3

Hydrology of Glen Canyon and the Grand Canyon

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INTRODUCTION—NATURAL FLOWS INTO LAKE POWELL

To understand the hydrology of the Colorado River in the Grand Canyon, we must know the natural flows that would have flowed through the canyon without the effects of manmade changes. We must know the effect of the manmade changes that result in the current inflows into Lake Powell. In addition, the law of the river affects the releases from Glen Canyon Dam. The law of the river includes the actual law, which determines the division of the waters between upper and lower states, and the interpretation of the law, which determines the interyear and interday variation of the releases to meet the law of the river. To understand the present concerns about the canyon reach of the Colorado, we must look at those natural flows, i.e., the flows during the filling of Lake Powell, and the sudden and abrupt realization that a full dam spills. The period from the closure of the dam until its spill is a transition period. The future hydrology of the canyon reach will be different from any hydrology yet experienced. This paper will not look at all facets of hydrology but rather will highlight what is needed in terms of data and analysis in order to better understand the hydrology of the Grand Canyon.

EARLY UNDERSTANDING OF COLORADO RIVER FLOWS

The Colorado River basin both above and below the Grand Canyon has been influenced by diversions from the early days of settlement of the West.

The Mormons settled along the Green River in Wyoming in 1854 and immediately began irrigated agriculture. Other irrigated settlements began in the 1870s along the lower Colorado in California, in the 1880s near Grand Junction, Colorado, in 1890 at Yuma and on the Salt River in Arizona.

The earliest assessment of the hydrology of the Colorado River basin and its potential for development was undertaken by E. C. La Rue, a hydrologist with the U.S. Geological Survey (USGS). N. C. Grover, then head of the Water Resources Division, wrote in the foreword to La Rue's second major work on the Colorado, "The need for further agricultural development in the Colorado River basin will increase gradually, while the demand for electric energy in the basin and in regions outside the basin, but within economic transmitting distance will increase more rapidly. It would not be economical, however, to proceed with a program of development that is greatly in advance of actual requirements. Such a program would be unwise because it's uneconomical and would surely result in losses of invested capital. It is important also that any developments...shall conform to a rational scheme for the full development of the river that will not needlessly sacrifice head available for power or unnecessarily waste water by evaporation from reservoir surfaces" (Grover, cited in La Rue, 1925, p. 5).

A considerable amount of data were available to La Rue for that first assessment of the hydrology of the Colorado. Stream-gaging stations were established by the USGS as early as 1895 on the Green River, 1902 at Yuma, and 1904 on the lower San Juan. The USGS established the gaging station at Lee's Ferry in the summer of 1921 and the station at Bright Angel in 1923. In 1925 Larue published Water Supply Paper (WSP) 556, which used records through the 1922 water year. He reconstituted streamflows from 1895 through 1922 for the Colorado River at Lee's Ferry by use of gaged records upstream and downstream. His estimate of the reconstituted mean annual flow equaled 16.8 million acre-feet, which was the same as that used for that period by Leopold (1959). "Under future conditions the flow in and below the Grand Canyon will be reduced. When development in the upper basin is completed . . . the average annual flow is estimated at 12,000 second-feet at Lee's Ferry" (La Rue, 1925, p. 9), which is about 8.7 million acre-feet per year. La Rue estimated the depletions from the river for irrigation for the period 1895-1922 and listed them in WSP 556.

Earlier, La Rue had written, "The Colorado-San Juan reservoir site is in Glen Canyon on Colorado River in northern Arizona and southern Utah. By constructing a dam at the head of Marble Canyon, a few miles below the mouth of the Paria River, to a height of 244 feet, a reservoir of 3,000,000 or 4,000,000 acre-feet would be formed . . . . The average annual run-off available for storage at the Colorado-San Juan reservoir site is about 15,000,000 acre-feet . . . . The position . . . is good . . . but the capacity of the reservoir might be seriously reduced in 50 years by the deposition of silt" (La Rue, 1916, p. 214-215). Thus, Glen Canyon and nearby sites were under consideration for development from the earliest assessments of the Colorado River basin.

THE EARLY HEARINGS ON DEVELOPMENT OF THE LOWER COLORADO

La Rue was the first USGS engineer assigned to the Division of Water Utilization for field work needed in the examination of withdrawals under the act of June 25, 1910, and in applications for rights-of-way for irrigation and hydropower projects across public lands, Carey Act segregations, and examination of land for designation under the Enlarged Homestead Act. La Rue emphasized that demands for water from the Colorado would exceed the available supply, and thus water losses by evaporation should be a serious and critical planning criterion.

