Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah

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ABSTRACT

The Green River is one of the principal tributaries in the Colorado River basin and drains 44,700 mi² in Wyoming, Colorado, and Utah. Since October 1962, flows of the Green River have been regulated by Flaming Gorge Reservoir, which is located 412 river miles upstream from its confluence with the Colorado River. Mean annual runoff has not been affected by the reservoir. The duration of the relatively large discharges that transport most of the annual sediment load, however, has decreased significantly. As a result, the mean annual sediment discharge has decreased by 54% to $3.21 \times 10^8$ tons from $6.92 \times 10^8$ tons at the Jensen gage located 105 river miles downstream from the reservoir and by 48% to $8.83 \times 10^8$ tons from $17.8 \times 10^8$ tons at the Green River, Utah, gage located 290 river miles downstream from the reservoir. Sediment supply to the channel equals the annual transport within a relatively short distance, 68 river miles, downstream from the reservoir. Downstream from river mile 166, the supply of sediment from upstream tributary inflow exceeds the transport of sediment by $5.4 \times 10^8$ tons per year on average. The quasi-equilibrium that appears to have existed prior to the reservoir no longer occurs along a majority of the Green River.

In response to the reduced peak discharges, the bankfull channel width of the Green River has decreased by ~10%. Adjustment of the channel to decreased peak flows and altered sediment loads is nowhere complete. At present, it appears that a century or more will be required for the Green River to adjust to the effects of Flaming Gorge Reservoir.

INTRODUCTION

Alluvial channels adjust over a period of years, so that the sediment supplied to the channel is transported with the available discharge. When there is no net accumulation or depletion of sediment in the bed, banks, or flood plain, the average hydraulic characteristics width, depth, velocity, roughness, slope, and channel pattern, through a reach of channel at a given discharge, will be nearly constant. Such river channels are in quasi-equilibrium. Although this condition may not be exact, the uniform elevation of flood plains along many rivers indicates that quasi-equilibrium is approached for periods of several decades to centuries. An appreciable and persistent change in the water discharge, sediment load, or sediment size will cause a disequilibrium between the quantity of sediment supplied to the reach and the quantity transported out of the reach. Thus, the hydraulic characteristics will readjust, so as to attain a new quasi-equilibrium.

The quasi-equilibrium adjustment of a river channel located downstream from a reservoir typically will be altered to a substantial degree by the storage of sediment in the reservoir and the decrease of river discharge, especially the peak flows. The nature of the disequilibrium will vary longitudinally downstream in magnitude, direction (sediment surplus or deficit), and duration. Williams and Wolman (1984) described the complex channel changes that have occurred downstream of 21 dams. Degradation of the riverbed immediately downstream of a reservoir has been the most commonly studied channel impact (for example, see Hathaway, 1948; Komura and Simons, 1967; and Petts, 1979). These investigations usually have been limited to a reach extending only a few hundred channel widths downstream from the dam. Investigations into the downstream effects of reservoirs have rarely considered channel adjustments that might occur downstream from the confluence of the first major tributary, although there is evidence that the changes are quite significant. Lawson (1925) described extensive channel aggradation in a reach of the Rio Grande beginning >100 mi downstream from Elephant Butte Reservoir. Degradation and aggradation of the Missouri River channel have become serious problems in the nearly 800-mi reach between the last downstream reservoir and the river mouth. Sayre and Kennedy (1978) attributed this channel disequilibrium, in part, to reservoirs.

The opportunity to study the downstream effects of reservoirs has been limited by two primary difficulties. In most alluvial rivers, the mean annual sediment discharge is small compared to the quantity of sediment stored within a reach of a few hundred channel widths in length. Consequently, the annual sediment deficit caused by reservoir storage also is small compared to the volume of sediment available for transport. Major channel adjustments may occur only after an appreciable change in quantity of sediment within the channel. This condition may require several decades to develop, depending upon the distance downstream from the reservoir. Reservoirs with storage greater than 1,000,000 acre-feet have been built only within the past 50 yr or so. The vast majority have been constructed since 1950. The far-downstream effects of these reservoirs upon channel equilibrium are only now becoming evident.

The second difficulty is closely related. Comprehensive, long-term records of river flows and sediment transport at several locations downstream from the reservoirs, as well as on major tributaries, usually do not exist (Petts and Lewin, 1979). Thus, the information required to describe the characteristics of river flows and sediment transport prior to a reservoir and the change since regulation is usually unavailable.

Several of the longest records of daily sediment transport that exist for North American rivers have been collected at gaging stations in the Colorado River basin. As of 1983, the length of most of these records of sediment transport was almost 40 yr. Large reservoirs were constructed on each of the three major headwater tributaries during the early 1960s. The pre- and post-reservoir periods of record therefore are now ~20 yr. This investigation considered the downstream effects of Flaming Gorge Reservoir on the Green River.

Long-term channel change is of particular interest for the Green River because of the impacts it may have on the survival of several species of

Figure 1. Locations of principal water and sediment gaging stations.

