Summary of Sediment Data from the Yampa River and Upper Green River Basins, Colorado and Utah, 1993–2002

By John G. Elliott and Steven P. Anders

Prepared in cooperation with the
Colorado Division of Wildlife and the
U.S. Fish and Wildlife Service

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Conversion Factors, Vertical Datum, and Abbreviations

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot (ft)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (mi^2)
square mile (mi^2)	2.590	square kilometer (km^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
ton, short	0.9072	megagram (Mg)
foot per day (ft/d)	0.3048	meter per day (m/d)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83).

Summary of Sediment Data from the Yampa River and Upper Green River Basins, Colorado and Utah, 1993–2002

By John G. Elliott and Steven P. Anders

Abstract

The water resources of the Upper Colorado River Basin have been extensively developed for water supply, irrigation, and power generation through water storage in upstream reservoirs during spring runoff and subsequent releases during the remainder of the year. The net effect of water-resource development has been to substantially modify the predevelopment annual hydrograph as well as the timing and amount of sediment delivery from the upper Green River and the Yampa River Basins tributaries to the main-stem reaches where endangered native fish populations have been observed. The U.S. Geological Survey, in cooperation with the Colorado Division of Wildlife and the U.S. Fish and Wildlife Service, began a study to identify sediment source reaches in the Green River main stem and the lower Yampa and Little Snake Rivers and to identify sediment-transport relations that would be useful in assessing the potential effects of hydrograph modification by reservoir operation on sedimentation at identified razorback spawning bars in the Green River. The need for additional data collection is evaluated at each sampling site.

Sediment loads were calculated at five key areas within the watershed by using instantaneous measurements of streamflow, suspended-sediment concentration, and bedload. Sediment loads were computed at each site for two modes of transport (suspended load and bedload), as well as for the total-sediment load (suspended load plus bedload) where both modes were sampled. Sediment loads also were calculated for sediment particle-size range (silt-and-clay, and sand-and-gravel sizes) if laboratory size analysis had been performed on the sample, and by hydrograph season. Sediment-transport curves were developed for each type of sediment load by a least-squares regression of logarithmic-transformed data.

Transport equations for suspended load and total load had coefficients of determination of at least 0.72 at all of the sampling sites except Little Snake River near Lily, Colorado. Bedload transport equations at the five sites had coefficients of determination that ranged from 0.40 (Yampa River at Deerlodge Park, Colorado) to 0.80 (Yampa River above Little Snake River near Maybell, Colorado). Transport equations for silt and clay-size material had coefficients of determination that ranged from 0.46 to 0.82.

Where particle-size data were available (Yampa River at Deerlodge Park, Colorado, and Green River near Jensen, Utah), transport equations for the smaller particle sizes (fine sand) tended to have higher coefficients of determination than the equations for coarser sizes (medium and coarse sand, and very coarse sand and gravel). Because the data had to be subdivided into at least two subsets (rising-limb, falling-limb and, occasionally, base-flow periods), the seasonal transport equations generally were based on relatively few samples. All transport equations probably could be improved by additional data collected at strategically timed periods.

Introduction

The water resources of the Upper Colorado River Basin have been extensively developed for water supply, irrigation, and power generation. The net effect of the development has been to substantially modify the predevelopment annual hydrograph by water storage in upstream reservoirs during spring runoff and subsequent releases during the remainder of the year. Another effect has been a change in the amount of sediment delivery from the basin to the main-stem reaches of the watershed. Hydrograph modification and sediment trapping by Flaming Gorge Dam on the Green River and land-use changes and water development in the Yampa and Little Snake River Basins have affected, and are likely to continue to affect, the habitat characteristics of the Yampa and Green Rivers (fig. 1). Changes in the hydrograph and in sediment delivery may have an effect on the suitability of spawning and other life-stage habitat for endangered fish.

The Yampa River is the only large river in the Upper Colorado River Basin in which the annual hydrograph has not been substantially altered by water-development projects and, therefore, is probably the best river to use as an example of the specific habitat requirements of endangered fish species. Closure of Flaming Gorge Dam on the Green River in 1962 has not appreciably affected the mean annual discharge of the Green River but has decreased the magnitude of peak flows and increased the magnitude of streamflow in the historical low-flow and base-flow seasons (this report). Regulation of

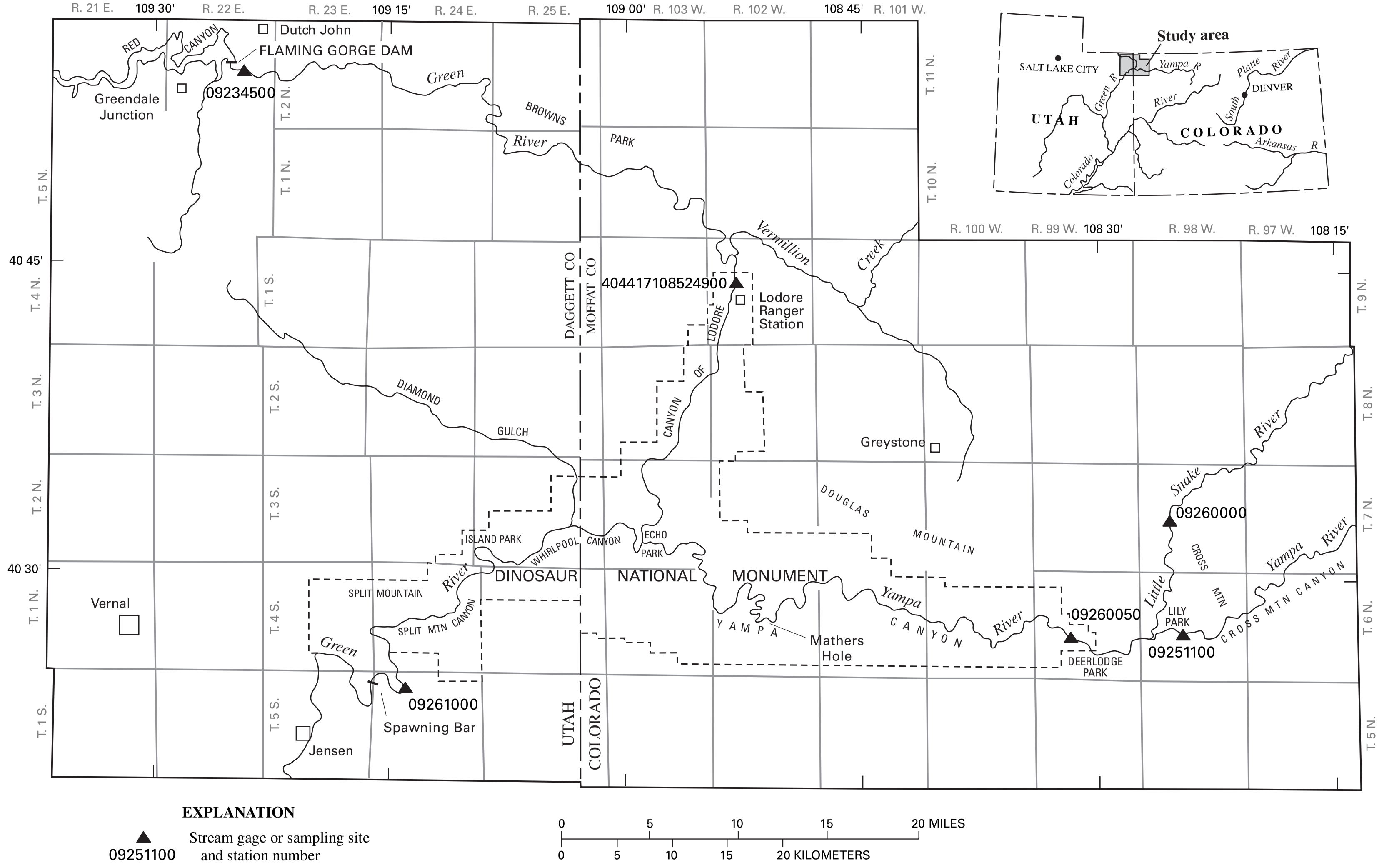

Figure 1. The Yampa River and upper Green River Basins showing streamflow-gaging stations and sediment-sampling locations.

the river also has altered the amount and timing of sediment delivery to an important spawning area (bar) of the endangered razorback sucker located downstream from the Yampa River confluence. Additional sediment-transport data are needed to augment existing data to evaluate the timing and magnitude of sediment movement in the vicinity of the spawning bar.

To address this need, the U.S. Geological Survey (USGS), in cooperation with the Colorado Division of Wildlife and the U.S. Fish and Wildlife Service, began a study in 1998 to collect and evaluate sediment data in the Yampa River and upper Green River Basins. The objectives of the study were to (1) identify sediment source reaches of the Green River main stem upstream from Jensen, Utah, and its major tributaries, the Yampa and Little Snake Rivers; (2) develop sediment-transport curves that account for the magnitude and timing of sediment delivery at five sites on the major tributaries and main stem; and (3) evaluate the need for additional or long-term data collection to improve the utility of sediment-transport curves at the five major tributary and main-stem sites.

Purpose and Scope

The purpose of this report is to present sediment data collected and compiled from five sites on the Yampa River and in the upper Green River Basin and to describe sediment-transport relations derived with these data that will be useful in assessing the potential effects of hydrograph modification by reservoir operation on sedimentation at identified razorback sucker spawning bars in the Green River. Such an assessment will be based on information included in this report that identifies the sources and size characteristics of the transported sediment, as well as an understanding of the timing and magnitude of suspended- and bedload-sediment transport in the major tributaries and main stem of the river system. This information supports site-specific studies of the hydraulic and depositional processes at specific spawning bars, such as the razorback spawning bar in the Green River downstream from Jensen, Utah. An assessment of site-specific conditions is beyond the scope of this report.

The five sediment-sampling sites were located at existing USGS streamflow-gaging stations: the Yampa River above Little Snake River near Maybell, Colorado, 09251100; the Little Snake River near Lily, Colorado, 09260000; the Yampa River at Deerlodge Park, Colorado, 09260050; the Green River above Gates of Lodore, Colorado, 404417108524900; and the Green River near Jensen, Utah, 09261000.

Sediment source reaches were identified from recent aerial photographs of the Green River main stem and the lower reaches of the Yampa and Little Snake Rivers. Sediment-transport, or rating, curves were derived from measurement of suspended sediment and bedload at streamflow-gaging sites. The sediment samples were collected several times per year during 1998–2002 for the study described in this report and combined with discharge readings at the gages. These data were combined with historical data from the sites that resulted in different periods of record, ranging from 1982–2001 to 1998–2002 for the derivation of sediment-transport curves. Linear regression of the sediment-load and discharge data was performed to derive the sediment-transport curves. Measurements were scheduled to cover a range of discharge from base flow to the annual instantaneous peak and to include both early season, or rising limb, and late season, or falling limb, hydrograph periods. Needs for additional or long-term data at each site were based on regression coefficient of determination (R^2) and mean square error (MSE) statistics, the sample size, and the distribution of measurements throughout hydrograph seasons and over the range of historical discharges.

Previous Investigations

Several previous studies have investigated the magnitude and effects of sediment transport and deposition in the upper Green River Basin. Andrews (1978) estimated existing and potential sediment yields in the Yampa and Little Snake River Basins in Colorado and Wyoming and found that the relative contributions of water and sediment from smaller subbasins were quite variable. Elliott and others (1984) estimated the annual sediment load supplied to the Yampa Canyon downstream from Deerlodge Park in Dinosaur National Monument based on regression analyses of measured sediment discharges and on sediment discharges estimated with the Modified-Einstein equation. Their estimates showed the average annual supply to the Yampa Canyon to be in the range of 2,040,000 to 2,420,000 tons per year.

Martin and others (Utah State University, written commun., 1998) studied sediment transport, channel geometry, and streambank topography of the Green River in the Canyon of Lodore during 1995–97, a period that included an 8,560-ft^3/s release from Flaming Gorge Reservoir, the largest release in the previous 13 years. They observed channel scour of as much as 6.5 ft and the redistribution of sand into eddies and along the channel margins, as well as channel widening due to erosion of some previously vegetated, post-dam-deposited, flood-plain sediment.

O’Brien (1984a) made suspended- and bedload-sediment measurements at Mathers Hole on the Yampa River in Dinosaur National Monument (figs. 1, 5*B*) and derived sediment-transport curves. He determined that the mean annual sediment load at Mathers Hole was highly correlated with the annual sediment load calculated for the Yampa River at Deerlodge Park, 30 mi upstream (Elliott and others, 1984). O’Brien (1984b) also monitored the evolution of riffle-pool morphology and composition at two Colorado pike-minnow spawning bars in Yampa Canyon in 1982 and 1983. His identification of the hydraulic conditions responsible for transporting the supplied sand load over the undisturbed cobble substrate, as well as the conditions under which the cobble material itself was entrained, led to a recommended hydrograph for habitat maintenance in Yampa Canyon.

Harvey and others (1993) developed a one-dimensional, physical- and biological-process response model for pikeminnow spawning habitat at another known spawning bar in Yampa Canyon. Their study identified the hydraulic conditions and discharge ranges associated with sediment deposition and bar formation, as well as those associated with scour and bar dissection at that spawning site. Later efforts by Mussetter and others (2001) resulted in a two-dimensional, finite element-based model that predicted the optimum hydrodynamic conditions for spawning at the bar studied by Harvey and others (1993). Pitlick and others (2001) noted a decrease over the last 30 years in the area of side channel and backwater zones, critical habitat for many endangered fish in the Upper Colorado River Basin. Their study found an association between this geomorphic change on the main stem and the decrease in annual peak discharges and mean annual sediment loads in the Upper Colorado River Basin.

The channel responses typical of rivers downstream from reservoirs were addressed by Williams and Wolman (1984). Some of the effects noted by Williams and Wolman were observed on the Green River downstream from Flaming Gorge Reservoir by Fischer and others (1983). The Fischer study quantified changes in riparian vegetation as well as streambank stability and steepness at several locations in the Canyon of Lodore. Lyons and others (1992) used repeated aerial photographs to estimated changes in channel width on the Green River downstream from the mouth of the Yampa River since construction of Flaming Gorge Dam. Andrews (1986) evaluated changes in the Green River channel width in response to the reduced peak discharges that resulted from reservoir operation. He determined that the bankfull channel width decreased by about 10 percent between 1962 and 1986. Merritt and Cooper (2000) observed a complex sequence of changes in channel geometry, island formation, sediment-transport mode, and vegetation community in the Browns Park area following the construction of Flaming Gorge Reservoir in 1962.