La Rue advocated a principle of engineering determinism, which is the advocacy of a single best plan. He was hydrologically correct, but the principle of engineering determinism fails to consider uncertainty. Engineering determinism has controlled the development of the Colorado, as it has development of most water resources, and that may be a cause for part of the concerns with the Grand Canyon today.

Arthur Powell Davis, a nephew of John Wesley Powell, was head of the Reclamation Service, later the Bureau of Reclamation, from 1914 to 1923. Davis and the Reclamation Service wanted water and power for California and Los Angeles immediately. La Rue advocated phased, integrated development. In the planning of Boulder Canyon Dam and the division of the waters, Davis and the Reclamation Service prevailed.

UNCERTAINTY IN AVERAGE STREAMFLOW

The division of the waters was not finally settled, however, and the lawsuit *California* v. *Arizona* resulted. During that case, Luna Leopold and Walter Langbein of the USGS analyzed the water availability in the upper Colorado, the uncertainty concerning the availability, and the effect of evaporation on yield from the upper basin (Leopold, 1959). 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. Also, northern California is in its fourth year of drought. 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. This is illustrated in Figures 3-1 and 3-2, taken from Leopold's paper. Figure 3-1 shows that the reduction of the variability in mean flow for records of streamflow in general is less than would be expected for a random sequence of uncorrelated flows. Because the reduction in variability of estimates of the mean flow is not as fast as for random sequences, a longer period of record is required to obtain a given level of accuracy concerning the mean flow. This amount of increased record is shown in Figure 3-2. Leopold's figure shows that 100 years of record is required to obtain as much accuracy as expected from an uncorrelated 25-year record. Leopold's analysis showed that the 70 years of record on the Colorado is the equivalent of a streamflow record with about 20 years of record of uncorrelated data.

Uncertainty in the average inflow results in uncertainty in the average yield, which determines the hydrology of the Grand Canyon. Uncertainty concerning hydrology determines the reliability of estimates of water and sediment throughput of the Colorado River and the resultant impact on growth and erosion of beaches in the Grand Canyon. The capability of Lake Powell and Lake Mead to store sufficient water to deliver the 75 million acre-feet every 10 years to the lower states plus 1.5 million acre-feet per year to Mexico depends on the reliability of the estimates of streamflow. The study of Leopold and Langbein should be updated, and the reliability of

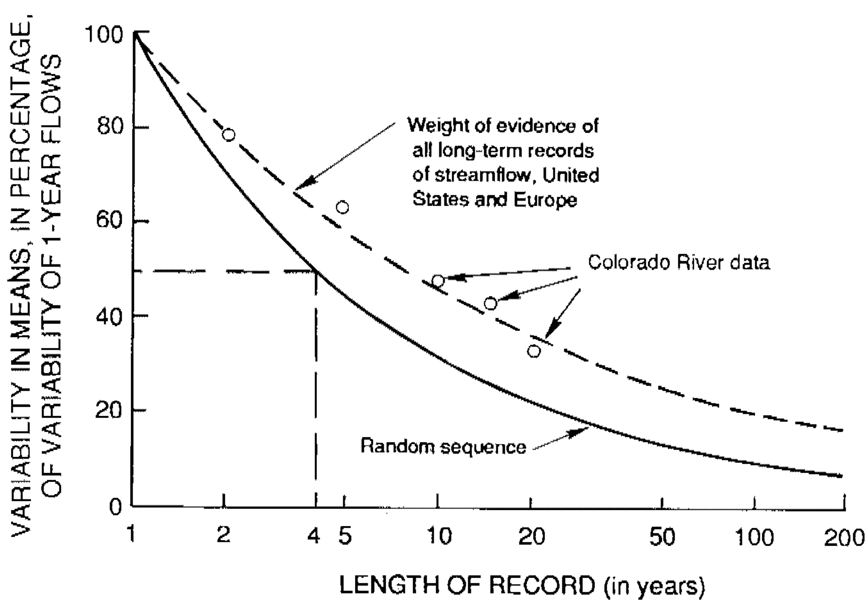

FIGURE 3-1 Variability of mean values of streamflow for records of various lengths. **SOURCE:** Leopold, 1959.

