                   1983          610.0
 1959          228.0                   1984          840.0
 1960          212.0                   1985         1270.0
 1961         5100.0                   1986          146.0
 1962         3010.0                   1987          460.0
 1963         3160.0                   1988          561.0
 1964          895.0                   1989           51.0
 1965         1690.0                   1990          574.0
 1966         1230.0                   1991         1360.0
 1967          250.0                   1992          141.0
 1968          917.0                   1993         1470.0
 1969         1090.0


 Explanation of peak discharge qualification codes

PEAKFQ   WATSTORE
 CODE      CODE     DEFINITION

   D                Dam failure, non-recurrent flow anomaly
   G                Discharge greater than stated value
   X                Both of the above
   L                Discharge less than stated value
   K                Known effect of regulation or urbanization
   H                Historic peak




 Station - 09184000                          MILL CREEK NEAR MOAB, UT
                        1998 SEP 8 13:53:34


EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

  WATER        RANKED       SYSTEMATIC     BULL.17B
   YEAR      DISCHARGE        RECORD       ESTIMATE

   1953        5110.0        0.0208         0.0208
   1961        5100.0        0.0417         0.0417
   1957        4450.0        0.0625         0.0625
   1974        3450.0        0.0833         0.0833
   1963        3160.0        0.1042         0.1042
   1976        3160.0        0.1250         0.1250
   1962        3010.0        0.1458         0.1458
   1951        2940.0         .1667         0.1667
   1954        2080.0         .1875         0.1875
   1978        2080.0         .2083         0.2083
   1965        1690.0         .2292         0.2292
   1993        1470.0         .2500         0.2500
   1991        1360.0        0.2708         0.2708
   1985        1270.0        0.2917         0.2917
   1966        1230.0         .3125         0.3125
   1969        1090.0         .3333         0.3333
   1958        1060.0         .3542         0.3542
   1968         917.0         .3750         0.3750
   1964         895.0         .3958         0.3958
   1984         840.0         .4167         0.4167
   1973         790.0         .4375         0.4375
   1980         768.0         .4583         0.4583
   1981         685.0        0.4792         0.4792
   1982         665.0        0.5000         0.5000
   1983         610.0         .5208         0.5208
   1979         600.0         .5417         0.5417
   1990         574.0         .5625         0.5625
   1988         561.0         .5833         0.5833
   1987         460.0        0.6042         0.6042
```

```
      1917          450.0        0.6250         0.6250
      1977          375.0        0.6458         0.6458
      1971          322.0        0.6667         0.6667
      1956          257.0        0.6875         0.6875
      1950          255.0        0.7083         0.7083
      1967          250.0        0.7292         0.7292
      1916          235.0        0.7500         0.7500
      1959          228.0        0.7708         0.7708
      1915          220.0        0.7917         0.7917
      1960          212.0        0.8125         0.8125
      1952          202.0        0.8333         0.8333
      1970          194.0        0.8542         0.8542
      1949          163.0        0.8750         0.8750
      1955          163.0        0.8958         0.8958
      1986          146.0        0.9167         0.9167
      1992          141.0        0.9375         0.9375
      1975          106.0        0.9583         0.9583
      1989           51.0        0.9792         0.9792


                          U. S. GEOLOGICAL SURVEY
                     ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                     Following Bulletin 17-B Guidelines
                              Program peakfq
                          (Version 2.4, Apr, 1998)



      Station - 09334000          NORTH WASH NEAR HANKSVILLE (KITE), UTAH
                           1998 SEP 8 13:53:34


                      I N P U T   D A T A   S U M M A R Y

                 Number of peaks in record           =       21
                 Peaks not used in analysis          =        0
                 Systematic peaks in analysis        =       21
                 Historic peaks in analysis          =        0
                 Years of historic record            =        0
                 Generalized skew                    =   -0.080
                 Standard error of generalized skew  =    0.550
                 Skew option                         =   WEIGHTED
                 Gage base discharge                 =      0.0
                 User supplied high outlier threshold =
                 User supplied low outlier criterion  =
                 Plotting position parameter         =     0.00



               NOTICE  --  Preliminary machine computations.
               User responsible for assessment and interpretation.

     WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                  0.0
     WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.            73.3
     WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.     18457.3

      Station - 09334000          NORTH WASH NEAR HANKSVILLE (KITE), UTAH
                           1998 SEP 8 13:53:34

             ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                         FLOOD BASE     -            LOGARITHMIC
                    ----------------------------------------------------
                               EXCEEDANCE                STANDARD
                    DISCHARGE  PROBABILITY     MEAN      DEVIATION     SKEW
                    ----------------------------------------------------

    SYSTEMATIC RECORD      0.0     1.0000     3.0655     0.4986      -0.134
    BULL.17B ESTIMATE      0.0     1.0000     3.0655     0.4986      -0.110

     ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

       ANNUAL                               'EXPECTED   95-PCT CONFIDENCE LIMITS
     EXCEEDANCE      BULL.17B    SYSTEMATIC PROBABILITY'  FOR BULL. 17B ESTIMATES
     PROBABILITY     ESTIMATE      RECORD     ESTIMATE        LOWER        UPPER
```

```
0.9950        53 .7       52 .3        35 .0       16 .5       112 .0
0.9900        73 .4       71 .9        52 .8       24 .9       144 .9
0.9500       169 .9      168 .6       146 .5       74 .4       293 .3
0.9000       263 .6      262 .9       240 .6      130 .6       429 .0
0.8000       445 .4      446 .1       425 .5      251 .0       687 .6
0.5000      1187 .0     1193 . 0  .  1187 .0      776 .0      1823 .0
0.2000      3073 .0     3077 .0      3206 .0     1989 .0      5468 .0
0.1000      4993 .0     4977 .0      5419 .0     3078 .0     10010 .0
0.0400      8304 .0     8224 .0      9625 .0     4780 .0     19190 .0
0.0200     11480 .0    11310 .0     14120 .0     6286 .0     29230 .0
0.0100     15310 .0    15010 .0     20140 .0     7999 .0     42610 .0
0.0050     19880 .0    19370 .0     28170 .0     9933 .0     60070 .0
0.0020     27180 .0    26300 .0     43010 .0    12860 .0     90810 .0


Station - 09334000          NORTH WASH NEAR HANKSVILLE  (KITE),  UTAH
                       1998 SEP 8 13:53:34


                    I N P U T   D A T A   L I S T I N G


WATER  YEAR    DISCHARGE    CODES      WATER YEAR    DISCHARGE    CODES

   1950         1080.0                    1961         2630.0
   1951          942.0                    1962          188.0
   1952         8900.0                    1963         1810.0
   1953          865.0                    1964          168.0
   1954          273.0                    1965         2780.0
   1955         1050.0                    1966         2010.0
   1956          198.0                    1967         5010.0
   1957          592.0                    1968         2680.0
   1958         1790.0                    1969         6770.0
   1959          529.0                    1970         1980.0
   1960          630.0


  Explanation of peak discharge qualification codes

 PEAKFQ  WATSTORE
  CODE     CODE   DEFINITION

    D        3    Dam failure, non-recurrent flow anomaly
    G        8    Discharge greater than stated value
    X       3+8   Both of the above
    L        4    Discharge less than stated value
    K     6 OR C  Known effect of regulation or urbanization
    H        7    Historic peak

Station - 09334000          NORTH WASH NEAR HANKSVILLE  (KITE),  UTAH
                       1998 SEP 8 13:53:34

EMPIRICAL  FREQUENCY  CURVES  --  WEIBULL  PLOTTING  POSITIONS

  WATER        RANKED       SYSTEMATIC      BULL.17B
   YEAR       DISCHARGE       RECORD        ESTIMATE

   1952         8900.0        0.0455          .0455
   1969         6770.0        0.0909          .0909
   1967         5010.0        0.1364          .1364
   1965         2780.0        0.1818          .1818
   1968         2680.0        0.2273          .2273
   1961         2630.0        0.2727          .2727
   1966         2010.0        0.3182          .3182
   1970         1980.0        0.3636          .3636
   1963         1810.0        0.4091         0.4091
   1958         1790.0        0.4545         0.4545
   1950         1080.0        0.5000         0.5000
   1955         1050.0        0.5455         0.5455
   1951          942.0        0.5909         0.5909
   1953          865.0        0.6364         0.6364
   1960          630.0        0.6818         0.6818
   1957          592.0        0.7273         0.7273
   1959          529.0        0.7727         0.7727
```