HYDROLOGY OF THE GREEN RIVER BASIN

The Green River drains ~44,700 mi² along the west flank of the Rocky Mountains in Wyoming, Colorado, and Utah (Fig. 1). It is one of the principal tributaries in the Colorado River basin. The main-stem Green River originates in the Wind River Mountains of Wyoming and flows southerly to its confluence with the Colorado River near Moab, Utah. The principal tributaries of the Green River are the Blacks Fork, Yampa, Duchesne, White, Price, and San Rafael Rivers. Flow in the Green River has been regulated by Flaming Gorge Reservoir since October 1962. Fontenelle Reservoir, also located on the main-stem Green River, is the second largest impoundment in the Green River basin and was completed in April 1964. Tributaries to the Green River have numerous small impoundments, especially in their headwaters. Except for the Duchesne River, however, the tributaries are generally free flowing and unregulated at present (1985). Several reservoirs have been proposed and are being considered for the principal tributaries.

The location of the long-term gaging stations in the Green River basin are shown in Figure 1. Water discharge has been recorded daily at most gages for several decades. Extensive records of suspended-sediment concentration also have been collected at the gages shown in Figure 1. At those gages where the suspended-sediment concentration has been measured daily for five years or more, the mean annual sediment discharge was determined by averaging the series of annual values. At the other gages, the relation between sediment discharge and water discharge (sediment-discharge rating curve) was computed from a least-squares regression of the log-transformed values. The mean annual sediment discharge was computed by the sediment-discharge rating curve and flow-duration method.

The water- and sediment-discharge records were compiled to determine mean annual water and sediment budgets prior to construction of Flaming Gorge Reservoir, for three reaches of the Green River. Reach 1 extends downstream from Flaming Gorge Reservoir to the Jensen gage. Reach 2 extends downstream from the Jensen gage to the Ouray gage. Reach 3 extends downstream from the Ouray gage to the Green River, Utah, gage.

The mean annual inflow and outflow of water and sediment to each reach are summarized in Table 1. The periods of record used to compute the mean annual values are indicated. The mean annual water and sediment discharges at the Jensen and Green River, Utah, gages since regulation by Flaming Gorge Dam began were computed from the measured daily values. Sampling of suspended-sediment concentration in the Green River at the Ouray gage was discontinued in September 1966, 4 yr after the beginning of reservoir regulation. This record was extended by correlating the 4 yr of measured sediment loads with the sediment loads determined for the Green River, Utah, gage. The coefficient of determination for the relation is 0.95.

For some tributaries, the mean annual contributions of water and sediment to the Green River were computed from daily measurements collected after regulation of flow by Flaming
Gorge Reservoir had begun. These tributaries, however, have not been affected significantly by any regulation or impoundment. Mean annual values shown in Table 1, therefore, are a reasonable estimate of inflow and outflow of water and sediment to reaches of the Green River prior to appreciable water-resources development. The estimated contributions from ungauged areas were computed by assuming that inflow and outflow to the reaches were equal. In terms of the sediment budgets, this assumes that the reaches were in long-term quasi-equilibrium prior to flow regulation. The presence of extensive flood plains along most alluvial reaches supports this assumption.

SOURCE AREAS OF RUNOFF AND SEDIMENT

Water and sediment are not contributed to the channel network uniformly across the Green River basin (Iorns and others, 1965). Furthermore, the principal source areas of water and sediment differ greatly. A majority of the annual water discharge from the basin is supplied by the headwater areas. Conversely, the semiarid parts of the basin at lower elevations contribute most of the sediment. The mean annual water discharge and sediment discharge prior to 1962 at gaging stations in the Green River basin are shown in Figure 2. Immediately upstream from Flaming Gorge Reservoir, the unregulated mean annual flow was 1,575 ft³/s or 27% of the total basin outflow. The mean annual sediment discharge at this gage, however, was only 3.7 × 10⁶ tons or 2.2% of the basin outflow. Similar contrasts are shown by the comparison between the water and sediment discharges of the Green River basin and the quantities measured by the farthest upstream gages on the Yampa and White Rivers. The combined mean annual discharge at the 3 farthest upstream gages is 2,680 ft³/s or 46% of the basin discharge, whereas the sediment contribution is only 0.44 × 10⁶ tons or 2.6% of the basin-sediment discharge. The contributing drainage area is ~27% of the total basin.

The large sediment-contributing areas in the Green River basin are indicated, similarly, in Figure 2. All tributaries joining the Green River downstream from the gage near Green River, Wyoming, supply relatively large percentages of the basin-sediment outflow. In all instances, however, the sediment is contributed primarily by the downstream part of the tributary drainage basins. Thus, the large water-contributing parts of the Green River basin lie around the rim, especially along the northeast divide. Conversely, the large sediment-contributing areas are located in the central and southern parts of the basin.