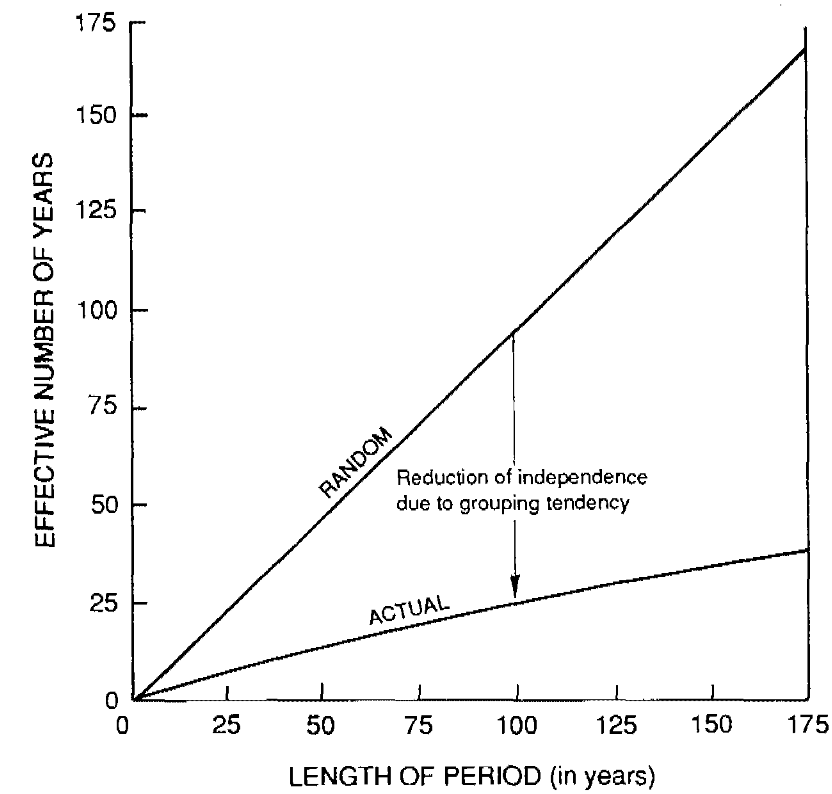

FIGURE 3-2 Effect of grouping tendency in streamflow.
SOURCE: Leopold, 1959.

the "reconstructed flows" and the actual Lake Powell inflows should be reassessed.

EVAPORATION, BANK STORAGE, AND LAKE POWELL WATER BALANCE

Leopold also discussed increased evaporation resulting from added storage and the net effect on water availability. As we know, the effect of storage on streamflow is to reduce the variability and thus to increase the average yield from the basin. However, each additional increment of storage capacity gives a smaller increment of flow regulation and a smaller marginal increase in yield. Leopold demonstrated that an increase in total reservoir capacity in the Colorado River basin would achieve practically no additional water regulation if evaporation loss is subtracted from annual regulation. Evaporation loss offsets the hydrologic benefit of the regulation so achieved. Such an analysis should be updated routinely to determine the firm yield of the flows through the canyon and the capability of Lake Powell to deliver the contract amounts downstream as development increases upstream.

Evaporation loss from Lake Powell was assumed by La Rue to be about five acre-feet per acre per year, which amounts to about 750,000 acre-feet per year for the approximately 150,000 acres of surface area of the lake. Lake Mead evaporation was found to be about 7 feet per year (Harbeck et al, 1958). A similar evaporation at Glen Canyon would produce about 1 million acre-feet of evaporation per year. The U.S. Bureau of Reclamation (USBR) appears to use slightly under four feet per year (perhaps based on Jacoby et al., 1977), with a constant distribution in the year, irrespective of climate variation. USBR computes evaporation as a function of stage, however, so that their computed evaporation varies from 560,000 acre-feet for 1989 to 633,000 acre-feet for 1983 (USBR, 1965-1990). The U.S. Weather Bureau (USWB) (1959) estimates 80 inches per year for a Class A pan and a coefficient of .68 to convert to lake evaporation for an average loss of 4.5 feet, or about 15% higher than the USBR figure, which would give 650,000-730,000 acre-feet of loss per year. The USWB says 74% of the evaporation should be in May through October; USBR shows only 63%. Therefore, if lake evaporation is underestimated, it is in the spring runoff and summer months, when the reservoir will be highest in stage. An assessment should be undertaken to determine the basis for the seemingly low evaporation values used by the USBR, how they were determined, and how they are used. In particular, if they are used for the determination of releases, evaporation values should be based on local meteorologic data.