Elliott and others (1984) derived a sediment budget for the Yampa River at Deerlodge Park under streamflow conditions that existed until the early 1980s and under various reduced-flow scenarios. Under one scenario, Yampa River streamflows were altered in the same way that Green River streamflows were altered by Flaming Gorge Dam (for example, with the same annual streamflow volume but with a decreased duration of high-range discharges and an increased duration of low-range discharges). Under this scenario, the estimated annual total-sediment load of the Yampa River decreased by 150,000 tons per year, or 7 percent, from the load transported by the prevailing streamflow regime.

Acknowledgments

The authors wish to acknowledge J.E. (Ed) Vaill who initiated and directed this project in its early years. Rich Carver's experience was indispensable in measurements made by boat, from bridges, and by wading. Joe Dungan, Cam Adibi, Cory Williams, Patricia Solberg, and Michael Whiteman of the USGS Colorado District and J.R. (Rod) Tibbetts and Terry Kenney of the Utah District assisted with data collection. Sediment samples were processed by the USGS Sediment Laboratory in Iowa City, Iowa. The authors also wish to thank Steven Petersburg of Dinosaur National Monument and other staff of the National Park Service for their cooperation and permission to collect sediment samples within Dinosaur National Monument. Technical reviews of the manuscript were performed by John W. Roberts and David L. Butler of the USGS.

Study Area

Geographic Setting

The Green River is the largest tributary and most important source of runoff in the Upper Colorado River Basin. At the Jensen, Utah, streamflow gage, the Green River transports runoff and sediment from over 25,400 mi^2 in Wyoming, Colorado, and Utah. The upper tributaries of the watershed generally drain snowmelt from the igneous and metamorphic lithologies of several mountain ranges, whereas the lower tributaries generally drain more arid regions of sedimentary lithologies. Sediment sources tend to correlate with lithology and precipitation patterns, and a large amount of the annual sediment load is supplied to the Green River from the Little Snake River, by way of the Yampa River (Andrews, 1978, 1986).

The major tributaries in the study area—the Little Snake, the Yampa, and the upper Green Rivers—flow through a succession of wide, parklike reaches and narrow, steep canyons (figs. 1 and 2). The geomorphology of the park and canyon reaches may have an effect on the transport and temporary storage of sediment carried by the rivers. Steep, confined canyon reaches may function as sediment-conveying zones during floods, whereas broad, parklike reaches with low gradients may be associated with depositional environments during the same floods.

Locations on the Little Snake, the Yampa, and the upper Green Rivers are referred to in this report in terms of river miles upstream from some reference point. River miles on the Little Snake River are measured upstream from its confluence with the Yampa River in Lily Park (fig. 1). River miles on the Yampa are measured upstream from its confluence with the Green River at Echo Park. River miles on the Green River between Flaming Gorge Dam and the Jensen

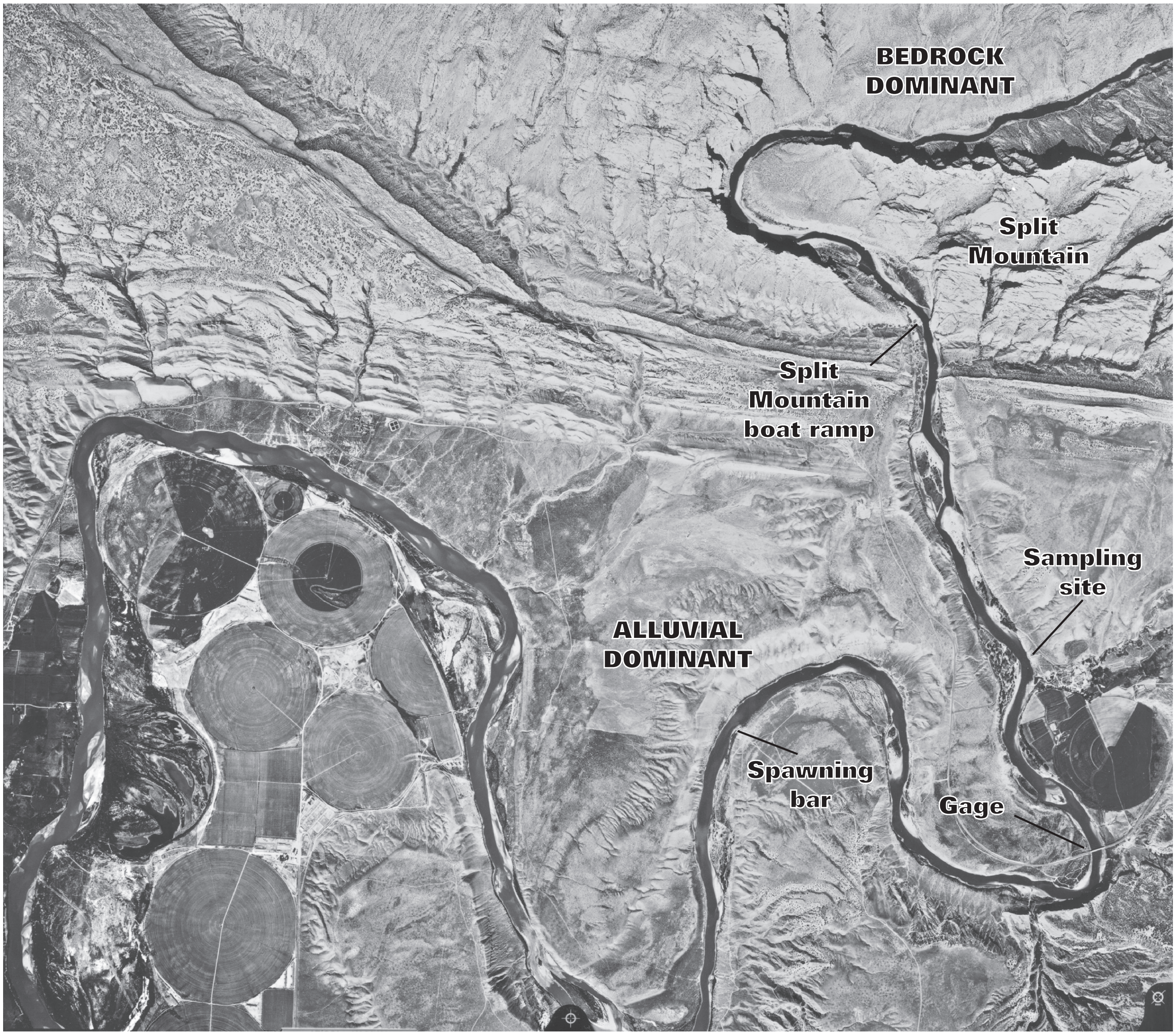

Figure 2. Aerial photograph (1988) showing a bedrock-dominated reach and an alluvial reach of the Green River between Split Mountain and the Jensen, Utah, streamflow gage.

streamflow gage are the same as those published in the widely used Dinosaur River Guide (Evans and Belknap, 1973). Evans and Belknap measured river miles upstream from the town of Green River, Utah, which is about 117 river miles upstream from the confluence of the Green River with the Colorado River.

Streamflow

Long-term streamflow records have been collected at the Little Snake River near Lily gage (1921–present), the Green River near Greendale gage (USGS station number 09234500; 1951–present), and the Green River near Jensen gage (1947–present). The Yampa River at Deerlodge Park gage was installed in 1982 and has operated almost continuously since then. A new streamflow-gaging station was installed on the Yampa River upstream from Little Snake River in 1996. All gages are active at this time (2004).

Flow in the Green River upstream from the two Green River streamflow-gaging stations has been regulated by Flaming Gorge Reservoir since November 1962. Regulation by the reservoir has altered the magnitude and timing of the instantaneous peak discharge in the Green River downstream from the reservoir, but not the annual volume of runoff (Andrews, 1986).

Streamflow characteristics were derived for each sampling site based on the recorded discharge data. The frequency of annual, instantaneous peak discharges and the duration of daily mean discharges were calculated by standard USGS procedures (U.S. Interagency Advisory Committee on Water Data, 1982) using records from gaging stations in the study area. Peak-flow frequency for the Yampa River above Little Snake River gage was calculated from only 6 years of record (1997–2002). Peak-flow frequency was not calculated for the Green River near Greendale gage because the magnitude of streamflow at that site is entirely controlled by the operation of Flaming Gorge Reservoir. Flow-duration statistics and peak-flow frequency for the Green River near Jensen are presented only for the years after completion of the Flaming Gorge Dam (1963–2002). Streamflow characteristics for each sampling site are summarized later in this report in tables 1, 4, 7, 10, and 13, which are in the respective sections for individual sampling-site summaries.

Streamflow and sediment transport in the Little Snake and Yampa Rivers have been affected only slightly by water storage and transbasin diversions within the respective watersheds, and no major dams have been constructed on the main stems of these rivers. However, Flaming Gorge Reservoir, completed in 1962, has had a significant effect on streamflow, sediment transport, and the geomorphology of the Green River downstream from the dam (Andrews, 1986). The Green River near Jensen gage has operated since 1947, and discharge characteristics from that gage reflect alterations in streamflow as a result of reservoir operation. Andrews (1986) used discharge data recorded at this site from 1962 through 1981 in his analyses of downstream reservoir effects on the Green River. Annual peak discharges and flow-duration curves for the Green River near Jensen gage, updated through water year 2002, reveal the changes in streamflow caused by Flaming Gorge Reservoir (figs. 3 and 4).

Fluvial Sediment Transport and Deposition

Sediment transported by the Green River downstream from Flaming Gorge Reservoir has been affected by impoundment of upstream-supplied sediment and by changes in the streamflow regime. Andrews (1986) determined that, at the time of his study, the sediment supply to the river was exceeded by the sediment transport for a relatively short distance downstream from the reservoir. This reach included

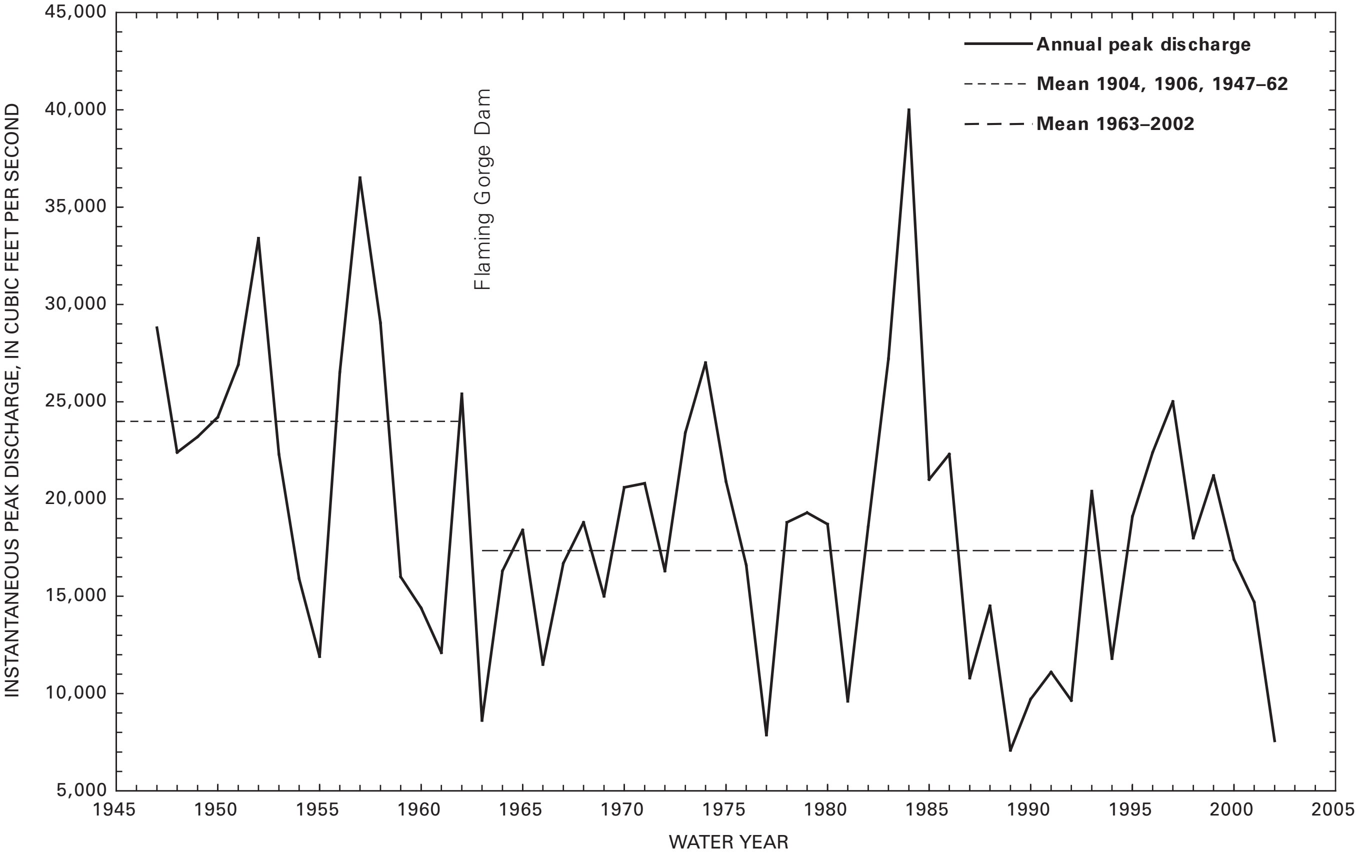

Figure 3. Annual peak-flow series for station 09261000, Green River near Jensen, Utah, 1947–2002.

most of the river from Flaming Gorge Dam at river mile 290 to the confluence of the Yampa River at river mile 225. Andrews (1986) noted the channel of the Green River appeared to be in equilibrium from the mouth of the Yampa River (river mile 225) to the mouth of the Duchesne River (river mile 46). Downstream from the Duchesne River, the combined sediment supply from upstream, from within the channel, and from tributaries joining the river downstream from the reservoir exceeded the transport by about 5,400,000 tons per year on average. In response to reduced peak discharges and a net surplus of sediment, the bankfull channel width had decreased by about 10 percent by 1986; but according to Andrews, these adjustments were not complete and would continue for perhaps another century.