CHANGES IN CHANNEL EQUILIBRIUM DOWNSTREAM OF FLAMING GORGE RESERVOIR

The mean annual inflow and outflow of water and sediment to three reaches of the Green River after the construction of Flaming Gorge Reservoir are summarized in Table 1. Comparing the pre- and post-reservoir periods, mean annual water discharge at the Green River near Jensen, Utah, gage has not been affected. Mean annual discharge of the Green River near Jensen, Utah, gage was 4,200 ft³/s from 1963 to 1981 compared to 4,320 ft³/s from 1947 to 1962. The range of daily flows throughout the year, however, has been altered considerably and will be discussed below. The mean annual sediment discharge at the Jensen gage has decreased by 54% to 3.21 × 10⁶ tons. Mean annual inflow of sediment to the river reach downstream from Flaming Gorge Reservoir to the Jensen gage is 3.31 × 10⁶ tons. Thus, there exists a near balance of sediment supply and transport in this reach of Green River after regulation.

Downstream from Flaming Gorge Dam, the Green River flows through a narrow, bedrock canyon for 12 river miles. Degradation of the riverbed in this reach has been limited. In 1982, bed material in this reach consisted primarily of coarse gravel, cobbles, and boulders. Photo-
Figure 2. Mean annual runoff and sediment load prior to 1962 at selected gaging stations.

Graphs taken of the channel prior to 1962 indicate that the size of bed material has not changed significantly. Entrainment of such coarse bed material probably was only a few days a year on an average before flows were regulated (Graf, 1980). As a result of flow regulation, discharges larger than 5,000 ft$^3$/s no longer occur. Prior to 1962, a daily mean discharge of 5,000 ft$^3$/s was equaled or exceeded 10% of the time, and the maximum value for the water years from 1951 to 1962 was 19,000 ft$^3$/s. Since 1962, discharges large enough to entrain bed material and thus degrade the riverbed have occurred only very rarely as a result of extreme floods on tributaries. Further degradation of the riverbed is inhibited by the coarse bed-material armor that has developed.

Downstream from the canyon, the Green River flows through the wide Browns Park Valley for 40 river miles before entering Lodore Canyon. The size of bed material decreases through the reach, until the channel bed becomes entirely sand with a median diameter of 0.40 mm in the last 15 river miles. Owing to channel degradation and tributary inflow, the quantity of sediment transported increases rapidly through the reach from between river miles 34 to 50 downstream from Flaming Gorge Reservoir. The Yampa River joins the Green River 68 mi downstream of the reservoir and contributes $1.9 \times 10^6$ tons/yr. An equilibrium between sediment supply and transport occurs downstream from the mouth of the Yampa River and may exist for some distance upstream. Thus, the reach of active channel degradation is relatively short, no more than 68 river miles. This result is a consequence of the location of the reservoir just upstream from the high sediment-yielding portion of the drainage basin.

Mean annual flow of the Green River at the Ouray gage has not changed appreciably since the construction of Flaming Gorge Dam. Mean annual water discharge of the Green River at the Ouray, Utah, gage was 5,500 ft$^3$/s from 1951 to 1962 compared to 5,450 ft$^3$/s from 1963 to 1981. The estimated mean annual sediment discharge at the Ouray gage, however, decreased 48% from $12.8 \times 10^6$ tons prior to 1962, to $6.61 \times 10^6$ tons during the post-reservoir period. The decrease in the mean annual sediment discharge at the Ouray gage, $6.2 \times 10^6$ tons, is significantly greater than the estimated annual quantity of material deposited in Flaming Gorge Reservoir, $3.6 \times 10^6$ tons. A comparison of mean annual sediment inflow and outflow to the Green River between the Jensen and Ouray gages (reach 2) shows that, on an average, $2.4 \times 10^6$ tons/yr have been deposited in this reach (Table 1). Substantial aggradation of reach 2, therefore, has occurred since the construction of Flaming Gorge Dam. This aggradation probably is concentrated near the downstream end of the reach. The two principal tributaries to reach 2, the White and Duchesne Rivers, join the Green River within a short distance upstream from the Ouray gage. These tributaries deliver to the Green River an estimated mean annual sediment discharge of $4.8 \times 10^6$ tons or 85% of the total quantity of material supplied to reach 2. Consequently, aggradation in reach 2 is most likely greatest in the reach immediately upstream from the Ouray gage.

Upstream from the mouth of the Duchesne River, there is an approximate balance between the supply and transport of sediment within reach 2 over a period of years. Consequently, the channel of the Green River appears to be in equilibrium from the mouth of the Yampa River downstream to the mouth of the Duchesne River under the hydraulic conditions that have existed since flow regulation by Flaming Gorge Reservoir began in October 1982.

Mean annual water discharge of the Green River at the Green River, Utah, gage was 5,580 ft$^3$/s from 1963 to 1981 compared to 5,830 ft$^3$/s from 1944 to 1962. As shown previously for the Green River gages at Jensen and Ouray, Flaming Gorge Reservoir has not had an appreciable effect on the mean annual flow of the
Green River. The estimated mean annual sediment discharge at the Green River, Utah, gage, however, has decreased 48% from 17.0 \times 10^6 to 8.83 \times 10^5 tons. The decrease in the mean annual sediment discharge at the Green River, Utah, gage, 8.1 \times 10^6 tons/yr, is much greater than the estimated annual quantity of material deposited in Flaming Gorge Reservoir, 3.6 \times 10^6 tons. The comparison of mean annual sediment inflow and outflow in Table 1 shows that 2 \times 10^6 tons/yr, on an average, have accumulated in reach 3 since 1962. Tributaries deliver \sim 4.2 \times 10^6 tons/yr to reach 3. The principal tributary, Price River, joins the Green River 18 mi upstream from the Green River, Utah, gage and supplies an estimated mean annual load of 2.18 \times 10^6 tons. The other tributaries deliver sediment throughout reach 3. Therefore, aggradation of the Green River channel probably occurs along the entire length of reach 3.