The USBR computes a water budget for Lake Powell on a daily basis. The water budget calculations are a basis for planning of releases from the dam. Therefore, an analysis should be undertaken to substantiate the USBR calculations. Evaporation is not a function of weather in the USBR estimates, as stated above, so when it rains and a cold front passes through, inflow rather than evaporation is affected. Therefore, inflow is a derived figure. Bank storage sometimes goes down when stage rises, and vice versa. For example, from September through December 1989, the stage is constantly falling yet there is a gain in bank storage each month. The stage falls over 11 feet, and bank storage increases by over 110,000 acre-feet. Therefore, bank storage must be a derived figure or at any rate seems not to be derived from a physically based model of the surrounding aquifer. The USBR should develop a physically based groundwater model for the determination of bank storage, such as is used in reservoirs in the Columbia River basin (Thompson, 1973, 1974). Such models are particularly useful if any long-term forecasts are used for managing releases from Lake Powell.

Many months have a water balance for Lake Powell for which inflow minus outflow equals the change in storage in the system, but some apparently do not. This may be because when results get too far from reality, adjustments are made to bring the apparent numbers back into agreement with the state of the system. Precipitation on the lake is not included in the water balance, as far as can be seen, although it should be included in any water balance calculations. Evaporation is computed as described above. Discharge is computed incorrectly based on turbine ratings. The discharge at the Lee's Ferry gaging station of the USGS should be used. If more accuracy is required, then a study should be undertaken to improve the accuracy at that station. If turbine ratings are used for day-to-day operations, then each turbine should be calibrated based on the USGS gage. The gravel bars immediately below Glen Canyon Dam should affect the different turbine ratings differently. A study should be undertaken to determine whether, in fact, some turbines are more efficient and what can be done to improve the performance of the less effective ones. Removal of part of the gravel deposits immediately below the dam might be feasible.

Change in storage in the lake is computed from a capacity table, which should change with sediment deposition in the upper reaches of the reservoir. A determination should be made of the effect of the changes in the storage on the capacity curve and thus on the water balance. There are two degrees of freedom in the USBR water balance for Lake Powell, apparently: bank storage and inflow. Because these calculations may influence what is released down the river, the calculations should be checked and verified. Bank storage should be calculated from a ground water model, such as is done in the Columbia River basin. Evaporation should be based on meteorologic data, such as suggested by the Lake Mead report. Precipitation should be taken into account; only then can a rational assessment of water availability be made.

RECONSTITUTED, NATURAL INFLOWS TO LAKE POWELL

Figure 3-3 shows the reconstituted natural inflows to Lake Powell. Shown are estimates by La Rue (1895-1922), discharges published by Leopold provided by USBR in 1959 (1896-1956), and current values used by the USBR (1906-1983). 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 USBR estimates are about 500,000 acre-feet greater than the values provided Leopold (14.35 million versus 13.85 million). The figures provided by Leopold agree with the earlier figure of La Rue. The source of the difference of 500,000 acre-feet should be determined, and its