Andrews (1986) noted that the sediment transported by the Green River downstream from Flaming Gorge Reservoir was contributed primarily by the downstream part of tributary drainage basins. These tributary basins range from small, ephemeral watersheds to the large, perennial Yampa River Basin (fig. 1). Elliott and others (1984) estimated that the mean annual sediment load of the Yampa River at Deerlodge Park ranged from 2,040,000 to 2,420,000 tons per year. Of this annual load, 78 to 95 percent was sand, silt, and clay transported in suspension. Andrews (1978) estimated that approximately 60 percent of the Yampa River sediment load at Deerlodge Park was contributed by tributaries draining the lower Little Snake River Basin (fig. 1).

Sediment Storage Areas

Onsite observations and an examination of aerial photographs of the lower Little Snake, lower Yampa, and lower Green Rivers taken during the autumn of 1988 reveal that a large amount of sediment is stored in the river channel and flood plain in the form of alluvial banks, bars, and islands. Best observed as subaerial alluvial deposits during low-stage periods, these near-channel areas may be important secondary sources of sediment that periodically is entrained by the Green River and its larger tributaries. Base-flow season aerial photographs of the channels of the Little Snake River downstream from the Lily streamflow gage, the Yampa River downstream from Cross Mountain, and the Green River from the Lodore Ranger Station to Jensen were assessed to determine the relative abundance of alluvial materials in the banks and bars. It was assumed that this material has a potential for remobilization. Neither the condition of the streambed, the thickness of alluvial deposits, nor the particle-size characteristics of the alluvial materials could be determined from the aerial photographs.

Subaerial alluvial banks and bars visible in the aerial photographs were mapped by 1-mile subreaches on 7.5-minute topographic maps. The total length of alluvial channel boundaries was then expressed as a percentage of twice the 1-mile subreach length. For example, if both banks of a 1-mile subreach were alluvial, then the alluvial-boundary percentage would be [(1+1) / (2×1)] × 100 = 100. If one bank of the

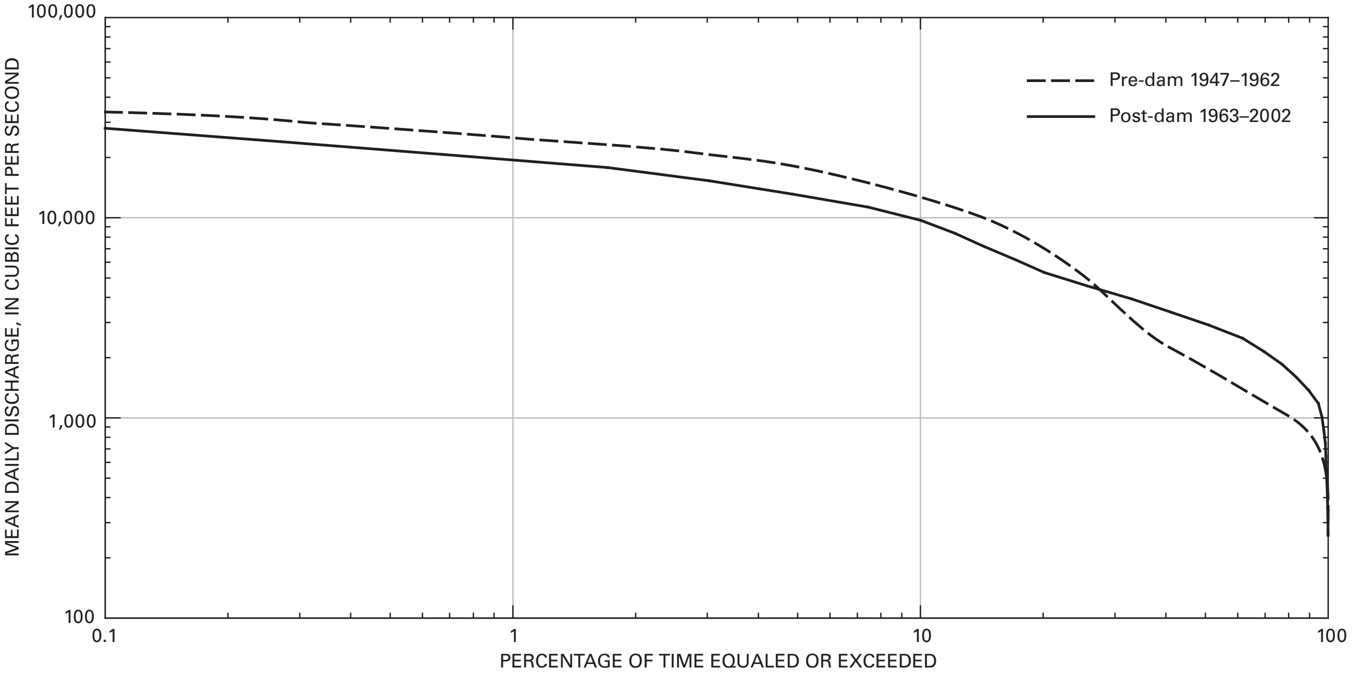

Figure 4. Flow-duration curves for station 09261000, Green River near Jensen, Utah, for the periods before and after closure of Flaming Gorge Dam.

1-mile subreach was alluvial and the other bank was bedrock or coarse talus (that is, nonalluvial), the percentage would be [(1+0) / (2×1)] × 100 = 50. Midchannel alluvial islands were treated as an alluvial bank if one or both banks were nonalluvial. Lengths of these islands were not factored in when both riverbanks adjacent to the island were alluvial; this constrained the alluvial boundary percentage to a maximum of 100 percent.

The relative abundance of subaerial alluvial deposits in the 1988 photographs varied from river to river in the watershed and from subreach to subreach along a river. Although the flood-plain width was relatively narrow and the surface area of subaerially exposed alluvial deposits was small, the Little Snake River, a few miles downstream from streamflow-gaging station 09260000, had a consistently high percentage of its banks consisting of alluvial deposits (fig. 5*A*).

The large sediment yield of the Little Snake River, noted by Andrews (1978), is reflected in the increase in relative abundance of alluvial deposits in the Yampa River immediately downstream from the Little Snake River confluence at river mile 50.5 (fig. 5*B*). The relative abundance of alluvial deposits drops abruptly from greater than 80 percent to less than 20 percent as the Yampa River flows into the steep and narrow Yampa Canyon (fig. 1). Alluvial deposits are relatively scarce in Yampa Canyon between river miles 45 and 21. The canyon geomorphology in this reach is dominated by the massive limestone of the Morgan Formation, and the river is steep and the canyon floor is narrow, providing little area suitable for significant alluvial sediment storage. The Yampa River flows through the massive Weber Sandstone downstream from river mile 21 and, from here to the mouth, the canyon floor is wider and more conducive to sediment deposition.

The abundance of subaerial alluvial sediment in the Green River downstream from the Lodore Ranger Station is less uniform than in the Little Snake or Yampa Rivers. The relative abundance of alluvial deposits ranges from less than 10 to more than 80 percent of the visible channel boundary between the Lodore Ranger Station and the downstream end of the study reach at river mile 194 (figs. 1 and 5*C*). The regional structural geology and lithology at river level may be significant in determining variations in canyon-floor width and gradient that influence the relative abundance of alluvial deposits in the Green River.

The sediment-transport equations presented in the “Sediment-Transport Curves” section of this report indicate that the transport of gravel, sand, silt, and clay in these rivers is strongly dependent on the streamflow magnitude and, to a lesser degree, on the season. The timing of annual runoff, and consequently the timing of sediment entrainment, transport, and deposition, affects aquatic habitat and is dependent on long-term climate, seasonal weather patterns, and on the operation of upstream reservoirs. Reach-specific estimates of the timing, volume, and particle size of sediment deposited at critical aquatic-habitat sites other than at the gaged sampling sites require streamflow routing simulations through the drainage network and are beyond the scope of this report.

Sampling Sites

Understanding the timing and mechanics of sediment delivery at a specific location, such as the spawning bar on the Green River, requires an understanding of the timing and mechanics of sediment delivery from the entire watershed. A first step in determining sediment delivery to a specific location or in creating a sediment budget for the watershed is to derive sediment-transport equations (sediment-transport curves) on the principal streams. These transport curves should reflect the transport of sediment by both suspended and bedload modes, the transport of sediment particles in various size ranges, and the seasonal variability of supply and transport in order to be useful in modeling and budget computations.

Sediment-transport curves were derived using instantaneous measurements of streamflow, suspended-sediment concentration, and bedload. Sediment samples were collected at five sites within the watershed where streamflow data also were collected (fig. 1):

1. Yampa River above Little Snake River near Maybell, Colorado, 09251100;
2. Little Snake River near Lily, Colorado, 09260000;
3. Yampa River at Deerlodge Park, Colorado, 09260050;
4. Green River above Gates of Lodore, Colorado; 404417108524900 (the nearest streamflow gage is Green River near Greendale, Utah, 09234500); and
5. Green River near Jensen, Utah, 09261000.

Sampling-site locations, descriptions, and periods of streamflow and sediment records are given in later sections of the report that pertain to the five specific sites.

Sediment Sampling

Suspended-sediment and bedload samples were collected using conventional methods described in Guy and Norman (1970) and Edwards and Glysson (1999). Bedload-sediment samples were collected with a 3-inch Helley-Smith bedload sampler (Helley and Smith, 1971). Suspended-sediment and bedload samples were collected at two sites on the Yampa River to bracket the inflow from the Little Snake River, a major sediment source in the Yampa River Basin (Andrews, 1978). Suspended- and bedload-sediment sampling at the Yampa River above Little Snake River site began in 1998. Suspended- and bedload-sediment measurements at the Yampa River at Deerlodge Park site were made in 1982 and 1983 (Elliott and others, 1984), in 1994, and from 1997 through 2001. Suspended-sediment samples were collected at the Little Snake River near Lily in 1983, from 1994 through 1998, and from 2000 through 2002. Bedload samples were collected only in 2001 and 2002. Data collected before the beginning of this study (1998) were incorporated into the present analyses.

No sediment data before 1999 were available from the Green River immediately downstream from Flaming Gorge Reservoir. Suspended-sediment and bedload measurements

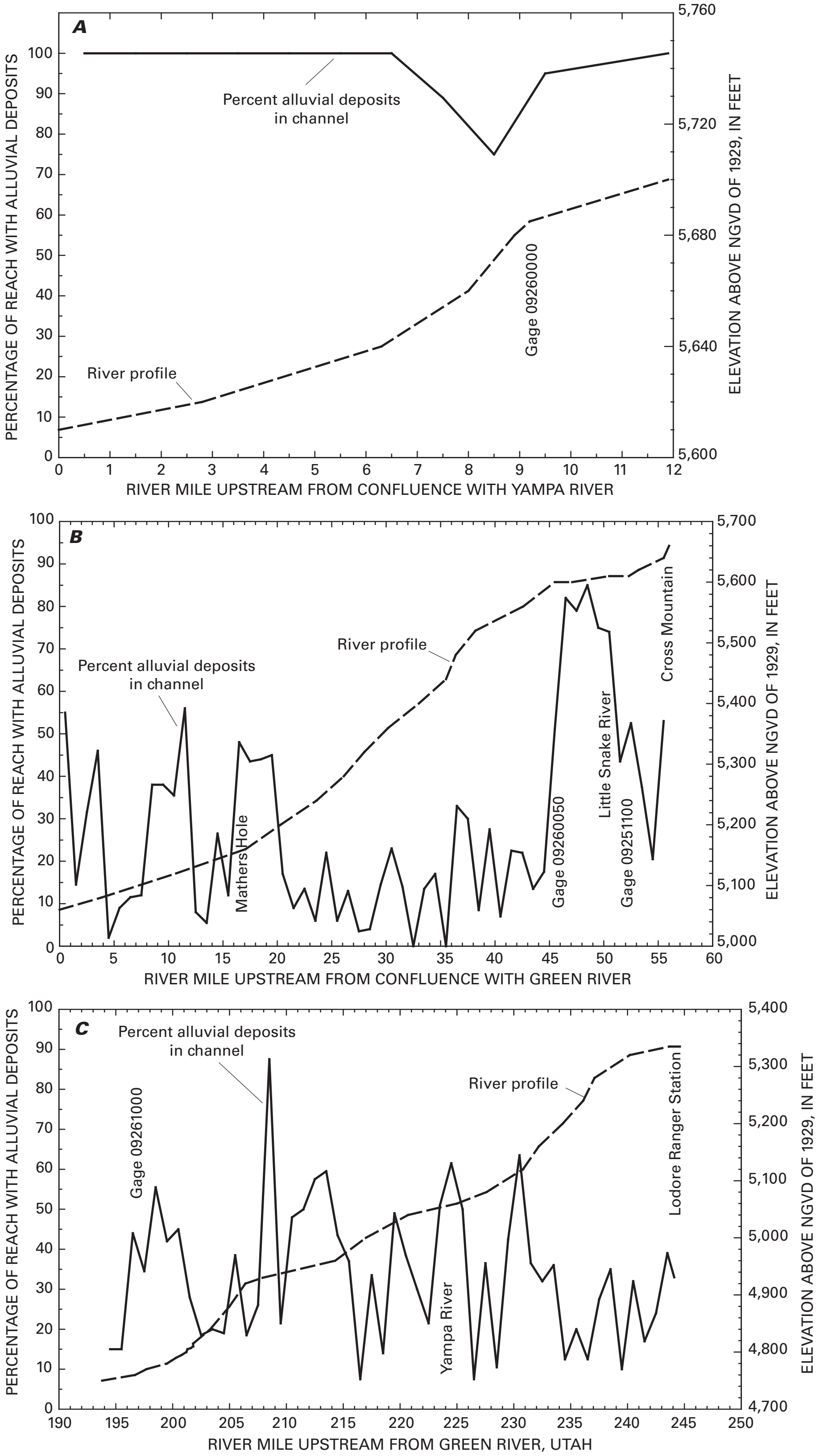

Figure 5. Relative abundance of alluvial deposits: *A*, Little Snake River from 3 miles above the Lily streamflow gage to the confluence with the Yampa River; *B*, Yampa River from Cross Mountain to the confluence with the Green River; and *C*, Green River from the Lodore Ranger Station to Jensen, Utah.

were made on the Green River above the Gates of Lodore Canyon from 1999 through 2002. Although little sediment passes through the reservoir, the variability of streamflow is regulated by operation of the reservoir and has an effect on tributary-supplied sediment downstream. Downstream effects on discharge fluctuations, streambed scour, and sediment entrainment can be significant for many miles downstream from large reservoirs (Williams and Wolman, 1984).