```
      1954            273.0           0.8182           0.8182
      1956            198 .0          0.8636           0.8636
      1962            188.0           0.9091           0.9091
      1964            168 .0          0.9545           0.9545


                              U. S. GEOLOGICAL SURVEY
                        ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                        Following Bulletin 17-B Guidelines
                                   Program peakfq
                              (Version 2.4, Apr, 1998)

     Station - 09315500                SALERATUS WASH AT GREEN RIVER, UTAH
                             1998 SEP 8 13:53:34

                        I N P U T   D A T A   S U M M A R Y

                   Number of peaks in record           =       22
                   Peaks not used in analysis          =        0
                   Systematic peaks in analysis        =       22
                   Historic peaks in analysis         =         0
                   Years of historic record            =        0
                   Generalized skew                    =   -0.208
                   Standard error of generalized skew   =   0.550
                   Skew option                   '     =   WEIGHTED
                   Gage base discharge                 =      0.0
                   User supplied high outlier threshold =
                   User supplied low outlier criterion  =
                   Plotting position parameter         =     0.00

               NOTICE  --  Preliminary machine computations.
               User responsible for assessment and interpretation.

   WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                    0.0
   WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.             345.2
   WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.     16920.3

     Station - 09315500                SALERATUS WASH AT GREEN RIVER, UTAH
                             1998 SEP 8 13:53:34

          ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                          FLOOD BASE                  LOGARITHMIC
                    ----------------------------------------------------------
                               EXCEEDANCE              STANDARD
                     DISCHARGE PROBABILITY     MEAN    DEVIATION      SKEW
                    ----------------------------------------------------------
 SYSTEMATIC RECORD         0.0      1.0000     3.3833      0.3479     -0.110
 BULL.17B  ESTIMATE        0.0      1.0000     3.3833      0.3479     -0.153


   ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

     ANNUAL                                  1EXPECTED   95-PCT CONFIDENCE LIMITS
   EXCEEDANCE      BULL.17B    SYSTEMATIC PROBABILITY'   FOR BULL. 17B ESTIMATES
   PROBABILITY     ESTIMATE       RECORD     ESTIMATE         LOWER         UPPER

     0.9950          273 .7        282 .5       204 .2        121 .9        455.1
     0.9900.         342 .7        351 .3       273 .8        163 .7        548.3
     0.9500          625 .5        631 .3       565 .7        356 .9        909.9
     0.9000          855 .2        857 .9       803 .9        531 .1       1193.0
     0.8000         1240 .0       1237 .0      1202 .0        840 .7       1667.0
     0.5000         2467 .0       2453 .0      2467 .0       1847 .0       3303.0
     0.2000         4768 .0       4762 .0      4902 .0       3542 .0       7049.0
     0.1000         6654 .0       6681 .0      7018 .0       4783 .0      10640.0
     0.0400         9413 .0       9528 .0     10350 .0       6463 .0      16530.0
     0.0200        11720 .0      11940 .0     13380 .0       7788 .0      21930.0
     0.0100        14240 .0      14600 .0     16960 .0       9170 .0      28220.0
     0.0050        16970 .0      17520 .0     21170 .0      10610 .0      35470'.0
     0.0020        20910 .0      21790 .0     27930 .0      12620 .0      46650.0

     Station - 09315500                SALERATUS WASH AT GREEN RIVER, UTAH
                             1998 SEP 8 13:53:34
```

```
                    I N P U T   D A T A   L I S T I N G

   WATER YEAR     DISCHARGE    CODES       WATER YEAR     DISCHARGE    CODES

      1949          2550.0                    1960          1170.0
      1950          4850.0                    1961          1410.0
      1951          1670.0                    1962         14200.0
      1952          1810.0                    1963          1550.0
      1953          1340.0                    1964          2920.0
      1954          2340.0                    1965          6290.0
      1955           700.0                    1966          2800.0
      1956           372.0                    1967          6290.0
      1957          2250.0                    1968          3480.0
      1958          2700.0                    1969          4980.0
      1959          1510.0                    1970          4740.0

      Explanation of peak discharge qualification codes

     PEAKFQ  WATSTORE
      CODE      CODE   DEFINITION

                 3     Dam failure, non-recurrent flow anomaly
                 8     Discharge greater than stated value
                3+8    Both of the above
                 4     Discharge less than stated value
                OR C   Known effect of regulation or urbanization
                 7     Historic peak