The discussion has emphasized the downstream impact on channel equilibrium (sediment budget) of the Green River due to flow regulation at Flaming Gorge Reservoir. Immediately downstream from the dam, potential transport of sand-sized material greatly exceeds availability. Tributaries draining areas of relatively large sediment yields, however, significantly increase the sediment load of the Green River within the first 68 river miles downstream from the reservoir. As a result, the supply and transport of sediment probably are in equilibrium downstream from the mouth of the Yampa River. The zone of equilibrium under present (1985) conditions probably extends downstream to the mouth of the Duchesne River, which joins the Green River at river mile 166. Within this reach of the Green River, there has been no net accumulation or depletion of sediment. Downstream from the mouth of the Duchesne River, the mean annual supply of sediment from upstream and tributaries has exceeded the transport. As a result, there is a long-term net accumulation of sediment. The zone of aggradation probably extends downstream on the Green River to its confluence with the Colorado, although there are no gage records of annual water and sediment discharge downstream from Green River, Utah, to confirm this conclusion. The principal tributary to the Green River downstream from Green River, Utah, is the San Rafael River. Irons and others (1965) estimated that the San Rafael River supplied on an average in excess of 1 \times 10^6 tons/yr to the Green River, but relatively small mean annual water discharge of \sim 140 ft^3/s.

Two aspects concerning the downstream sequence of degradation, equilibrium, and aggradation that have existed since flow regulation began in 1962 are especially noteworthy. First, the reach of channel degradation has a much more limited extent than do either the reaches of equilibrium or of aggradation. Second, the absolute magnitude of the disequilibrium between sediment inflow and outflow throughout the aggrading reach is as large as or larger than within the degrading reach. The aggrading reach of the Green River is much longer than the degrading reach, and the volume of accumulated sediment is much larger. In terms of channel equilibrium, the greatest impact of Flaming Gorge Dam is not immediately downstream, but instead several hundred miles downstream. This effect is a direct result of the location of Flaming Gorge Reservoir within the drainage basin downstream from those parts of the basin with large water yield, but upstream of those parts of the basin with large sediment yields.

The sediment-transporting characteristics of a river are altered in complex and manifold aspects by a storage reservoir. Principally, a storage reservoir may change the magnitude and frequency of river flows, as well as the quantity of sediment transported by a given discharge due to alteration of the channel morphology and/or the availability of sediment within the channel. Each of these factors varies downstream from the reservoir. The following discussions describe adjustments of (1) the relation between sediment transport rate and water discharge for various size fractions; (2) the magnitude of effective water discharge; and (3) bankfull channel dimensions in the vicinity of the Jensen and Green River, Utah, gaging stations.

**Sediment Transport Rate**

It has been shown that the mean annual sediment discharge at the Jensen gage has decreased by 54% from 6.92 \times 10^6 to 3.21 \times 10^6 tons since 1962. This change was determined from measured daily values of suspended-sediment concentration and water discharge. During the period of record at the Jensen gage, water years 1947–1979, the size distribution of suspended sediment was determined for 218 of the daily concentration samples, 161 before October 1962 and 57 after October 1962. The daily sediment transport (I_k) for a given size fraction, k, was computed from the measured percentage of sediment in a size fraction, P_k, the total concentration, C, and the daily mean discharge, Q:

\[ I_k = 0.0027 \left( \frac{C}{Q} \right). \]  

(1)

Daily sediment transport rates were determined for 6 size fractions: <0.004 mm, 0.004–0.016 mm, 0.016–0.0625 mm, 0.0625–0.125 mm, 0.125–0.250 mm, and 0.250–0.500 mm, as well as for all sand-sized material and all material for the pre- and post-reservoir periods at the Green River near the Jensen, Utah, gage. The transport rate of suspended sediment in 4 size fractions, 0.004–0.016 mm, 0.0625–0.125 mm, sand-sized, and all material measured during the pre- and post-reservoir periods, are plotted in Figure 3 versus the associated water discharge. Regardless of particle size, no appreciable difference in the suspended-sediment transport rate at a given discharge between the pre- and post-reservoir periods is apparent at the Jensen gage.

For each sediment-sized fraction, a least-squares linear regression was fit to the logarithm-transformed values of water discharge and daily sediment transport rate measured during the pre- and post-reservoir periods. The regression equations are summarized in Table 2. The regression equations for the pre- and post-reservoir periods were compared, using the F-test, to detect whether a statistically significant change in the relation between sediment transport rate and water discharge has occurred. The results of this analysis are summarized in Table 2. The level of confidence at which there is no significant difference between the pre- and post-reservoir periods varies somewhat, but without any apparent trend, among the several size fractions. For sand-sized sediment, there is no significant difference in the relation between transport rate and water discharge during the pre- and post-reservoir periods at the 90th percentile level. For all sediment sizes, there is no significant difference in the pre- and post-reservoir transport relations at the 75th percentile level of confidence. These tests are quite strict. It is thus concluded that the sediment-transport rate at a given discharge has changed very little, if at all, at the Jensen gage as a result of flow regulation and sediment storage by Flaming Gorge Reservoir. Any changes in the sediment-transport relations probably are limited to those particles <0.062 mm in diameter.