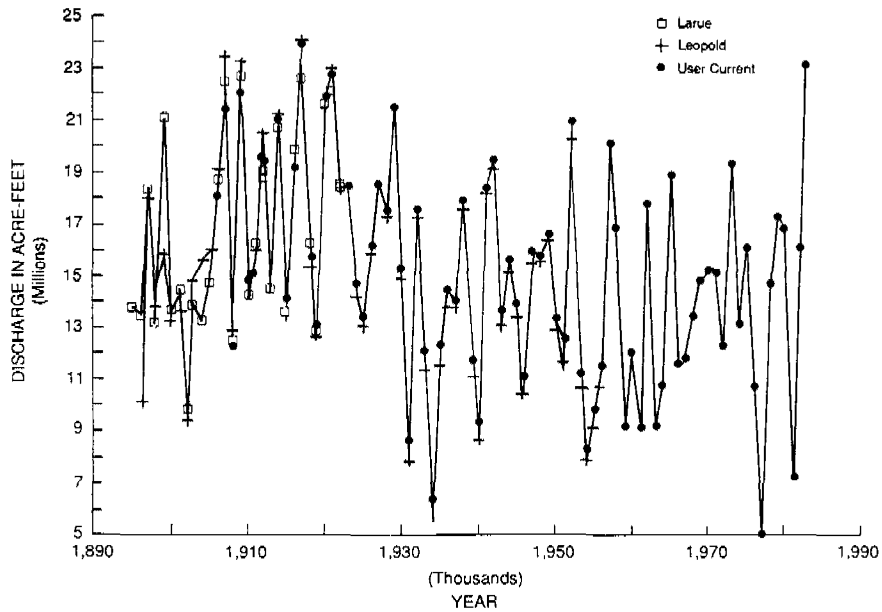

FIGURE 3-3 Reconstituted natural inflows into Lake Powell.
SOURCES: LaRue (1895-1922), Leopold (1896-1956), USBR (1906-1983).

validity should be assessed. Once again, releases may be determined by the accuracy of that determination. Certainly, long-term planning should be affected by the estimates of water availability. Subtracting 550,000 acre-feet of evaporation (possibly underestimated, as stated above) gives only 13.3-13.8 million acre-feet rather than the 16 million acre-feet needed to meet the contract. Who loses the evaporation is not known, but how this is decided will determine the total releases in the future.

GLEN CANYON AND THE RELEASE RULES

The release rules under the law of the river affect the flexibility of operation of Glen Canyon Dam and the flow of water through the canyon. Releases from Hoover Dam require releases from Lake Powell because the contents of Lake Powell are related to the contents of Hoover Dam. The "equal contents" rule keeps control of flows through the canyon in the lower states. Therefore, the release rules from Hoover Dam should be considered a part of the hydrology of the Grand Canyon.

The resulting hydrology of the Grand Canyon depends on water availability. That, in turn, depends on inflow into Glen Canyon, evaporation from the lake surface, storage in the lake and in its banks, precipitation on the lake, and water left for outflow from Glen Canyon. Hydrology controls the canyon.

RELATIONSHIP OF SEDIMENT TRANSPORT TO STREAM FLOW IN THE CANYON

Fluctuations of flow, not mean flow for the day, control sediment transport and stability of the ecosystem in the Grand Canyon. Pulses of flow released at Glen Canyon Dam will be attenuated as the flow travels downstream through the canyon. Daily flows alone cannot be used to predict sediment transport. Attenuation of flows will result in modification of the channel system, because the channel will adjust to carry the load of water and sediment imposed from upstream. Pools may fill in or bars (beaches) may be eroded or added to in the adjustment of the channel geometry to the hydrology. Because flow pulses attenuate as they travel through the canyon, the same daily average flow will cause the channels to adjust differently in different reaches of the canyon in order to carry the same sediment through the system. Added flows and sediment at the Paria and the Little Colorado determine the channel configuration, bars, beaches, and sediment discharge through the canyon. Therefore, discharge and sediment must be monitored for those two streams in order to understand the canyon flows and their relationship to the beaches.

Attempts to estimate sediment transport through use of a sediment rating curve require a considerable amount of data. The present set of data can be used to do a quick assessment of what flows are required to maintain an approximate balance of sediment throughout the system. This quick-and-dirty assessment will show what average set of high and low flows plus ramping rates will approximately move through the canyon the sediment available on an average basis. However, it will not predict where the sediment will be stored, and the channels will adjust during the period of transition to a quasi-equilibrium state. This results both from an inadequate data base (which must be improved by monitoring) and from an inadequate model with enough detail to predict changes in sediment transport for short reaches of the canyon. The sediment and discharge monitoring are necessary to verify the results of improved models of sediment discharge through the canyon. The canyon ecosystem cannot be managed properly without the data base and the analytical tools to predict flows and sediment discharges through the Grand Canyon.

Flows must cover the beach areas in order to add to them. Otherwise, all adjustment will be made by eroding beaches or adding bars which are wet at high flows. Therefore, this first assessment, which has not yet been made, is only a first step. The next step will require a model of beach building, based on the mechanics of flow in the vicinity of selected beaches, to determine what flows are required and how long to store sediments on the higher beaches and to clear the vegetation so that the beaches remain beaches rather than jungles of willows, salt cedar, and Russian olive. An understanding of the hydrology is necessary to predict and understand the movement of sediment in the canyon. An understanding of the sediment movement is necessary to predict the results of various flow regimes on the ecosystem of the canyon.