    Station - 09315500               SALERATUS WASH AT GREEN RIVER, UTAH
                           1998 SEP 8 13:53:34

 EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

    WATER          RANKED       SYSTEMATIC      BULL.17B
     YEAR        DISCHARGE        RECORD        ESTIMATE

     1962         14200.0         0.0435         0.0435
     1965          6290.0         0.0870         0.0870
     1967          6290.0         0.1304         0.1304
     1969          4980.0         0.1739         0.1739
     1950          4850.0         0.2174         0.2174
     1970          4740.0         0.2609         0.2609
     1968          3480.0          .3043         0.3043
     1964          2920.0          .3478         0.3478
     1966          2800.0          .3913         0.3913
     1958          2700.0          .4348         0.4348
     1949          2550.0          .4783         0.4783
     1954          2340.0          .5217         0.5217
     1957          2250.0          .5652         0.5652
     1952          1810.0         0.6087         0.6087
     1951          1670.0         0.6522         0.6522
     1963          1550.0         0.6957         0.6957
     1959          1510.0         0.7391         0.7391
     1961          1410.0         0.7826         0.7826
     1953          1340.0         0.8261         0.8261
     1960          1170.0         0.8696         0.8696
     1955           700.0         0.9130         0.9130
     1956           372.0         0.9565         0.3565


                          U. S. GEOLOGICAL SURVEY
                    ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                     Following Bulletin 17-B Guidelines
                              Program peakfq
                         (Version 2.4, Apr, 1998)

    Station - 09182600                     SALT WASH NEAR THOMPSON, UTAH
                           1998 SEP 8 13:53:34



              Number of peaks in record                    15
              Peaks not used in analysis                    0
              Systematic peaks in analysis                 15
              Historic peaks in analysis                    0
```

```
            Years of historic record            =       0
            Generalized skew                    =  -0.227
            Standard error of generalized skew  =   0.550
            Skew option           "             =  WEIGHTED
            Gage base discharge                 =     0.0
            User supplied high outlier threshold=
            User supplied low outlier criterion =
            Plotting position parameter         =    0.00

         NOTICE  --  Preliminary machine computations.
         User responsible for assessment and interpretation.

     WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                     0.0
     WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.               19.6
     WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.        3710.4

       Station - 09182600                    SALT WASH NEAR THOMPSON, UTAH
                               1998 SEP 8 13:53:34

           ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                          FLOOD BASE                 LOGARITHMIC
                       ------------------------------------------------------
                                 EXCEEDANCE               STANDARD
                         DISCHARGE PROBABILITY    MEAN    DEVIATION    SKEW
                       ------------------------------------------------------
    SYSTEMATIC RECORD        0.0     1.0000     2.4303     0.5069     -0.207
    BULL.17B ESTIMATE        0.0     1.0000     2.4303     0.5069     -0.218


     ANNUAL FREQUENCY CURVE -- DISCHARGES AT SELECTED EXCEEDANCE PROBABILITIES

       ANNUAL                               'EXPECTED    95-PCT CONFIDENCE LIMITS
     EXCEEDANCE    BULL.17B    SYSTEMATIC  PROBABILITY1  FOR BULL. 17B ESTIMATES
     PROBABILITY   ESTIMATE      RECORD      ESTIMATE        LOWER        UPPER

       0.9950        10.5         10.6          5.2           2.2         25.5
       0.9900        14.8         14.9          8.7           3.5         33.5
       0.9500        36.8         37.0         29.3          12.6         70.4
       0.9000        58.9         59.0         51.2          23.9        104.8
       0.8000       102.3        102.2         95.5          49.7        171.3
       0.5000       281.0        280.4        281.0         167.5        475.7
       0.2000       726.9        726.6        770.9         433.3       1508.0
       0.1000      1167.0       1169.0       1306.0         660.7       2821.0
       0.0400      1900.0       1909.0       2325.0         999.8       5484.0
       0.0200      2579.0       2597.0       3414.0        1287.0       8375.0
       0.0100      3373.0       3405.0       4876.0        1603.0      12190.0
       0.0050      4290.0       4341.0       6843.0        1947.0      17090.0
       0.0020      5705.0       5792.0      10470.0        2447.0      25560.0