The longest period of sediment record in the study area is from the Green River near Jensen. Suspended sediment was measured at this site from 1948 through 1979, but no bedload measurements were made. Suspended-sediment and bedload samples were collected at the Jensen site in 1996. After a 1-year hiatus, suspended-sediment and bedload samples were collected from 1998 through 2002.

Seasonal, or hysteretic, variability in sediment supply and transport is common on many rivers. The daily sediment load for a specific discharge may be greater during the spring than for the same discharge in the summer or fall. The opposite relation can exist on some rivers as well. If the hysteresis effect is strong on a particular river reach, use of a single sediment-transport curve for all seasons may result in less precise estimates of annual sediment load than if curves for each season are used. Separate transport curves for the early, or rising-limb hydrograph, and later, or falling-limb hydrograph, periods are desirable if there are data to indicate a strong hysteresis and if enough measurements are available to derive representative and statistically significant sediment-transport curves.

The sampling strategy of this project was to collect enough samples to cover the full range of expected discharges at a site and to account for seasonality or hysteresis effects. Base-flow periods usually were not sampled because only a small portion of the annual sediment load is transported during that time. Normally, such a strategy would require several dozen measurements for each sediment-transport curve (Elliott and others, 1984); however, the design of this study was to collect a few samples at each site over a period of several years rather than to sample all sites intensively for a 1- or 2-year period. This strategy allowed year-to-year adjustments in the sampling schedule so appropriate discharge ranges could be sampled.

Sediment-Transport Curves

Sediment loads, or sediment discharges, were calculated for the five sampling sites by using instantaneous measurements of streamflow, suspended-sediment concentration, and bedload. Sediment loads, in tons per day, were computed for two modes of transport (suspended load and bedload) as well as for the total sediment load (suspended load plus bedload) if both modes had been sampled. Suspended-sediment load (tons per day) was calculated as the product of water discharge (cubic feet per second), suspended-sediment concentration (milligrams per liter), and a coefficient of 0.0027 (Porterfield, 1972, p. 43). Bedload (tons per day) was calculated as the product of the channel width (feet), the mass of the bedload sample (grams), and a units conversion factor of 0.381 (for a 3-inch sampler orifice), divided by the time the Helley-Smith sampler was in contact with the streambed (seconds) (Edwards and Glysson, 1999, p. 80).

Sediment loads also were calculated for sediment particle-size range (silt-and-clay, and sand-and-gravel sizes) if laboratory size analysis had been done on the sample. Silt-and-clay load included all sediment finer than 0.062 mm in diameter, mostly transported as suspended load; sand-and-gravel load included any sediment with a diameter greater than or equal to 0.062 mm, including both suspended load and bedload. The size-range designation was independent of transport mode.

Each sediment measurement was given a seasonal classification based on when the sample was collected relative to the date of the annual peak discharge (rising-limb season or falling-limb season). In the case of sediment collected at the Green River above Gates of Lodore site, where streamflow peaks are regulated by Flaming Gorge Dam, seasons were classified as "early" or "late" with respect to the timing of the annual peak discharge on the Yampa River at Deerlodge Park.

Sediment-transport curves were derived for each transportation mode, particle-size range, and season by fitting a line to the sediment-discharge and water-discharge data so that the deviation of all points from the line was minimized. Sediment-transport curves commonly are approximated by a least-squares regression of logarithmic-transformed data (Walling, 1977) and, as presented in this analysis, are expressed in the form of a power equation:

$$Q_s = aQ^b \tag{1}$$

where

Q_s is sediment discharge, in tons per day;
a is regression constant, or intercept;
Q is water discharge, in cubic feet per second;

and

b is regression exponent, or slope.

Linear regression may not always be appropriate because it assumes that the linear relation is continuous from low streamflows to high streamflows. Other curve-fitting techniques may be appropriate in certain circumstances, but Troutman and Williams (1987) indicate that ordinary least-squares regression is an appropriate technique when the prediction of the dependent variable is the objective and when the assumption of linearity can be met. When the transport curve is used as a predictive tool, it usually is used to estimate the mean response of the dependent variable (sediment load) given a value of the independent variable (measured water discharge).

The use of the transport curves presented in this report to estimate sediment loads could result in biased estimates of the loads because logarithmic transformation of data can result in biased estimates of the dependent variable in regression analysis. Transformation bias occurs when regression estimates (expressed in log values) are detransformed (to nonlog values, for example, tons per day) and usually results in underestimation of the mean response of the dependent variable (estimated sediment load). Transformation bias is greatest when the sediment and water discharge data are characterized by a relatively large number of measurements at low discharges and when the scatter of data points around the regression curve is great (Jansson, 1985).

Miller (1984) discussed transformation bias when fitting curves to natural logarithm-transformed data and shows that, for estimates of the dependent variable, transformation bias is multiplicative and increases exponentially with the variance. Therefore, it is possible to eliminate most transformation bias by multiplying the sediment-discharge estimate by a correction factor:

$$C_b = e^{0.5(\mathrm{MSE})} \qquad (2)$$

where

C_b is transformation-bias correction factor;
e is base of the natural logarithm;

and

MSE is mean square error, an unbiased estimator of the error variance.

The relative accuracy and representativeness of the transport relations derived in this study can be assessed on the values of the coefficients of determination (R^2) of regression equations, the MSE (or variance), the range of discharges sampled relative to typically observed discharges, the seasonality of the relations, and the number of samples. The transport equations in this report are considered to be reasonably representative if the R^2 value is greater than about 0.70, if sediment samples are evenly distributed over the likely range of water discharges in a year, if the samples are distributed between the rising-limb and falling-limb hydrograph seasons, and if the number of samples is large enough to reflect the variance in the sediment load to water-discharge relation.

Yampa River above Little Snake River, near Maybell, Colorado

Site Description

Streamflow and sediment measurements were made at streamflow-gaging station 09251100 Yampa River above Little Snake River, near Maybell, Colorado. The gage is located at latitude 40°27'39", longitude 108°25'30", in NW1/4 NE1/4 sec. 20, T. 6 N., R. 98 W., Moffat County, on the Moffat County Road 25 bridge, 1 mile upstream from the mouth of the Little Snake River. Drainage area at the gaging station is 3,837 mi^2.

The sampling site is in an area known as Lily Park, a broad alluvial valley, approximately 2.5 miles downstream from the mouth of Cross Mountain Canyon, a steep, bedrock-dominated reach of the Yampa River (fig. 1). Discharge and sediment measurements were made from the bridge at most streamflows. Measurements at low streamflows were made approximately 150 ft upstream from the bridge by wading.

Streamflow and Sediment Data

Streamflow characteristics from streamflow data collected at the streamflow-gaging station are presented in table 1 and sediment-load data are presented in table 2. Plots of the sediment-load data are presented in figure 6.

Analysis

Streamflow data have been collected at gaging station 09251100 Yampa River above Little Snake River, near Maybell, Colorado, since May 1996. Streamflow-duration and peak-flow statistics based on 6 years of record are presented in table 1. During this period, annual instantaneous discharge peaks ranged from 7,920 ft^3/s in 2001 to 16,400 ft^3/s in 1997 (Crowfoot and others, 2002). Base-flow conditions occur at discharges of less than about 500 to 600 ft^3/s and are equaled or exceeded about 45 to 55 percent of the time (table 1).

Table 1. Streamflow characteristics at streamflow-gaging station 09251100 Yampa River above Little Snake River, near Maybell, Colorado, 1997–2002.

[Streamflow duration in percentage of time specific discharge is equaled or exceeded, calculated with daily mean discharge; ft^3/s, cubic foot per second; %, percentage; nc, not calculated]

Recurrence interval of peak discharge		Duration of daily mean discharge	
Recurrence interval (years)	Discharge (ft^3/s)	Duration (% time)	Discharge (ft^3/s)
1.05	nc	95	92.9
1.11	nc	90	177.8
1.25	7,779	85	215.6
2	9,836	80	246.9
5	12,500	75	278.1
10	14,190	70	309.3
25	16,270	65	341.7
50	17,790	60	375.6
100	19,280	55	409.4
200	20,770	50	453.0
500	22,740	45	508.4
		40	565.9
		35	800.9
		30	1,175.7
		25	1,556.1
		20	2,121.5
		15	3,384.2
		10	4,933.9
		5	7,205.4

Table 2. Summary of discharge and sediment loads by transport mode, particle-size range, and season, 09251100 Yampa River above Little Snake River near Maybell, Colorado, 1998–2002.

[dd min yy, day month year; ft³/s, cubic feet per second; tons/d, tons per day; %, percent; <, less than; >, greater than; mm, millimeter; Sand&Gvl, sand and gravel; M&C, medium and coarse; VCS & FG, very coarse sand and fine gravel; Susp Sed, suspended sediment; nd, no data]

Sample date (dd mm yy)	Instantaneous discharge (ft^3/s)	Hydrograph season	Suspended-sediment load (tons/d)	Bedload (tons/d)	Total sediment load (tons/d)	Bedload percentage of total load (%)	Total load <0.062 mm (tons/d)	Sand&Gvl load >0.062 mm (tons/d)	Suspended load <0.062 mm (tons/d)	Suspended load >0.062 mm (tons/d)	Fine sand 0.062 to <0.250 mm (tons/d)	M&C sand 0.250 to <1.00 mm (tons/d)	VCS & FG 1.00 to >8.00 mm (tons/d)	Remarks
06 May 98	9,590	Rising	22,400	69	22,469	0.3	16,800	5,669	16,800	5,600	nd	nd	nd	No suspended size fractions
19 May 98	7,580	Rising	9,930	174	10,104	1.7	7,944	2,160	7,944	1,986	nd	nd	nd	Peak 22 May 1998
27 May 98	6,760	Falling	6,420	210	6,630	3.2	4,494	2,136	4,494	1,926	nd	nd	nd	No suspended size fractions
03 June 98	7,640	Falling	5,710	264	5,974	4.4	3,883	2,091	3,883	1,827	nd	nd	nd	No suspended size fractions
10 June 98	4,950	Falling	3,680	50	3,730	1.3	2,098	1,632	2,098	1,582	nd	nd	nd	No suspended size fractions
17 June 98	5,130	Falling	6,900	36	6,936	0.5	3,864	3,072	3,864	3,036	nd	nd	nd	No suspended size fractions
30 June 98	4,740	Falling	1,330	35	1,365	2.5	638	726	638	692	nd	nd	nd	No suspended size fractions
31 Mar 99	1,420	Rising	372	13	385	3.4	294	91	294	78	nd	nd	nd	No suspended size fractions
20 May 99	4,820	Rising	5,400	101	5,501	1.8	4,105	1,396	4,104	1,296	992	387	16	Peak 31 May 1999
05 Apr 00	908	Rising	81	0.22	81	0.3	74	7	74	7	nd	nd	nd	
19 Apr 00	3,930	Rising	4,150	43	4,193	1.0	2,432	1,761	2,432	1,718	981	780	1	
02 May 00	5,670	Rising	7,010	72	7,082	1.0	4,900	2,182	4,900	2,110	1,432	745	4	
26 May 00	7,620	Rising	10,700	221	10,921	2.0	6,720	4,202	6,720	3,980	1,930	2,196	75	Peak 31 May 2000
05 July 00	558	Falling	20	0.15	20	0.7	17	3	17	3	nd	nd	nd	No suspended size fractions
16 Mar 01	558	Base flow	21	nd	nd	nd	nd	nd	16	5	nd	nd	nd	No bedload 16 Mar 2001
26 Mar 01	1,720	Rising	1,410	4.5	1,414	0.3	1,156	258	1,156	254	0	4	0	Susp Sed sand break only
16 Apr 01	1,160	Rising	254	3.5	257	1.4	224	34	224	30	0	3	1	Peak 18 May 2001
12 June 01	3,070	Falling	796	35	831	4.2	390	441	390	406	287	145	9	
14 June 01	2,390	Falling	542	21	563	3.8	314	249	314	228	211	30	8	
19 June 01	1,410	Falling	278	2.7	281	1.0	125	156	125	153	92	63	0	
20 June 01	1,330	Falling	104	1.7	106	1.6	81	25	81	23	0	1	0	Susp Sed sand break only
02 Apr 02	1,150	Rising	357	5.1	362	1.4	325	37	325	32	32	5	0	
23 Apr 02	1,320	Rising	2,190	2.3	2,192	0.1	1,467	725	1,467	723	0	2	0	Susp Sed sand break only
14 May 02	1,590	Rising	219	23.9	243	9.8	186	57	186	33	33	23	1	
21 May 02	2,730	Rising	1,800	39.6	1,840	2.2	1,206	634	1,206	594	558	72	3	
04 June 02	2,810	Falling	1,690	191.6	1,882	10.2	862	1,020	862	828	597	411	11	Peak about 2 May 2002