This analysis is in good agreement with the pre- and post-reservoir sediment budgets summarized in Table 1. Although the mean annual sediment load decreased by 54% after 1962, the inflow and outflow of sediment to the reach upstream from the Jensen gage have remained in approximate equilibrium. Consequently, the quantity of sediment stored in the reach upstream has remained nearly constant. Assuming the size distribution of sediment has not changed appreciably, the transport rate of sediment at a given discharge should be unaffected by presence and operation of Flaming Gorge Reservoir.

At the Green River, Utah, gage, the size distribution of suspended sediment was determined for 286 of the daily concentration samples, 220
before October 1962 and 66 after October 1962. Using these measurements, daily sediment transport rates were determined for 6 size fractions—<0.004 mm, 0.004–0.016 mm, 0.016–0.0625 mm, 0.0625–0.125 mm, 0.125–0.250 mm, and 0.250–0.500 mm—as well as for all sand-sized material and all material for the pre- and post-reservoir periods at the Green River at the Green River, Utah, gage. The transport rate of suspended sediment in 4 size fractions—0.004–0.016 mm, 0.0625–0.125 mm, sand-sized, and all material measured during the pre- and post-reservoir periods—are plotted in Figure 4 versus the associated water discharge. As shown previously for the Jensen gage, no appreciable difference in the suspended-sedi-

Figure 3. Measured suspended-sediment transport rates for various-sized material as a function of water discharge at the Green River near Jensen, Utah, gage during the pre-reservoir (open triangles) and post-reservoir (solid dots) periods. A. 0.004–0.016 mm fraction. B. 0.0625–0.125 mm fraction. C. Sand-size fraction. D. All sizes.

ment transport rate of any particle size at a given discharge is apparent between the pre- and post-reservoir periods.

For each sediment-sized fraction, a least-squares linear regression was fit to log-transformed values of water discharge and daily sediment transport rate measured at the Green River, Utah, gage during the pre- and post-reservoir periods. The regression equations determined for the pre- and post-reservoir periods were compared, using the F-test statistic. The regression equations and results of this analysis are summarized in Table 3. As was the case for values measured at the Jensen gage, the level of confidence at which no significant difference between the pre- and post-reservoir periods is detected varies considerably among the several size fractions. In general, the confidence level improves with increasing particle size. For the sand-sized sediment, there is no significant difference in the relation between transport rate and water discharge during the pre- and post-reservoir periods at the 90th percentile level. For all sediment sizes, there is no significant difference in the pre- and post-reservoir transport relations at the 95th percentile level of confidence. The confidence levels are slightly less than those determined for the Jensen gage. Nevertheless, the analysis indicates that there has been no significant change in the sediment transport rate at the Green River, Utah, gage as a result of Flaming Gorge Reservoir. As shown earlier, the inflow of sediment to the reach upstream from the Green River, Utah, gage, exceeds the outflow by a considerable quantity, and the reach is accumulating nearly $2.0 \times 10^6$ tons/yr on an average. In spite of the large quantity of material that has accumulated in the reach upstream from this gage, the sediment transport relations have remained remarkably constant.

The theory of alluvial river channels (see Mackin, 1948; Leopold and Maddock, 1953) holds that hydraulic characteristics of a channel will adjust over a period of years to transport the quantity of sediment supplied with the available discharge. With regard to the current condition of the Green River in the vicinity of the Green River, Utah, gage, this principle indicates that
the sediment transport rate at a given discharge should be increasing with time. The comparison of sediment transport rates as a function of water discharge at the Green River, Utah, gage for the pre- and post-reservoir periods, however, found no evidence of an appreciable increase in sediment transport rate for a given flow after the completion of Flaming Gorge Dam in 1962.

Change in Effective Discharge

One of the principal downstream effects of Flaming Gorge Reservoir is to decrease the range of daily mean flows. As noted previously, the mean annual discharges of the Green River during the pre- and post-reservoir periods are virtually identical at both the Jensen and the Green River, Utah, gages. The percentage of time that various daily mean discharges are equaled or exceeded, however, is substantially different for most flows. The durations for daily mean discharge for the pre- and post-reservoir periods are compared in Figure 5 for the Greendale gage, Figure 6 for the Jensen gage, and Figure 7 for the Green River, Utah, gage. The magnitude of flows that occur less than 10% of the time has been significantly decreased since regulation of the Green River by Flaming Gorge Reservoir began. For a given duration within this range, the decrease in discharge is about the same at all three gages. Maximum daily discharge, for example, has decreased by 14,000 ft^3/s, whereas the 2% exceedence discharge has decreased by 7,000 ft^3/s. Discharges equaled or exceeded <5% of the time at the Jensen and Green River, Utah, gages have decreased by ~25%. Thus, although the drainage area is 2.7 times greater at the Green River, Utah, gage than at Flaming Gorge Reservoir, the effect of the reservoir is still substantial 290 river miles downstream.