       Station - 09182600                    SALT WASH NEAR THOMPSON, UTAH
                               1998 SEP 8 13:53:34


                             I N P U T   D A T A   L I S T I N G


      WATER YEAR    DISCHARGE    CODES      WATER YEAR    DISCHARGE    CODES

         1959        1380.0                    1967          950.0
         1960          41.0                    1968          650.0
         1961        1110.0                    1969          317.0
         1962         251.0                    1970          287.0
         1963         930.0                    1971           44.0
         1964         110.0                    1973          170.0
         1965         480.0                    1974           79.0
         1966         111.0


        Explanation of peak discharge qualification codes

       PEAKFQ   WATSTORE
```

```
     CODE      CODE   DEFINITION

       D         3    Dam failure, non-recurrent flow anomaly
       G         8    Discharge greater than stated value
       X        34+8  Both of the above
       L         4    Discharge less -than stated value
       K       6. OR C Known effect of regulation or urbanization
       H         7    Historic peak

   Station - 09182600                     SALT WASH NEAR THOMPSON, UTAH
                      1998 SEP 8 13:53:34

 EMPIRICAL FREQUENCY CURVES -- WEIBULL PLOTTING POSITIONS

   WATER          RANKED       SYSTEMATIC      BULL.17B
    YEAR        DISCHARGE        RECORD        ESTIMATE

    1959          1380.0         0.0625         0.0625
    1961          1110.0         0.1250         0.1250
    1967           950.0         0.1875         0.1875
    1963           930.0         0.2500         0.2500
    1968           650.0         0.3125         0.3125
    1965           480.0         0.3750         0.3750
    1969           317.0         0.4375         0.4375
    1970           287.0         0.5000         0.5000
    1962           251.0         0.5625         0.5625
    1973           170.0         0.6250         0.6250
    1966           111.0         0.6875         0.6875
    1964           110.0         0.7500         0.7500
    1974            79.0         0.8125         0.8125
    1971            44.0         0.8750         0.8750
    1960            41.0         0.9375         0.9375


                       U. S. GEOLOGICAL SURVEY
                  ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                  Following Bulletin 17-B Guidelines
                           Program peakfq
                      (Version 2.4, Apr, 1998)
   Station -  09334500                 WHITE CANYON NEAR HANKSVILLE UTAH
                      1998 SEP 8 13:53:34

                  I N P U T   D A T A . S U M M A R Y

          Number of peaks in record            =       20
          Peaks not used in analysis           =        0
          Systematic peaks in analysis         =       20
          Historic peaks in analysis           =        0
          Years of historic record             =        0
          Generalized skew            =               -0.076
          Standard error of generalized skew   =     0.550
          Skew option                          =    WEIGHTED
          Gage base discharge                  =       0.0
          User supplied high outlier threshold =
          User supplied low outlier criterion  =
          Plotting position parameter          =      0.00

       NOTICE  --  Preliminary machine computations.
       User responsible for assessment and interpretation.

  WCF134I-NO SYSTEMATIC PEAKS WERE BELOW GAGE BASE.                 0.0
  WCF195I-NO LOW OUTLIERS WERE DETECTED BELOW CRITERION.          329.2
  WCF163I-NO HIGH OUTLIERS OR HISTORIC PEAKS EXCEEDED HHBASE.   14421.8

   Station - 09334500                   WHITE CANYON NEAR HANKSVILLE UTAH
                      1998 SEP 8 13:53:34

      ANNUAL FREQUENCY CURVE PARAMETERS -- LOG-PEARSON TYPE III

                   FLOOD BASE                  LOGARITHMIC

                         EXCEEDANCE                 STANDARD
                 DISCHARGE  PROBABILITY     MEAN     DEVIATION     SKEW

SYSTEMATIC RECORD      0.0      1.0000     3.3382     0.3442     -0.085
```

```
BULL.17B ESTIMATE        0.0      1.0000      3.3382      0.3442     -0.081

     ANNUAL  FREQUENCY  CURVE  --  DISCHARGES  AT  SELECTED  EXCEEDANCE  PROBABILITIES

     ANNUAL                                       1EXPECTED   95-PCT  CONFIDENCE  LIMITS
   EXCEEDANCE       BULL.17B      SYSTEMATIC    PROBABILITY1   FOR BULL.  17B ESTIMATES
   PROBABILITY      ESTIMATE        RECORD        ESTIMATE          LOWER          UPPER