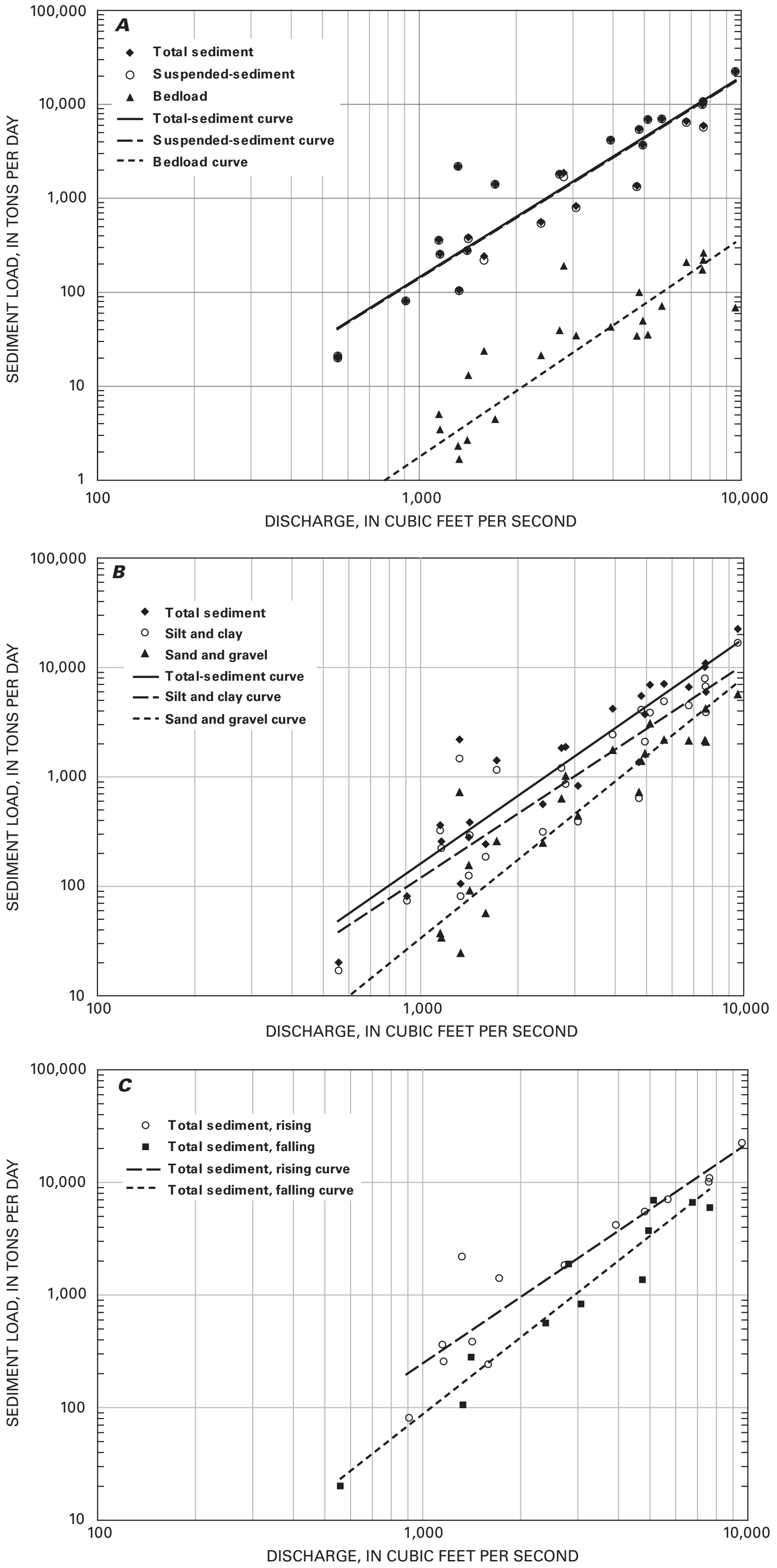

Figure 6. Relation of sediment load at 09251100 Yampa River above Little Snake River near Maybell, Colorado, 1998–2002, *A*, to water discharge; *B*, by particle size to water discharge; and *C*, by season to water discharge.

Sediment-load measurements were made at gaging station 09251100 from 1998 through 2002 (table 2). Annual instantaneous discharge peaks for the years when sediment measurements were made ranged from 7,920 ft^3/s in 2001 to 9,980 ft^3/s in 1998. The instantaneous discharge peak for 2000 was not recorded due to equipment malfunction. Suspended sediment was measured 25 times at discharges ranging from 558 to 9,590 ft^3/s and included 14 measurements during the rising-limb hydrograph season and 11 measurements during the recessional- or falling-limb hydrograph season. Bedload as a percentage of total-sediment load ranged from 0.1 to 10.2 percent and averaged 2.4 percent.

The sediment-transport equation for total-sediment load had a coefficient of determination (R^2) of 0.85, the equation for suspended-sediment load had an R^2 of 0.87, and bedload discharge had an R^2 of 0.80 (table 3). The equations for silt-and-clay load and sand-and-gravel load had an R^2 of 0.82 and 0.86, respectively. The seasonality transport equations for total load during the rising-limb and falling-limb hydrograph seasons had R^2 values of 0.87 or greater, but were based on a relatively small number of samples. The relatively large R^2 values (greater than or equal to 0.80) for all transport equations at station 09251100 indicate that the transport equations may be useful for annual load estimation or sediment budget calculations for discharges ranging from about 500 to 10,000 ft^3/s. These transport equations may not adequately reflect transport conditions of higher discharges that occurred in 1997 or in the mid-1980s before the streamflow-gaging station was established. Additional measurements in the 500- to 10,000-ft^3/s range from both the rising-limb and falling-limb hydrograph seasons, and any measurements during discharges greater than 10,000 ft^3/s, would make these equations more representative of flow conditions at this site.

Table 3. Sediment-transport equations derived from sediment discharges measured at station 09251100 Yampa River above Little Snake River near Maybell, Colorado, 1998–2002.

[Q_s, sediment discharge in tons per day; Q, water discharge in cubic feet per second; R^2, coefficient of determination; MSE, mean square error; n, number of samples]

Type of sediment discharge	Regression equation	R^2	MSE	n
Total	$Q_s = 0.000106\ Q^{2.33}$	0.85	0.479	25
Suspended	$Q_s = 0.0000581\ Q^{2.13}$	0.87	0.492	26
Bedload	$Q_s = 0.000000188\ Q^{2.33}$	0.80	0.885	25
Silt and clay	$Q_s = 0.000151\ Q^{1.96}$	0.82	0.564	25
Sand and gravel	$Q_s = 0.00000223\ Q^{2.39}$	0.86	0.640	25
Total, rising	$Q_s = 0.000335\ Q^{1.96}$	0.87	0.427	14
Total, falling	$Q_s = 0.0000137\ Q^{2.26}$	0.94	0.246	11

Little Snake River near Lily, Colorado

Site Description

Streamflow and sediment measurements were made at streamflow-gaging station 09260000 Little Snake River near Lily, Colorado. The gage is located at latitude 40°32'50", longitude 108°25'25", in NW1/4 NE1/4 sec. 20, T. 7 N., R. 98 W., Moffat County, Colorado, on the left bank 170 ft downstream from the highway bridge, approximately 10 mi upstream from the mouth (fig. 1). Drainage area at the gaging station is approximately 3,730 mi^2.

The sampling site is at a bedrock-constricted river reach immediately downstream from a wide, sandy reach of the Little Snake River. Discharge and sediment measurements were made from the bridge at moderate and high streamflows and approximately 300 ft downstream from the bridge at low streamflows by wading.

Streamflow and Sediment Data

Streamflow characteristics from discharge data collected at the streamflow-gaging station are presented in table 4, and sediment-load data are presented in table 5. Plots of the sediment-load data are presented in figure 7.

Analysis

Streamflow data have been collected at gaging station 09260000 Little Snake River, near Lily, Colorado, since October 1921, and representative peak-flow and streamflow-duration statistics for the period are presented in table 4. During the period of streamflow data collection, annual instantaneous discharge peaks ranged from 996 ft^3/s in 1934 to 16,700 ft^3/s in 1984 (Crowfoot and others, 2002). Base-flow conditions occur at discharges of less than about 100 to 200 ft^3/s and are equaled or exceeded about 40 to 60 percent of the time (table 4).

Suspended-sediment measurements were made at gaging station 09260000 from 1994 through 2002 (table 5). Bedload measurements were made in 2001 and 2002. Annual instantaneous discharge peaks for the years when sediment measurements were made ranged from 2,840 ft^3/s in 1994 to 6,480 ft^3/s in 1999. Suspended sediment was measured 96 times at discharges ranging from 1 to 5,840 ft^3/s and included 40 measurements during the rising-limb hydrograph season and 28 measurements during the recessional- or falling-limb hydrograph season. The 10 bedload measurements were made at discharges ranging from 346 to 1,280 ft^3/s. Bedload as a percentage of total-sediment load ranged from 10.8 to 52.1 percent and averaged 23.5 percent.

Table 4. Streamflow characteristics at streamflow-gaging station 09260000 Little Snake River near Lily, Colorado, 1922–2002.

[Recurrence interval, in years, equals reciprocal of exceedance probability, calculated with annual instantaneous discharge peak; streamflow duration in percentage of time specific discharge is equaled or exceeded, calculated with daily mean discharge; ft^3/s, cubic foot per second; %, percentage]

Recurrence interval of peak discharge		Duration of daily mean discharge	
Recurrence interval (years)	Discharge (ft^3/s)	Duration (% time)	Discharge (ft^3/s)
1.05	2,171	95	2.15
1.11	2,626	90	12.3
1.25	3,283	85	27.8
2	4,934	80	44.6
5	7,225	75	57.6
10	8,730	70	69.0
25	10,600	65	81.3
50	11,970	60	95.2
100	13,320	55	109.0
200	14,650	50	130.2
500	16,390	45	159.0
		40	196.0
		35	249.1
		30	342.6
		25	515.8
		20	818.4
		15	1,279.0
		10	1,968.7
		5	3,032.7

The sediment-transport equations for total-sediment load ($R^2 = 0.22$) and bedload ($R^2 = 0.60$) are based on only 10 measurements and probably are inadequate for annual load or sediment budget calculations. The sediment-transport equation for suspended-sediment load had an R^2 of 0.74 (table 6). Regression of subsets of suspended-sediment data on the basis of particle size and seasonality produced generally poorer results with individual transport equation R^2 values ranging between 0.46 and 0.54. An exception was the transport equation for suspended load during the falling-limb hydrograph season with an R^2 of 0.76.

The suspended-sediment measurements at station 09260000 are relatively evenly distributed over streamflows from about 40 to 6,000 ft^3/s; however, streamflows at conditions approaching the 1984 historical instantaneous peak discharge have not occurred in recent years. The transport equation for suspended-sediment load is adequate for estimating annual suspended loads for discharges ranging from about 40 to 6,000 ft^3/s and may have some applicability for discharges ranging from about 1 to 40 ft^3/s. The suspended-sediment load transport equation must be recomputed with data from discharges greater than 6,000 ft^3/s for it to be applicable at extremely high discharges. Transport equations by suspended-particle size show greater variance (mean square error, MSE, greater than 2), but are applicable for discharges ranging from about 50 to 6,000 ft^3/s. Although the distribution of data indicates a seasonal sediment-load hysteresis may exist (fig. 7*C*), the relatively low R^2 value for the rising-hydrograph season could be improved with additional data collected in the appropriate season. Also, because bedload data have been collected for only 2 years at this site, neither the total-annual sediment load nor the relative portion of total-sediment load transported as bedload are well documented. Bedload is an important component of the annual sediment budget in the Little Snake River at Lily and could be quantified with future measurements.

Yampa River at Deerlodge Park, Colorado

Site Description

Streamflow and sediment measurements were made at streamflow-gaging station 09260050 Yampa River at Deerlodge Park, Colorado. The gage is located at latitude 40°27'06", longitude 108°31'28", in SE1/4 SW1/4 sec. 21, T. 6 N., R. 99 W., Moffat County, at the eastern entrance to Dinosaur National Monument, 5 river miles downstream from the mouth of the Little Snake River. Drainage area at the gage is approximately 7,660 mi^2.

The sampling site is in an area known as Deerlodge Park, a broad alluvial valley, approximately 0.5 mi upstream from the entrance to Yampa Canyon, a steep, bedrock-dominated reach of the Yampa River (fig. 1). Discharge and sediment measurements were made from a boat at most streamflows. One low-streamflow measurement was made approximately 100 ft downstream from the gage by wading.

Streamflow and Sediment Data

Streamflow characteristics from discharge data collected at the streamflow-gaging station are presented in table 7, and sediment-load data are presented in table 8. Plots of the sediment-load data are presented in figure 8.

Analysis

Streamflow data have been collected at gaging station 09260050 Yampa River, at Deerlodge Park, Colorado, since April 1982. The station was inactive in 1995 and 1996 but was reactivated in 1997. Peak-flow and streamflow-duration statistics for the period of record are presented in table 7. During the period of streamflow-data collection, annual instantaneous discharge peaks ranged from 3,810 ft^3/s in 2002 to 33,200 ft^3/s in 1984 (Crowfoot and others, 2002). Base-flow conditions occur at discharges of less than about 600 to 700 ft^3/s and are equaled or exceeded about 50 percent of the time (table 7).

Table 5. Summary of discharge and sediment loads by transport mode, particle-size range, and season, 09260000 Little Snake River near Lily, Colorado, 1994–2002.

[dd mm yy, day month year; ft³/s, cubic feet per second; tons/d, tons per day; %, percent; <, less than; >, greater than; mm, millimeter; Sand&Gvl, sand and gravel; M&C, medium and coarse; VCS & FG, very coarse sand and fine gravel; nd, no data]