Discharges equaled or exceeded <10% of the time usually transport a majority of the annual sediment load (Wolman and Miller, 1960). Furthermore, the increment of discharge that transports the largest quantity of sediment over a period of years, called the effective discharge, typically is equaled or exceeded <5% of the time, but it determines the bankfull-channel dimensions and pattern. Andrews (1980) computed the effective discharge for 15 gages in the Yampa River basin and showed that the effective discharge was nearly identical to the bankfull discharge at all sites. The bankfull-channel dimensions thus appeared to be adjusted to the effective discharge.

In order to determine the effect of flow regulation on the effective discharge in the Green River, the mean annual quantity of sediment transported during the pre- and post-reservoir periods by various increments of discharge was computed for three reaches. These reaches are representative of conditions in alluvial sections of channel in each of the downstream zones—degradation, equilibrium, and aggradation—defined by the sediment-budget analysis. Selected reaches are (1) through Browns Park (degrading); (2) immediately downstream from the Jensen gage (equilibrium); and (3) in the vicinity of the Green River, Utah, gage (aggrading). The duration of discharges and the relation of sediment transport rate to discharge need to be known to compute the effective discharge. This information is provided at the latter two reaches by the records of the nearby gages. There are no comparable gage records of discharge and sediment transport in the Browns Park reach. The duration of discharges recorded at the Greendale gage therefore were assumed to be representative, because the contribution by intervening tributaries is rarely significant. The quantity of bed-material transport by various discharges was computed, using the Engelund-Hansen relation (Engelund and Hansen, 1967), with measured values for slope, width, and bed-material size distribution.

The object of the analysis is to assess the potential for channel changes, and so it is preferable to consider only those sediment sizes that are present in the channel bed and banks in quantities of more than a few percent. The transport rate of those particle sizes that are present in the channel perimeter tends to be more closely correlated with flow, because the quantity of material available does not vary greatly over a period of years. Analysis of the relations between sediment transport rate and discharge for various sediment-size fractions found that the coefficient of determination (r^2) increased significantly for particles larger than 0.016 mm in diameter (see Tables 2 and 3). Consequently, particles with a fall diameter of 0.016 mm were assumed to be the smallest particles present to an appreciable degree in the channel bed and banks in the vicinity of the Jensen and Green River, Utah, gages.

Sediment-load duration relations for each size fraction >0.016 mm were computed from the transport rate versus discharge (Figs. 3 and 4) and the flow duration relations. The ranges of discharge were divided into ~30 equal increments. The sediment-discharge duration relations then were integrated between the limits of each increment and the result multiplied by 365 days. The mean annual quantity of sediment
Figure 4. Measured suspended-sediment transport rates for various-sized material as a function of water discharge at the Green River at Green River, Utah, gage during the pre-reservoir (open triangles) and post-reservoir (solid dots) periods. A. 0.004-0.016 mm fraction. B. 0.0625-0.125 mm fraction. C. Sand-size fraction. D. All sizes.

transported by an increment of discharge was determined by summing over the several size fractions.

The quantities of sediment transported by different increments of discharge during the pre- and post-reservoir periods are compared in Figure 8 for the Browns Park reach, in Figure 9 for alluvial sections in the vicinity of the Jensen gage, and in Figure 10 for alluvial sections in the vicinity of the Green River, Utah, gage. The effective discharge (modal value) for the Green River in the Browns Park reach was computed to be 7,450 ft³/s during the pre-reservoir period, water years 1951–1962. This discharge was equaled or exceeded 5.5% of the time, or 20.0 days/yr on an average. During the post-reservoir period, water years 1966–1981, the effective discharge decreased by 63% to 2,750 ft³/s. This discharge has a duration of 27% of the time, or 99 days/yr on an average. The effective discharge (modal value) for the Green River near Jensen gage was 20,500 ft³/s during the pre-reservoir period, water years 1947–1962. This discharge was equaled or exceeded 3% of the time, or 11 days/yr on an average. During the post-reservoir period, water years 1966–1981, the effective discharge decreased by 44% to 11,500 ft³/s. This discharge has a duration of 7.5% of the time or 27.4 days/yr. The effective discharge of the Green River in the vicinity of the Green River, Utah, gage was 26,500 ft³/s during the pre-reservoir period, water years 1944–1962. The effective discharge was equaled or exceeded 2.8% of the time or 10.2 days/yr. During the post-reservoir period, water years 1966–1981, the effective discharge decreased by 23% to 20,500 ft³/s. The duration of effective discharge has decreased slightly to 2.4% of the time or 8.8 days/yr.