The rapids which make river running a challenge are the result of debris flows. If only average flows are maintained, the debris flows will collect at the rapids and not be reworked. Eventually, some rapids may become more dangerous if not impassable by boat. A study should be undertaken to determine what flows are necessary to move the materials that collect from debris flows in order to manage the rapids.

EFFECT OF OPERATION OF UPPER BASIN STATE RESERVOIRS ON GLEN CANYON AND THE GRAND CANYON

Present upstream use of waters in the Colorado River basin are on the order of a little over 4 million acre-feet, based on the difference between the USBR figures on water availability and inflows to Lake Powell. For 1968-1974 upstream depletions varied from 3.6 million acre-feet in 1969 to 4.96 million acre-feet in 1971, with an average of 4.28 million acre-feet for the 7 years. If 13.5 million acre-feet is available and 4.3 million is consumed upstream, this leaves 9.2 million acre-feet available to meet the downstream requirement of 8.25 million acre-feet (7.5 million acre-feet to the lower states plus half of the 1.5 million acre-feet to Mexico).

If water use increases by as much as 1 million acre-feet in the upper basin states, there is a possible effect on the future flow regimes through the canyon. Once the uses are in place, the depletions will increase so that the average inflow to Glen Canyon will be less than the required average release. This means that Lake Powell will be drawn down until an emergency results, at which time a lawsuit will start. A drought during the next 10 years after the start of the lawsuit and before its final adjudication can cause Lake Powell to go dry. At the very least, the lake level could change such that the temperature and chemistry of releases will change. During the next wet cycle Lake Powell may return to the "filling mode" similar to the period prior to 1983. As the upper basin states utilize their legal allotment and the average inflow approaches approximately the required average releases, major fluctuations in Lake Powell will result.

One effect of the fluctuation of the level of Lake Powell as average inflows decrease to be equal to or less than the average required release would be an increase in temperature in the release water. If Lake Powell goes dry or almost so, the releases will revert to warm water, and the area immediately downstream will become a warmwater fishery again. The trout population will be affected, if not eliminated. Management of the Glen Canyon National Recreation Area should be concerned with this problem and should be involved in any study of the future changes in average inflow into Lake Powell.

A general systems analysis of the inflows to Lake Powell and the effect of future increased usage by the upper basin states on those inflows should be undertaken. The uncertainty of water availability should be considered in the analysis, and the consequences of future development of increased water use by the upper basin states should be anticipated.

As mentioned earlier, autocorrelation in time of the streamflows in the Colorado River basin increases the uncertainty concerning the average streamflows in the basin. Autocorrelation in time means that high years tend to follow high years and low years tend to follow low years. Estimates such as 16 million, 14 million, and 13.5 million acre-feet of natural inflows to Lake Powell are very uncertain figures. Therefore, the possibility of wide variations in the elevation of Lake Powell is fairly large because that possibility depends on the assumed average natural inflow.

TRAVEL TIMES THROUGH THE GRAND CANYON

The storage behind Glen Canyon Dam attenuates the fluctuation in discharges while power production reintroduces them and controls the hydrology of released flows; then travel down the canyon attenuates the pulses. Rapid ramping rates cause the hydrology of the canyon to change as pulses are attenuated as flow travels downstream.

The travel time through the canyon varies with discharge. During 1987, the Grand Canyon Environmental Studies measured flows at four stations from Lee's Ferry to Lake Mead. By choosing selected peaks and troughs and tracing them through the canyon, peak and trough travel times as a function of discharge can be estimated. Figure 3-4 shows the variation of travel time from Lee's Ferry to the Little Colorado River and to Bright Angel Creek. The average velocities are from 6 to 8 cubic feet per second (cfs).

As stated, travel times through the canyon are a function of discharge. Peak flows travel faster than the lower flows in the daily trough (Figure 3-4). At a flow of 3,000-4,000 cfs, the travel time from Lee's Ferry to the Little Colorado is about 15 hours and to Bright Angel is about 20 hours. For flows of 18,000 to 20,000 cfs, these travel times are reduced to 12 and 15 hours. Because high flows overtake low flows and because the peakedness is reduced through dynamic storage, the duration of time for the trough discharge is reduced as the release wave from Lake Powell travels downstream. Because the sediment transport is related to a power of the veloc-