Sample date (dd mm yy)	Instantaneous discharge (ft^3/s)	Hydrograph season	Suspended-sediment load (tons/d)	Bedload (tons/d)	Total sediment load (tons/d)	Bedload percentage of total load (%)	Total load <0.062 mm (tons/d)	Sand&Gvl load >0.062 mm (tons/d)	Suspended load <0.062 mm (tons/d)	Suspended load >0.062 mm (tons/d)	Fine sand 0.062 to <0.250 mm (tons/d)	M&C sand 0.250 to <1.00 mm (tons/d)	VCS & FG 1.00 to >8.00 mm (tons/d)	Remarks
12 Oct 93	248	Base flow	3,070	nd	nd	nd	nd	nd	2,824	246	nd	nd	nd	No bedload, water year 1994
01 Nov 93	157	Base flow	170	nd	nd	nd	nd	nd	95	75	nd	nd	nd	
22 Feb 94	85	Base flow	21	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	No sand break analysis
28 Mar 94	387	Rising	653	nd	nd	nd	nd	nd	438	215	nd	nd	nd	
26 Apr 94	2,070	Falling	12,100	nd	nd	nd	nd	nd	7,623	4,477	nd	nd	nd	Peak 25 April 1994
10 May 94	1,760	Falling	6,270	nd	nd	nd	nd	nd	3,511	2,759	nd	nd	nd	
21 May 94	1,790	Falling	2,330	nd	nd	nd	nd	nd	1,515	816	nd	nd	nd	
24 May 94	1,270	Falling	1,950	nd	nd	nd	nd	nd	605	1,346	nd	nd	nd	
22 June 94	105	Falling	27	nd	nd	nd	nd	nd	7	20	nd	nd	nd	
28 June 94	52	Base flow	6.5	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	No sand break analysis
13 July 94	1.6	Base flow	0.33	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	No sand break analysis
22 July 94	1.0	Base flow	0.03	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	No sand break analysis
03 Aug 94	121	Base flow	11,600	nd	nd	nd	nd	nd	11,484	116	nd	nd	nd	
19 Sept 94	25	Base flow	1,470	nd	nd	nd	nd	nd	1,470	nd	nd	nd	nd	
06 Oct 94	239	Base flow	8,880	nd	nd	nd	nd	nd	8,791	89	nd	nd	nd	No bedload, water year 1995
25 Nov 94	82	Base flow	83	nd	nd	nd	nd	nd	66	17	nd	nd	nd	
30 Jan 95	116	Base flow	168	nd	nd	nd	nd	nd	34	134	nd	nd	nd	
28 Feb 95	495	Rising	4,620	nd	nd	nd	nd	nd	2,911	1,709	nd	nd	nd	
31 Mar 95	228	Rising	520	nd	nd	nd	nd	nd	78	442	nd	nd	nd	
13 Apr 95	468	Rising	1,640	nd	nd	nd	nd	nd	951	689	nd	nd	nd	
01 May 95	513	Rising	658	nd	nd	nd	nd	nd	658	nd	nd	nd	nd	
31 May 95	4,900	Rising	28,500	nd	nd	nd	nd	nd	21,090	7,410	nd	nd	nd	
08 June 95	5,840	Rising	12,000	nd	nd	nd	nd	nd	11,160	840	nd	nd	nd	Peak June 7 and 8, 1995
12 June 95	3,340	Falling	17,600	nd	nd	nd	nd	nd	5,456	12,144	nd	nd	nd	
17 July 95	1,370	Falling	2,130	nd	nd	nd	nd	nd	2,130	nd	nd	nd	nd	
31 Aug 95	38	Base flow	1.6	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	No sand break analysis
20 Sept 95	49	Base flow	195	nd	nd	nd	nd	nd	137	59	nd	nd	nd	
30 Oct 95	351	Base flow	6,250	nd	nd	nd	nd	nd	6,188	63	nd	nd	nd	No bedload, water year 1996
06 Dec 95	196	Base flow	151	nd	nd	nd	nd	nd	112	39	nd	nd	nd	
07 Dec 95	178	Base flow	102	nd	nd	nd	nd	nd	90	12	nd	nd	nd	
07 Feb 96	77	Base flow	20	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	No sand break analysis
28 Mar 96	369	Rising	643	nd	nd	nd	nd	nd	579	64	nd	nd	nd	
01 Apr 96	477	Rising	744	nd	nd	nd	nd	nd	707	37	nd	nd	nd	
10 Apr 96	909	Rising	6,430	nd	nd	nd	nd	nd	5,401	1,029	nd	nd	nd	
15 Apr 96	1,110	Rising	1,830	nd	nd	nd	nd	nd	238	1,592	nd	nd	nd	
10 May 96	3,440	Rising	2,420	nd	nd	nd	nd	nd	2,372	48	nd	nd	nd	
21 May 96	3,960	Falling	6,060	nd	nd	nd	nd	nd	5,575	485	nd	nd	nd	Peak 19 May 1996
05 June 96	2,340	Falling	1,570	nd	nd	nd	nd	nd	1,413	157	nd	nd	nd	
10 June 96	2,610	Falling	5,590	nd	nd	nd	nd	nd	1,621	3,969	nd	nd	nd	

Table 5. Summary of discharge and sediment loads by transport mode, particle-size range, and season, 09260000 Little Snake River near Lily, Colorado, 1994–2002. —Continued

[dd mm yy, day month year; ft³/s, cubic feet per second; tons/d, tons per day; %, percent; <, less than; >, greater than; mm, millimeter; Sand&Gvl, sand and gravel; M&C, medium and coarse; VCS & FG, very coarse sand and fine gravel; nd, no data]

Sample date (dd mm yy)	Instantaneous discharge (ft^3/s)	Hydrograph season	Suspended-sediment load (tons/d)	Bedload (tons/d)	Total sediment load (tons/d)	Bedload percentage of total load (%)	Total load <0.062 mm (tons/d)	Sand&Gvl load >0.062 mm (tons/d)	Suspended load <0.062 mm (tons/d)	Suspended load >0.062 mm (tons/d)	Fine sand 0.062 to <0.250 mm (tons/d)	M&C sand 0.250 to <1.00 mm (tons/d)	VCS & FG 1.00 to >8.00 mm (tons/d)	Remarks
25 June 96	1,090	Falling	748	nd	nd	nd	nd	nd	741	7	nd	nd	nd	
24 July 96	61	Base flow	3.6	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	No sand break analysis
02 Aug 96	86	Base flow	164	nd	nd	nd	nd	nd	157	7	nd	nd	nd	
15 Oct 96	60	Base flow	27	nd	nd	nd	nd	nd	25	2	nd	nd	nd	No bedload, water year 1997
18 Nov 96	254	Base flow	1,750	nd	nd	nd	nd	nd	1,733	18	nd	nd	nd	
23 Dec 96	67	Base flow	31	nd	nd	nd	nd	nd	29	2	nd	nd	nd	
26 Feb 97	231	Base flow	130	nd	nd	nd	nd	nd	126	4	nd	nd	nd	
21 Mar 97	1,210	Rising	14,400	nd	nd	nd	nd	nd	11,952	2,448	nd	nd	nd	
25 Mar 97	958	Rising	4,240	nd	nd	nd	nd	nd	4,240	nd	nd	nd	nd	
03 Apr 97	885	Rising	1,750	nd	nd	nd	nd	nd	1,698	53	nd	nd	nd	
18 Apr 97	620	Rising	5,360	nd	nd	nd	nd	nd	4,181	1,179	nd	nd	nd	
07 May 97	3,060	Rising	11,900	nd	nd	nd	nd	nd	11,067	833	nd	nd	nd	
08 May 97	4,480	Rising	21,400	nd	nd	nd	nd	nd	19,260	2,140	nd	nd	nd	
14 May 97	4,410	Rising	13,300	nd	nd	nd	nd	nd	11,172	2,128	nd	nd	nd	
27 May 97	4,290	Rising	5,680	nd	nd	nd	nd	nd	4,771	909	nd	nd	nd	
10 June 97	4,880	Falling	12,900	nd	nd	nd	nd	nd	10,965	1,935	nd	nd	nd	Peak 4 June 1997
07 July 97	603	Falling	130	nd	nd	nd	nd	nd	100	30	nd	nd	nd	
15 July 97	327	Falling	26	nd	nd	nd	nd	nd	23	3	nd	nd	nd	
06 Aug 97	128	Falling	52	nd	nd	nd	nd	nd	50	2	nd	nd	nd	
21 Oct 97	288	Base flow	284	nd	nd	nd	nd	nd	162	122	nd	nd	nd	No bedload, water year 1998
15 Dec 97	82	Base flow	14	nd	nd	nd	nd	nd	4	10	nd	nd	nd	
06 Mar 98	182	Base flow	128	nd	nd	nd	nd	nd	61	67	nd	nd	nd	
01 Apr 98	833	Rising	2,700	nd	nd	nd	nd	nd	2,565	135	nd	nd	nd	
09 Apr 98	587	Rising	872	nd	nd	nd	nd	nd	532	340	nd	nd	nd	
22 Apr 98	675	Rising	1,130	nd	nd	nd	nd	nd	463	667	nd	nd	nd	
27 Apr 98	1,850	Rising	5,990	nd	nd	nd	nd	nd	5,631	359	nd	nd	nd	
07 May 98	3,270	Rising	10,900	nd	nd	nd	nd	nd	6,540	4,360	nd	nd	nd	
20 May 98	3,450	Rising	9,690	nd	nd	nd	nd	nd	5,330	4,361	nd	nd	nd	
29 May 98	2,490	Rising	2,710	nd	nd	nd	nd	nd	1,870	840	nd	nd	nd	
01 June 98	2,920	Rising	6,090	nd	nd	nd	nd	nd	2,436	3,654	nd	nd	nd	
11 June 98	1,710	Rising	2,530	nd	nd	nd	nd	nd	784	1,746	nd	nd	nd	
15 June 98	1,320	Rising	7,810	nd	nd	nd	nd	nd	625	7,185	nd	nd	nd	
19 June 98	3,900	Falling	45,100	nd	nd	nd	nd	nd	35,178	9,922	nd	nd	nd	Peak 18 June 1998
01 July 98	1,270	Falling	1,630	nd	nd	nd	nd	nd	375	1,255	nd	nd	nd	
06 July 98	950	Falling	285	nd	nd	nd	nd	nd	242	43	nd	nd	nd	
09 July 98	749	Falling	5,720	nd	nd	nd	nd	nd	286	5,434	nd	nd	nd	
19 Aug 98	96	Base flow	173	nd	nd	nd	nd	nd	157	16	nd	nd	nd	

Table 5. Summary of discharge and sediment loads by transport mode, particle-size range, and season, 09260000 Little Snake River near Lily, Colorado, 1994–2002. —Continued

[dd mm yy, day month year; ft³/s, cubic feet per second; tons/d, tons per day; %, percent; <, less than; >, greater than; mm, millimeter; Sand&Gvl, sand and gravel; M&C, medium and coarse; VCS & FG, very coarse sand and fine gravel; nd, no data]

Sample date (dd mm yy)	Instantaneous discharge (ft^3/s)	Hydrograph season	Suspended-sediment load (tons/d)	Bedload (tons/d)	Total sediment load (tons/d)	Bedload percentage of total load (%)	Total load <0.062 mm (tons/d)	Sand&Gvl load >0.062 mm (tons/d)	Suspended load <0.062 mm (tons/d)	Suspended load >0.062 mm (tons/d)	Fine sand 0.062 to <0.250 mm (tons/d)	M&C sand 0.250 to <1.00 mm (tons/d)	VCS & FG 1.00 to >8.00 mm (tons/d)	Remarks
27 Mar 00	271	Rising	2,350	nd	nd	nd	nd	nd	2,348	2	nd	nd	nd	No bedload, water year 2000
4 Apr 00	250	Rising	448	nd	nd	nd	nd	nd	207	241	nd	nd	nd	
18 Apr 00	792	Rising	5,260	nd	nd	nd	nd	nd	4,618	642	nd	nd	nd	
27 Apr 00	1,160	Rising	1,940	nd	nd	nd	nd	nd	1,810	130	nd	nd	nd	
2 May 00	1,970	Rising	7,070	nd	nd	nd	nd	nd	3,280	3,790	nd	nd	nd	
25 May 00	3,070	Rising	1,820	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	No suspended size analysis
6 June 00	1,270	Falling	665	nd	nd	nd	nd	nd	344	321	nd	nd	nd	Peak May 27
16 Mar 01	533	Rising	2,480	302	2,782	10.8	1,513	1,269	1,513	967	12	229	60	First bedload
26 Mar 01	709	Rising	43,100	nd	nd	nd	nd	nd	42,669	431	nd	nd	nd	No bedload
16 Apr 01	485	Rising	852	255	1,107	23.1	417	690	417	435	13	199	43	Peak 3 May 2001
15 May 01	2,040	Falling	7,580	nd	nd	nd	nd	nd	3,259	4,321	nd	nd	nd	No bedload
24 May 01	1,280	Falling	1,730	495	2,225	22.2	588	1,636	588	1,142	608	969	59	
12 June 01	766	Falling	521	249	770	32.4	198	572	198	323	234	291	47	
14 June 01	346	Falling	139	151	290	52.1	42	248	42	97	73	147	27	
09 July 01	5	Base flow	0	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	No bedload
03 Apr 02	468	Rising	2,000	246	2,246	11.0	1,720	526	1,720	280	147	312	66	
24 Apr 02	527	Falling	1,650	341	1,991	17.1	479	1,513	479	1,172	3	1,188	140	Peak about 18 April 2002
15 May 02	386	Falling	744	235	979	24.0	141	838	141	603	72	652	40	
21 May 02	451	Falling	763	145	908	16.0	290	618	290	473	90	423	15	
05 June 02	695	Falling	1,110	399	1,509	26.5	611	899	611	500	271	520	108	

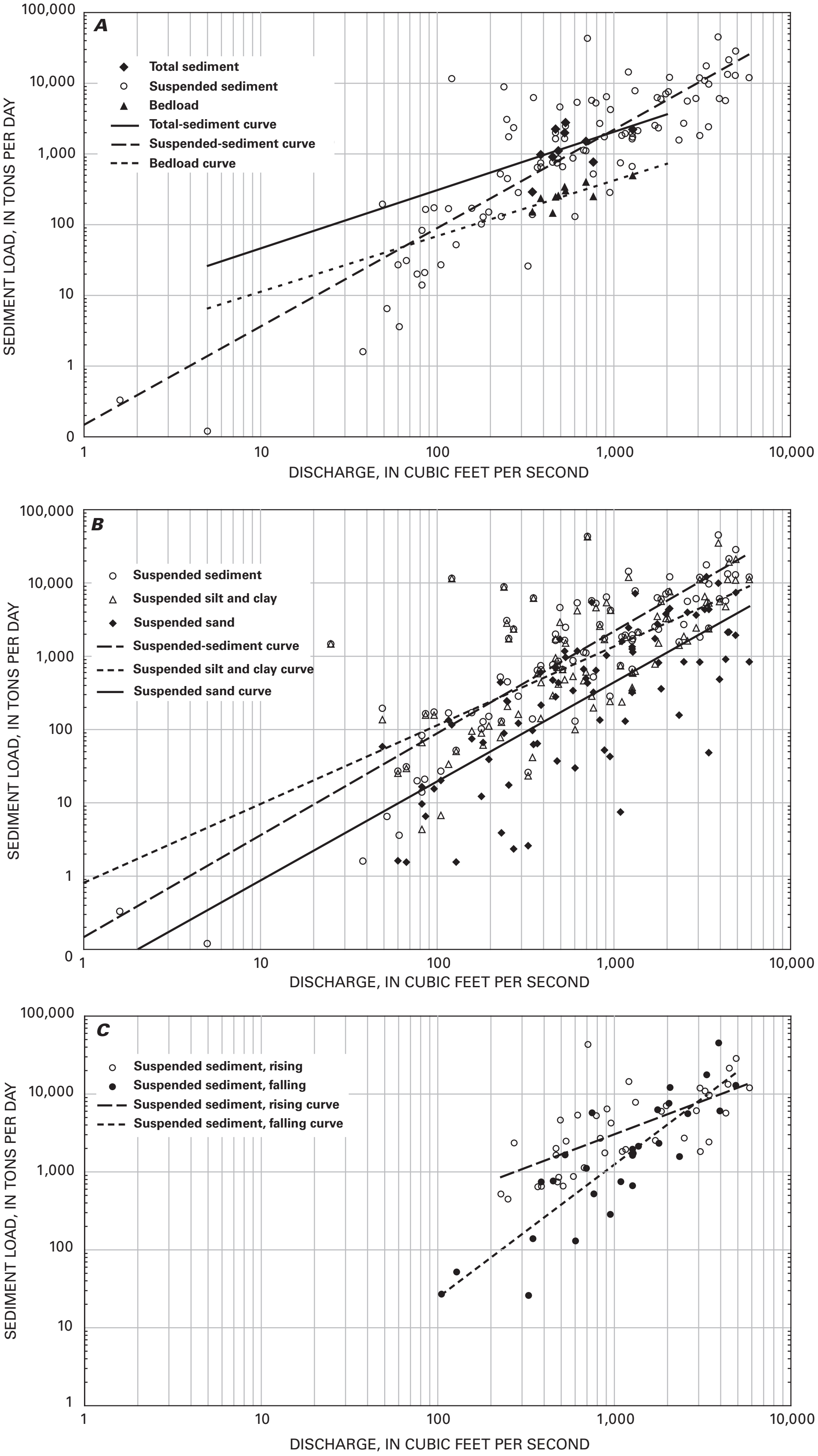

Figure 7. Relation of suspended load at 09260000 Little Snake River near Lily, Colorado, 1994–2002, *A*, to water discharge; *B*, by particle size to water discharge; and *C*, by season to water discharge.