     0.9950          266,.4          265.6          196.6           115.4          445.6
     0.9900          329,.0          328.2          260.3           152.8          530.0
     0.9500          581,.2          580.7          522.7           323.2          853.4
     0.9000          783.9           783.7          734.3           475.5         1105.0
     0.8000         1122.0          1122.0         1086.0           745.8         1525.0
     0.5000         2202,.0         2203.0         2202.0          1629.0         2983.0
     0.2000         4257.0          4258.0         4391.0          3131.0         6414.0
     0.1000         .5973.0         5971.0         6345.0          4245.0         9810.0
     0.0400         8532.0          8522.0         9519.0          5773.0        15550.0
     0.0200        10710.0         10700.0        12500.0          6995.0        20960.0
     0.0100        13130.0         13100.0        16120.0          8285.0        27410.0
     0.0050        15800.0         15750.0        20520.0          9650.0        35030.0
     0.0020        19720.0         19650.0        27880.0         11580.0        47110.0

     Station - 09334500                       WHITE  CANYON  NEAR  HANKSVILLE  UTAH
                                1998 SEP 8 13:53:34

                       I N P U T   D A T A   L I S T I N G

    WATER  YEAR     DISCHARGE    CODES       WATER  YEAR     DISCHARGE    CODES

       1951           1890.0                    1961           6910.0
       1952            860.0                    1962           4210.0
       1953           7390.0                    1963           2490.0
       1954            804.0                    1964           2670.0
       1955           6350.0                    1965           3660.0
       1956            527.0                    1966           1270.0
       1957           5570.0                    1967           2880.0
       1958            939.0                    1968           2420.0
       1959            800.0                    1969           2230.0
       1960           2480.0                    1970           1240.0


       Explanation  of  peak  discharge  qualification  codes



         D         3      Dam failure,  non-recurrent  flow  anomaly
         G         8      Discharge  greater  than  stated  value
         X        3+8     Both  of  the  above
         L         4      Discharge  less  than  stated  value
         K      6 OR C    Known  effect  of  regulation  or  urbanization
         H         7      Historic  peak

     Station - 09334500                       WHITE  CANYON  NEAR  HANKSVILLE  UTAH
                                1998 SEP 8 13:53:34

   EMPIRICAL  FREQUENCY  CURVES  --  WEIBULL  PLOTTING  POSITIONS

     WATER         RANKED        SYSTEMATIC       BULL.17B
      YEAR        DISCHARGE        RECORD         ESTIMATE

      1953          7390.0         0.0476          0.0476
      1961          6910.0         0.0952          0.0952
      1955          6350.0         0.1429          0.1429
      1957          5570.0         0.1905          0.1905
      1962          4210.0         0.2381          0.2381
      1965          3660.0         0.2857          0.2857
      1967          2880.0         0.3333          0.3333
      1964          2670.0         0.3810          0.3810
      1963          2490.0         0.4286          0.4286
      1960          2480.0         0.4762          0.4762
      1968          2420.0         0.5238          0.5238
      1969          2230.0         0.5714          0.5714
      1951          1890.0         0.6190          0.6190
      1966          1270.0         0.6667          0.6667
```

```
      1970 .       1240.0          0.7143          0.7143
      1958          939.0          0.7619          0.7619
      1952          860.0          0.8095          0.8095
      1954          804.0          0.8571          0.8571
      1959          800.0          0.9048          0.9048
      1956          527.0          0.9524          0.9524


                     U. S. GEOLOGICAL SURVEY
                 ANNUAL PEAK FLOW FREQUENCY ANALYSIS
                 Following Bulletin 17-B Guidelines
                          Program peakfq
                    (Version 2.4, Apr, 1998)

End PEAKFQ analysis.
  Stations processed :       11
  Number of errors   :        2
  Stations skipped   :        0
  Station years      :      298


Unrecognized CARD type.  Must be Y,Z,N,H,I,2,3,4, or *.

Unrecognized CARD type.  Must be Y,Z,N,H,I,2,3,4, or *.
```