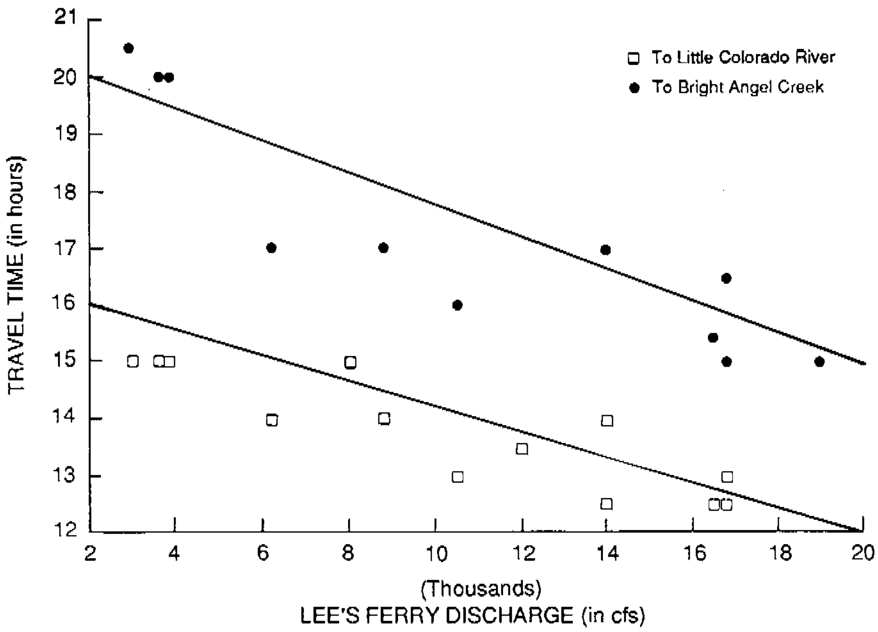

FIGURE 3-4 Relationship of travel time to stream discharge through the Grand Canyon from Lee's Ferry to Little Colorado River and Bright Angel Creek.

ity, as the pulse is attenuated less sediment will be transported, all other things being equal. However, all other things will not remain equal. The channel will adjust in those reaches where adjustment is possible and where the sediment transport is hydraulically controlled. Also, because the faster flows will overtake the slower, lower flows, the rising limb of the ramp will tend to steepen and the falling limb to be further attenuated by the effects of varying velocity.

Thus, the difference in travel times will cause a steepening of the ramping rate on the rising stage and a flattening of the ramping rate on the falling stage, with that effect added onto the attenuation because of storage in the canyon reach. Thus, if the ramping rate is the same on the rising stage as on the falling stage, the changes downstream will be more abrupt on the rising stage.

To understand the change in flood waves and their effect as they move through the canyon, a firm data base is required. Because the velocity determines the sediment discharge, sediment monitoring is required as well as discharge monitoring. In fact, sediment monitoring is more important than water monitoring. A discharge routing model can be developed more easily and more accurately than can a sediment routing model. As stated earlier, sediment rating curves, the basis for most sediment routing models, will be difficult to define with sufficient accuracy to define a sediment routing model. This is because we are interested in differences in sediment movement over rather short reaches to determine the storage and erosion of beach materials. Therefore, an intensive monitoring network for sediment transport in the canyon will be needed to determine the sediment processes and how they interact. Bottom materials must be monitored to determine how the system is reacting during its transition to a quasi-equilibrium state. The bottom materials determine both the resistance to flow and the sediment transport.

The channel will adjust to the newly introduced regime of flows. Therefore, any analysis of travel times and sediment transport requires a long-term monitoring program. To understand the canyon, the changes in the canyon over time must be understood. The monitoring data are an integral part of any research plan, and they should be demanded by management in order to manage the canyon, to assess the effects of management decisions on the canyon, and to modify the decisions to adjust to the better understanding of the ecosystem that will result from the data obtained by the long-term monitoring.

CONCLUSION

The hydrology of the Grand Canyon depends on the water in Lake Powell available for release. The computation of natural inflow into Lake Powell, the projection of trends in the net inflow into Lake Powell, and the water budget for Lake Powell should be carefully reviewed and updated. Evaporation and bank storage in Lake Powell should be estimated through use of physically based models. Any tracing of flows through the canyon should be based on streamflow records at the Lee's Ferry gage, not on turbine computations of streamflow. Travel times for the various reaches of the Grand Canyon should be determined and used to calibrate flow and sediment routing models. Discharge and sediment must be monitored intensively in the canyon system. Monitoring of the streamflow and sediment should be considered part of the research effort, just as cataloging species of fauna and flora over time is a research effort.

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