Table 6. Sediment-transport equations derived from sediment discharges measured at station 09260000 Little Snake River near Lily, Colorado, 1994–2002.

[Q_s, sediment discharge in tons per day; Q, water discharge in cubic feet per second; R^2, coefficient of determination; MSE, mean square error; n, number of samples]

Type of sediment discharge	Regression equation	R^2	MSE	n
Total	$Q_s = 6.87\ Q^{0.824}$	0.22	0.403	10
Suspended	$Q_s = 0.146\ Q^{1.39}$	0.74	1.94	96
Bedload	$Q_s = 1.82\ Q^{0.788}$	0.60	0.0662	10
Silt and clay (suspended)	$Q_s = 0.818\ Q^{1.07}$	0.46	2.14	87
Sand (Suspended)	$Q_s = 0.0387\ Q^{1.35}$	0.54	2.41	83
Suspended, rising	$Q_s = 8.35\ Q^{0.85}$	0.47	0.742	40
Suspended, falling	$Q_s = 0.00953\ Q^{1.71}$	0.76	0.925	28

Suspended-sediment and bedload measurements were made at gaging station 09260050 in 1982, 1983, and 1994, and from 1997 through 2001; no sediment measurements were made in 2002 (table 8). Annual instantaneous discharge peaks for the years when sediment measurements were made ranged from 7,670 ft^3/s in 1994 to 23,400 ft^3/s in 1983. Suspended- and bedload-sediment data were collected near the 1983 instantaneous peak discharge of 23,400 ft^3/s (table 8), but no sediment measurements were made the following year during the historical instantaneous peak discharge (33,200 ft^3/s). Suspended sediment was measured 79 times and bedload was measured 53 times at discharges ranging from 46 ft^3/s to 17,600 ft^3/s. Concurrent suspended-sediment and bedload measurements included 24 measurements made during the rising-limb hydrograph season and 29 measurements made during the recessional- or falling-limb hydrograph season. Bedload as a percentage of total-sediment load ranged from 0.5 to 38.8 percent and averaged 9.3 percent.

Sediment-transport equations were derived and annual sediment loads were estimated from the 1982 and 1983 data by Elliott and others (1984). These earliest data were combined with data collected since 1994, and updated transport equations were derived (table 9). The updated transport equations showed minor changes in R^2, slope, and intercept when compared to the 1984 equations. The updated transport equations for total-sediment load, suspended-sediment load, sand-and-gravel load, and fine sand load all had R^2 greater than 0.72. The updated transport equation for suspended-sediment load may be useful for annual suspended-sediment load calculations for discharges ranging from about 40 to 18,000 ft^3/s, whereas the updated transport equations for total-sediment load, sand-and-gravel load, and fine sand load may be useful for annual load calculations for discharges ranging from about 600 to 18,000 ft^3/s. The updated equation for bedload transport had an R^2 of 0.40, which was considerably lower than the R^2 of 0.54 that resulted from regression of the 1982 and 1983 data (Elliott and others, 1984, p. 16). Sediment transport appeared to have a seasonal component (fig. 8*C*), and the transport equation for the rising-limb season had an R^2 of 0.89; however, the falling-limb season equation had an R^2 of 0.68.

The recent effort to collect sediment data at Deerlodge Park for this analysis increased the number of suspended-sediment measurements by 139 percent and increased the number of total-sediment (suspended sediment plus bedload sediment) measurements by 71 percent since 1982–83. Based only on the relative magnitudes of the R^2 value, the additional data have resulted in a slightly improved suspended-sediment transport equation (0.80 compared to 0.76) and a slightly deteriorated total-load equation (0.72 compared to 0.79) compared to those equations published by Elliott and others (1984).

Additional data collection may not improve these transport equations; however, more bedload measurements made during streamflows of less than about 700 ft^3/s could improve the accuracy of both the bedload-transport and total-sediment transport equations (fig. 8*A*). Additional data collection during the rising-limb and falling-limb hydrograph periods at streamflows less than about 700 ft^3/s might improve the transport equations that describe seasonality (fig. 8*C*).

Table 7. Streamflow characteristics at streamflow-gaging station 09260050 Yampa River at Deerlodge Park, Colorado, 1982–94 and 1997–2002.

[Recurrence interval, in years, equals reciprocal of exceedance probability, calculated with annual instantaneous discharge peak; streamflow duration in percentage of time specific discharge is equaled or exceeded, calculated with daily mean discharge; ft^3/s, cubic foot per second; %, percentage]

Recurrence interval of peak discharge		Duration of daily mean discharge	
Recurrence interval (years)	Discharge (ft^3/s)	Duration (% time)	Discharge (ft^3/s)
1.05	4,979	95	128.5
1.11	6,184	90	213.0
1.25	7,963	85	259.7
2	12,550	80	301.8
5	19,040	75	340.6
10	23,350	70	381.5
25	28,710	65	438.5
50	32,620	60	495.5
100	36,450	55	575.8
200	40,230	50	659.1
500	45,160	45	780.1
		40	913.9
		35	1,132.8
		30	1,486.7
		25	2,088.7
		20	2,867.5
		15	4,442.5
		10	6,560.3
		5	9,912.9

Table 8. Summary of discharge and sediment loads by transport mode, particle-size range, and season, 09260050 Yampa River at Deerlodge Park, Colorado, 1982–2001.

[dd mm yy, day month year; ft^3/s, cubic feet per second; tons/d, tons per day; %, percent; <, less than; >, greater than; mm, millimeter; Sand&Gvl, sand and gravel; M&C, medium and coarse; VCS & FG, very coarse sand and fine gravel; nd, no data]

Sample date (dd mm yy)	Instantaneous discharge (ft^3/s)	Hydrograph season	Suspended-sediment load (tons/d)	Bedload (tons/d)	Total sediment load (tons/d)	Bedload percentage of total load (%)	Total load <0.062 mm (tons/d)	Sand&Gvl load >0.062 mm (tons/d)	Suspended load <0.062 mm (tons/d)	Suspended load >0.062 mm (tons/d)	Fine sand 0.062 to <0.250 mm (tons/d)	M&C sand 0.250 to <1.00 mm (tons/d)	VCS & FG 1.00 to >8.00 mm (tons/d)	Remarks
01 Apr 82	1,570	Rising	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	No loads published for April 1
27 Apr 82	7,590	Rising	61,550	1,356	62,906	2.2	40,300	22,606	40,008	21,543	12,220	10,200	194	1982 loads as published
12 May 82	9,410	Falling	45,862	1,525	47,387	3.2	10,900	36,487	10,548	35,314	11,690	23,410	1,374	Peak 7 May 1982
13 May 82	8,820	Falling	22,814	1,934	24,748	7.8	8,940	15,808	8,897	13,917	6,730	8,540	571	
24 May 82	9,700	Falling	26,562	826	27,388	3.0	15,700	11,688	15,672	10,890	8,880	2,745	36	
25 May 82	10,900	Falling	29,827	936	30,763	3.0	18,800	11,963	18,791	11,036	9,960	1,965	69	
08 June 82	9,400	Falling	25,981	1,524	27,505	5.5	5,280	22,225	5,196	20,785	6,340	15,850	80	
24 June 82	10,000	Falling	9,099	1,856	10,955	16.9	4,440	6,515	4,368	4,731	2,620	3,615	280	
25 June 82	9,600	Falling	23,672	4,736	28,408	16.7	4,210	24,198	4,024	19,648	2,740	20,560	862	
07 July 82	6,250	Falling	4,733	2,199	6,932	31.7	2,170	4,762	2,130	2,603	1,679	2,450	636	
08 July 82	6,240	Falling	19,329	1,751	21,080	8.3	1,510	19,570	1,546	17,783	1,080	16,750	1,748	
29 July 82	2,350	Falling	4,460	897	5,357	16.7	3,770	1,587	3,746	714	466	886	336	
23 Feb 83	646	Base flow	234	nd	nd	nd	nd	nd	124	110	nd	nd	nd	No bedload published Feb. 23
10 Mar 83	1,190	Rising	2,675	120	2,795	4.3	2,510	285	2,515	161	138	142	9	1983 loads as published
15 Mar 83	3,480	Rising	51,970	nd	nd	nd	nd	nd	36,899	15,071	nd	nd	nd	No bedload published March 15
29 Mar 83	1,190	Rising	917	139	1,056	13.2	820	236	816	101	72	129	35	
07 Apr 83	930	Rising	1,403	53	1,456	3.6	946	510	912	491	68	438	4	
08 Apr 83	859	Rising	746	72	818	8.8	684	134	686	60	56	70	8	
19 Apr 83	1,210	Rising	2,781	621	3,402	18.3	2,460	942	2,447	334	243	625	76	
21 Apr 83	3,620	Rising	23,869	349	24,218	1.4	15,900	8,318	15,754	8,115	3,140	5,130	47	
22 Apr 83	3,810	Rising	26,810	343	27,153	1.3	21,800	5,353	21,716	5,094	3,680	1,606	53	
07 May 83	6,530	Rising	24,521	1,157	25,678	4.5	17,300	8,378	17,165	7,356	4,250	4,000	163	
09 May 83	6,080	Rising	13,264	1,694	14,958	11.3	9,490	5,468	9,417	3,847	2,650	2,590	246	
12 May 83	11,900	Rising	92,515	1,268	93,783	1.4	60,200	33,583	60,135	32,380	15,710	17,400	545	
23 May 83	8,620	Rising	34,513	1,068	35,581	3.0	27,600	7,981	27,610	6,903	5,670	1,879	409	
26 May 83	15,200	Rising	94,975	989	95,964	1.0	78,200	17,764	77,880	17,096	15,480	2,222	101	
27 May 83	15,800	Rising	87,639	927	88,566	1.0	69,900	18,666	70,111	17,528	16,380	2,180	80	
28 May 83	17,600	Rising	96,073	992	97,065	1.0	70,600	26,465	70,133	25,940	18,070	8,310	48	Peak 31 May 1983
08 June 83	14,400	Falling	39,907	805	40,712	2.0	22,000	18,712	25,940	13,967	8,980	2,619	96	
10 June 83	15,000	Falling	33,115	535	33,650	1.6	26,000	7,650	21,856	11,259	11,530	2,990	167	
21 June 83	15,800	Falling	26,962	1,259	28,221	4.5	16,900	11,321	16,986	9,976	6,280	4,910	101	
23 June 83	15,700	Falling	23,367	634	24,001	2.6	15,400	8,601	15,422	7,945	6,460	2,070	48	
12 July 83	7,180	Falling	10,624	882	11,506	7.7	2,730	8,776	2,656	7,968	2,925	5,760	94	
14 July 83	5,540	Falling	5,667	761	6,428	11.8	2,680	3,748	2,663	3,004	2,085	1,565	98	
02 Aug 83	2,130	Falling	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	No loads published for Aug. 2

Table 8. Summary of discharge and sediment loads by transport mode, particle-size range, and season, 09260050 Yampa River at Deerlodge Park, Colorado, 1982–2001.—Continued

[dd mm yy, day month year; ft³/s, cubic feet per second; tons/d, tons per day; %, percent; <, less than; >, greater than; mm, millimeter; Sand&Gvl, sand and gravel; M&C, medium and coarse; VCS & FG, very coarse sand and fine gravel; nd, no data]