Magnitude of the effective discharge has decreased significantly in all three reaches as a consequence of flow regulation. The percentage change is greatest at the farthest upstream reach and decreases downstream as the influence of the reservoir diminishes. Nevertheless, the effect is still significant 290 river miles downstream at the Green River, Utah, gage, where the contributing area is 2.7 times that of the reservoir. No directly comparable studies showing the downstream influence of a reservoir are known. Gregory and Park (1974), however, described an example in which the decrease in channel area extended downstream to a point where the contributing area was four times that at the reservoir.

ADJUSTMENT OF BANKFULL-CHANNEL DIMENSIONS

Computed effective discharges were shown to be in excellent agreement with measured bankfull discharges at unaltered watersheds with self-formed channels in the Yampa River basin (Andrews, 1980). The bankfull characteristics of these self-formed channels therefore appeared to be determined by the effective discharge over a period of years. As shown above, the effective discharge computed for selected reaches of the Green River downstream from Flaming Gorge Reservoir has decreased significantly. Consequently, it is to be expected that the bankfull
channel of the Green River will adjust over a period of years to the locally prevailing effective discharge.

Detailed information describing the bankfull-channel dimensions of the Green River is limited, especially prior to construction of Flaming Gorge Dam. All of the gaging stations used in this investigation have rated cross sections where the discharge is measured several times a year. These cross sections, however, were selected because of their greater stability. At all locations, one or both of the banks are bedrock, and, except for the Ouray gage, the bed material is coarse gravel. The gaged cross sections thus cannot be considered typical of the channel in alluvial, self-formed reaches.

Aerial and terrestrial photographs are the primary sources of information from which the hydraulic adjustment of Green River can be reconstructed. Large-scale aerial photographs of some reaches of the Green River downstream from Flaming Gorge Dam were taken prior to 1962 and after 1980. Thus, it is possible to investigate some of the channel changes resulting from flow regulation over ~20 yr. Although aerial photographs do not provide a complete description of the bankfull-channel characteristics, several attributes can be measured and deduced, especially when combined with field inspection. (1) Bankfull-channel width and the...
extreme of channel migration were determined directly from the photographs. (2) Changes in the channel pattern were described. (3) The flood plain constructed during the pre- and post-reservoir periods was identified on photographs. Subsequently, the change in flood-plain elevation was surveyed during a field inspection.

Leopold and Maddock (1953) found that the variation of the hydraulic variables—mean velocity ($\bar{u}$), width ($w$), and mean depth ($d$), with increasing bankfull discharge ($Q_B$) in the downstream direction—could be described broadly by a set of simple power equations:

$$\bar{u} = k Q_B^m, \quad (2)$$

$$w = a Q_B^b, \quad (3)$$

$$d = c Q_B^f. \quad (4)$$

These relations are called the "downstream hydraulic geometry" of a river. Langbein (1964), Engelund and Hansen (1967), and Parker (1978, 1979) showed that the width-versus-discharge equation is the most consistent relation. The coefficient of determination ($r^2$) for the width equation typically is 0.95 or larger, and the exponent value, $b$, rarely differs much from 0.5. Underlying the hydraulic geometry analysis there is the assumption or determination that the hydraulic variables have attained a quasi-equilibrium adjustment to the magnitude and frequency of flows that have occurred over a period of years.

A significant deviation in the value of a hydraulic variable from the expected value is evidence that the particular variable is not in adjustment with the prevailing range and duration of sediment and water discharges. Given the prior bankfull width ($w_1$), the prior bankfull discharge ($Q_1$), and estimated future bankfull discharge ($Q_2$), the future bankfull width ($w_2$) can be estimated by equation 3, assuming that $a_1 = a_2$. This is not an unreasonable assumption as long as such factors as channel slope, composition and density of bank vegetation, bed-material-size distribution, and suspended-sediment concentration versus discharge relations remain unchanged. If the measured bankfull width after a large change in the effective discharge differs significantly from the estimated value, then one may conclude that the adjustment of channel width is incomplete.

Although the Green River has been affected by the spread of tamarisk during the past century, riparian vegetation has not been a major cause of any channel changes since 1951. Graf (1978) examined channel changes at 18 cross sections first photographed by river explorers prior to 1915 and found that thick stands of tamarisk had grown along the banks in many reaches. Concomitantly, channel width has decreased by an average of 27%. These data indicate, however, that all of this change occurred before 1951.
Adjustment of the Green River Channel in Browns Park

Bankfull-channel width of the Green River through Browns Park was measured at 24 cross sections spaced evenly throughout a reach of 22 river miles, using large-scale aerial photographs taken in 1951 and 1980. The channel was narrower at all locations except one. On an average, channel width decreased by 13% from 560 to 485 ft during the period. As described above, the effective discharge of the Green River in Browns Park decreased by 63% to 2,750 ft³/s from 7,450 ft³/s as a result of flow regulation by Flaming Gorge Reservoir.

At some time since the 1951 aerial photographs were taken, the Green River in Browns Park began building a new flood plain ~40 ft lower than the previous one. The lower floodplain elevation is due both to a decrease in bankfull depth associated with the decreased effective discharge and to degradation of the riverbed. Given the measured river slope, bankfull width, and bed-material-size distribution, stage-discharge relations were computed for the pre- and post-reservoir periods, using the Engelund-Hansen roughness equation (Engelund and Hansen, 1967). This analysis indicated that the bankfull depth has decreased from 4.7 ft to 3.1 ft. The mean channel degradation therefore has been ~2.4 ft. An estimated 9.5 × 10⁶ tons of sand-sized bed material was eroded from the 22 mi of alluvial channel within Browns Park between 1951 and 1980, when the aerial photographs were taken. All of the degradation probably occurred since 1962, when the upstream supply of sediment was substantially decreased by Flaming Gorge Reservoir.

Adjustment of channel width to the regulated flow and decreased sediment supply to the Green River through Browns Park is far from complete. The estimated quasi-equilibrium channel width associated with the decreased effective discharge as computed by equation 3 is 340 ft. This estimate is significantly less than the measured value of 485 ft. On the basis of the comparison of aerial photographs, as well as cross sections surveyed in 1983, the present channel primarily is the result of riverbed degradation. Deposition of new bank material does not appear to have been a significant factor contributing to the decrease in channel width. Rather, the present, smaller channel was formed by entrenched within the pre-1962 channel. Given the deficit in sediment supply compared to transport, net deposition of material along the banks would be inconsistent.

Adjustment of the Green River Channel Downstream from Jensen, Utah

A few miles downstream from the Jensen gage, the Green River enters an alluvial valley within which it flows for nearly 60 river miles. Bankfull-channel width in this reach was measured at 15 cross sections, using large-scale aerial photographs taken in 1964 and 1978. Although the earlier series of photographs were taken 2 yr after flow regulation had begun, they probably show a good representation of the pre-reservoir river channel. The channel was narrower at all locations examined except at one in 1978 compared to 1964. On an average, bankfull-channel width decreased by 13% from 700 to 610 ft. The computed effective discharge of the Green River at the Jensen, Utah, gage decreased by 44% from 20,500 to 11,500 ft³/s during the post-reservoir period, water years 1966–1981.

Adjustment of Green River channel width downstream from the Jensen, Utah, gage was incomplete in 1978. The estimated quasi-equilibrium channel width associated with the decreased effective discharge as computed by equation 3 is 524 ft. This estimate is substantially less than the measured value of 610 ft. If a constant rate of channel narrowing is assumed, ~30 yr will be required for the channel width to attain the expected value associated with the post-reservoir effective discharge. At many cross sections, the bankfull channel has become narrower as a result of accretion of material along one or both banks. Although the accretion of bank material was common, the most significant process narrowing the channel occurred where a distributary channel has filled with bed material and the mid-channel bar has become attached to the bank. Concomitantly, a thick vegetation cover has become established on these areas. Series of aerial photographs show the Green River at approximately the same discharge, 6,000 to 7,000 ft³/s. The number and areal extent of mid-channel bars was appreciably greater in 1978 than in 1964, in spite of the fact that some bars have become attached to banks.

Adjustment of the Green River Channel Downstream from Green River, Utah

An alluvial reach located downstream from the Green River, Utah, gage was selected to investigate changes in bankfull-channel width in reach 3, the aggrading part of the river. Large-scale aerial photographs of this reach were taken in 1952 and 1981. Bankfull-channel width was measured at 14 cross sections located in a reach of nearly 15 river miles. The channel was narrower at all cross sections in 1981 compared to 1952. On an average, the bankfull-channel width decreased by 10% from 515 to 465 ft.

Adjustment of channel width in the Green River downstream from the Green River, Utah, gage to the flow regulation by Flaming Gorge Reservoir appears to be nearly complete. The expected channel width under quasi-equilibrium conditions, given the decreased effective discharge, is 450 ft. This value is only slightly less than the measured value of 465 ft.

SUMMARY AND CONCLUSIONS

The contribution of runoff and sediment per unit area to the channel network varies greatly within the Green River basin. Furthermore, the principal source areas of runoff and sediment are different. A majority of the basin-wide runoff is supplied by the relatively high-elevation areas (>10,000 ft) near the rim of the basin. These areas, however, have very small sediment yields. The most important sediment-contributing areas are far downstream, within the middle- and lower-elevation parts of the basin.

The downstream effects of Flaming Gorge Reservoir are profoundly affected by its location in the drainage basin relative to the principal runoff and sediment-contributing areas. Compared to the farthest downstream gage, the Green River at Green River, Utah, the area upstream from Flaming Gorge Reservoir, prior to its construction, contributed 37% of the annual runoff but only 21% of the sediment load from 37% of the drainage area. Consequently, the reservoir controls a proportional share of the basin runoff but traps only a moderate proportion of the basin-sediment yield. The downstream effects of Flaming Gorge Reservoir on the Green River channel would be markedly different if either a larger or smaller proportion of the basin-sediment yield were trapped within the reservoir.

Pre- and post-reservoir sediment budgets were computed for three reaches of the Green River, using measured daily water and sediment discharges. Prior to the construction of a dam in Flaming Gorge, a quasi-equilibrium condition appears to have existed downstream in the Green River channel; that is, over a period of years, the transport of sediment out of a given river reach equaled the supply of sediment into the reach. Since reservoir regulation began in 1962, the mean annual sediment discharge at
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