Sample date (dd mm yy)	Instantaneous discharge (ft³/s)	Hydrograph season	Suspended-sediment load (tons/d)	Bedload (tons/d)	Total sediment load (tons/d)	Bedload percentage of total load (%)	Total load <0.062 mm (tons/d)	Sand&Gvl load >0.062 mm (tons/d)	Suspended load <0.062 mm (tons/d)	Suspended load >0.062 mm (tons/d)	Fine sand 0.062 to <0.250 mm (tons/d)	M&C sand 0.250 to <1.00 mm (tons/d)	VCS & FG 1.00 to >8.00 mm (tons/d)	Remarks
26 Oct 93	688	Base flow	526	nd	nd	nd	nd	nd	416	110	nd	nd	nd	No bedload, water year 1994
25 Feb 94	460	Base flow	386	nd	nd	nd	nd	nd	378	7.7	nd	nd	nd	
28 Mar 94	1,150	Rising	517	nd	nd	nd	nd	nd	445	72	nd	nd	nd	
02 May 94	2,770	Falling	3,140	nd	nd	nd	nd	nd	1,319	1,821	nd	nd	nd	Peak 25 April 1994
10 May 94	5,500	Falling	12,300	nd	nd	nd	nd	nd	5,781	6,519	nd	nd	nd	
24 May 94	5,650	Falling	9,030	nd	nd	nd	nd	nd	2,438	6,592	nd	nd	nd	
13 July 94	186	Base flow	10	nd	nd	nd	nd	nd	nd	10	nd	nd	nd	
22 July 94	114	Base flow	4.9	nd	nd	nd	nd	nd	nd	4.9	nd	nd	nd	
28 July 94	111	Base flow	6.3	nd	nd	nd	nd	nd	4.0	2.3	nd	nd	nd	
03 Aug 94	74	Base flow	31	nd	nd	nd	nd	nd	1.9	29	nd	nd	nd	
12 Sept 94	46	Base flow	5.2	nd	nd	nd	nd	nd	nd	5.2	nd	nd	nd	
19 Sept 94	83	Base flow	1,450	nd	nd	nd	nd	nd	1,450	nd	nd	nd	nd	
08 Nov 96	633	Base flow	3,930	nd	nd	nd	nd	nd	3,930	nd	nd	nd	nd	No bedload, water year 1997
20 Mar 97	2,320	Rising	14,500	nd	nd	nd	nd	nd	12,615	1,885	nd	nd	nd	
28 May 97	12,500	Rising	21,400	nd	nd	nd	nd	nd	15,622	5,778	nd	nd	nd	
03 June 97	17,600	Rising	25,500	nd	nd	nd	nd	nd	21,165	4,335	nd	nd	nd	Peak 4 June 1997
19 Aug 97	953	Falling	450	nd	nd	nd	nd	nd	216	234	nd	nd	nd	
17 Nov 97	630	Base flow	65	nd	nd	nd	nd	nd	49	16	nd	nd	nd	No suspended size breaks 1998
05 Mar 98	661	Base flow	269	nd	nd	nd	nd	nd	242	27	nd	nd	nd	No 8-mm bedload sieve
06 May 98	13,500	Rising	48,100	249	48,349	0.5	32,708	15,641	32,708	15,392	nd	nd	nd	
19 May 98	9,940	Rising	16,300	1,100	17,400	6.3	9,617	7,783	9,617	6,683	nd	nd	nd	Peak 22 May 1998
27 May 98	9,460	Falling	36,800	442	37,242	1.2	31,648	5,594	31,648	5,152	nd	nd	nd	
02 June 98	10,200	Falling	10,600	1,285	11,885	10.8	5,936	5,949	5,936	4,664	nd	nd	nd	
03 June 98	10,100	Falling	9,460	1,555	11,015	14.1	4,825	6,190	4,825	4,635	nd	nd	nd	
10 June 98	6,990	Falling	5,270	530	5,800	9.1	3,004	2,796	3,004	2,266	nd	nd	nd	
17 June 98	7,230	Falling	28,900	515	29,415	1.8	23,698	5,717	23,698	5,202	nd	nd	nd	
01 July 98	5,890	Falling	4,710	483	5,193	9.3	1,460	3,733	1,460	3,250	nd	nd	nd	
09 Sept 98	210	Base flow	6.7	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	

Table 8. Summary of discharge and sediment loads by transport mode, particle-size range, and season, 09260050 Yampa River at Deerlodge Park, Colorado, 1982–2001.—Continued

[dd mm yy, day month year; ft³/s, cubic feet per second; tons/d, tons per day; %, percent; <, less than; >, greater than; mm, millimeter; Sand&Gvl, sand and gravel; M&C, medium and coarse; VCS & FG, very coarse sand and fine gravel; nd, no data]

Sample date (dd mm yy)	Instantaneous discharge (ft^3/s)	Hydrograph season	Suspended-sediment load (tons/d)	Bedload (tons/d)	Total sediment load (tons/d)	Bedload percentage of total load (%)	Total load <0.062 mm (tons/d)	Sand&Gvl load >0.062 mm (tons/d)	Suspended load <0.062 mm (tons/d)	Suspended load >0.062 mm (tons/d)	Fine sand 0.062 to <0.250 mm (tons/d)	M&C sand 0.250 to <1.00 mm (tons/d)	VCS & FG 1.00 to >8.00 mm (tons/d)	Remarks
04 Mar 99	1,400	Rising	5,180	nd	nd	nd	nd	nd	4,766	414	nd	nd	nd	
30 Mar 99	2,300	Rising	2,400	1,013	3,413	29.7	1,824	1,589	1,824	576	161	920	508	
19 May 99	5,690	Rising	7,650	745	8,395	8.9	3,825	4,570	3,825	3,825	1,636	2,792	142	
25 May 99	12,600	Rising	49,000	3,547	52,547	6.8	26,460	26,087	26,460	22,540	9,835	12,163	4,088	
27 May 99	12,800	Rising	30,700	337	31,037	1.1	17,499	13,538	17,499	13,201	11,062	2,317	158	
02 June 99	12,700	Falling	20,500	124	20,624	0.6	9,430	11,194	9,430	11,070	9,657	1,527	10	Peak 1 June 1999
23 June 99	7,840	Falling	4,950	895	5,845	15.3	2,475	3,370	2,475	2,475	810	2,310	251	
21 Oct 99	410	Base	20	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	
1 Mar 00	641	Base	59	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	
05 Apr 00	1,240	Rising	609	255	864	29.5	370	494	370	239	58	332	104	
19 Apr 00	3,980	Rising	8,030	162	8,192	2.0	5,629	2,563	5,629	2,401	1,358	1,137	67	
03 May 00	7,780	Rising	16,400	1,047	17,447	6.0	8,086	9,361	8,085	8,315	4,939	4,031	391	
05 July 00	645	Falling	1,920	178	2,098	8.5	35	2,063	35	1,885	342	1,668	53	Peak 31 May 2000
15 Dec 00	456	Base	9	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	
12 June 01	3,470	Fall	600	381	981	38.8	600	381	600	0	34	335	11	Peak 18 May 2001
13 June 01	3,300	Fall	1,890	650	2,540	25.6	548	1,992	548	1,342	940	1,032	19	
19 June 01	1,700	Fall	1,650	226	1,876	12.1	165	1,711	165	1,485	325	1,380	7	
20 June 01	1,650	Fall	276	163	439	37.1	152	287	152	124	120	164	3	

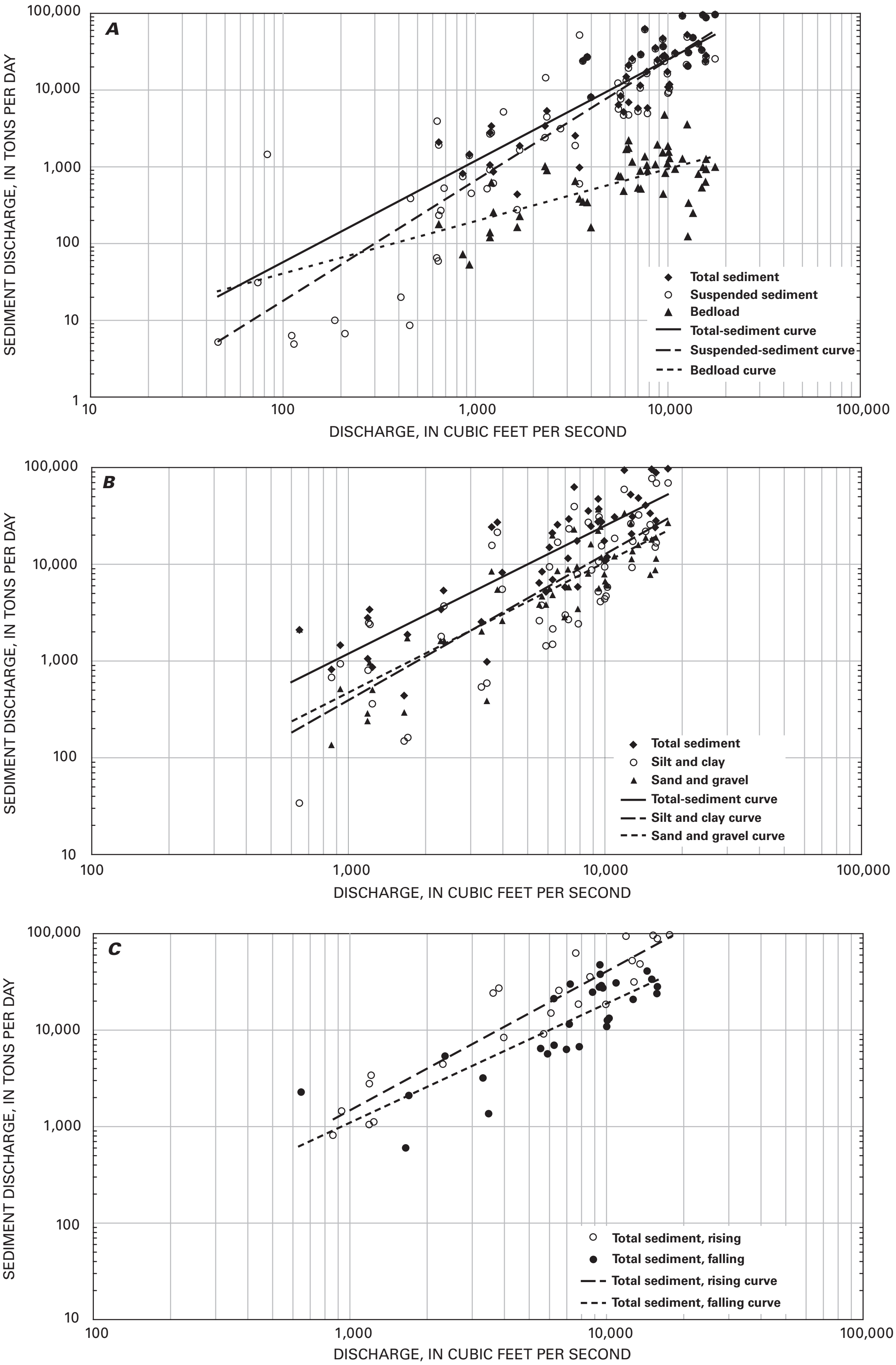

Figure 8. Relation of sediment load at 09260050 Yampa River at Deerlodge Park, Colorado, 1982–2001, *A*, to water discharge; *B*, by particle size to water discharge; and *C*, by season to water discharge.

Table 9. Sediment-transport equations derived from sediment discharges measured at station 09260050 Yampa River at Deerlodge Park, Colorado, 1982–2001.

[Q_s, sediment discharge in tons per day; Q, water discharge in cubic feet per second; R^2, coefficient of determination; MSE, mean square error; n, number of samples]

Type of sediment discharge	Regression equation	R^2	MSE	n
Total	$Q_s = 0.129\ Q^{1.32}$	0.72	0.534	53
Suspended	$Q_s = 0.129\ Q^{1.57}$	0.80	1.40	79
Bedload	$Q_s = 1.75\ Q^{0.682}$	0.40	0.573	53
Silt and clay	$Q_s = 0.0117\ Q^{1.51}$	0.63	1.08	53
Sand and gravel	$Q_s = 0.0435\ Q^{1.34}$	0.74	0.523	53
Fine sand	$Q_s = 0.00474\ Q^{1.77}$	0.80	0.700	45
Medium and coarse sand	$Q_s = 0.252\ Q^{1.05}$	0.51	0.951	45
Very coarse sand and fine gravel	$Q_s = 0.0904\ Q^{0.816}$	0.23	2.05	45
Total, rising	$Q_s = 0.0697\ Q^{1.44}$	0.89	0.280	24
Total, falling	$Q_s = 0.218\ Q^{1.23}$	0.68	0.424	29

Green River above Gates of Lodore, Colorado

Site Description

Streamflow was recorded at streamflow-gaging station 09234500 Green River near Greendale, Utah, 0.5 mi downstream from Flaming Gorge Dam. The gage is located at latitude 40°54'30", longitude 109°25'20", in sec. 15, T. 2 N., R. 22 E., Daggett County, Utah, 2 mi south of Dutch John. Drainage area at the streamflow-gaging station is approximately 19,350 mi^2.

Sediment data were collected at a site (404417108524900 Green River above Gates of Lodore) near the National Park Service Gates of Lodore Ranger Station, approximately 46 river miles downstream from the streamflow-gaging station. The sediment-sampling site is located at latitude 40°44'17", longitude 108°52'49", in NE1/4 SE1/4 sec. 17, T. 9 N., R. 102 W., Moffat County, Colorado, 0.8 mi upstream from the ranger station and 18 mi west of Greystone. Because of the great distance between the streamflow-gaging station and the sediment-sampling site, water-discharge measurements were made each time suspended sediment and bedload were sampled. Drainage area at the sediment sampling site is undetermined.

The sediment-sampling site is downstream from Browns Park (fig. 1), a low-gradient reach through a relatively wide valley, and just upstream from the beginning of Lodore Canyon, where the river gradient increases abruptly (fig. 5*C*). Sediment samples were collected from a boat at most streamflows and by wading at low streamflows.

Streamflow and Sediment Data

Discharge measured at the gaging station downstream from Flaming Gorge Dam has been entirely regulated since the dam was completed in November 1962. Consequently, no peak-flow statistics have been computed for the regulated-flow period. However, streamflow-duration statistics are presented in table 10 for comparison to other sites in this report. Sediment-load data are presented in table 11. Plots of the sediment-load data are presented in figure 9.

Analysis

Streamflow data have been collected 0.5 mi downstream from Flaming Gorge Dam at streamflow-gaging station 09234500 Green River, near Greendale, Utah, since October 1950. Before the completion of Flaming Gorge Dam in November 1962, annual instantaneous discharge peaks ranged from 4,660 ft^3/s in 1961 to 19,600 ft^3/s in 1957. Since the dam was completed, annual instantaneous peak discharges released from the dam have ranged from 833 ft^3/s in 1963 and 1964 to 13,700 ft^3/s in 1983 (Crowfoot and others, 2002). Baseflow conditions at this site are determined by reservoir releases and are greater than would be anticipated for an unregulated river. For comparative purposes, the streamflow equaled or exceeded 50 percent of the time is 1,802.5 ft^3/s (table 10).

Table 10. Streamflow characteristics at streamflow-gaging station 09234500 Green River near Greendale, Utah, 1963–2002.

[Recurrence interval, in years, equals reciprocal of exceedance probability, calculated with annual instantaneous discharge peak; streamflow duration in percentage of time specific discharge is equaled or exceeded, calculated with daily mean discharge; ft^3/s, cubic foot per second; %, percentage]

Recurrence interval of peak discharge		Duration of daily mean discharge	
Recurrence interval (years)	Discharge (ft^3/s)	Duration (% time)	Discharge (ft^3/s)
Instantaneous discharge peaks entirely controlled by Flaming Gorge Dam immediately upstream		95	763.8
		90	830.0
		85	896.2
		80	986.5
		75	1,081.6
		70	1,216.9
		65	1,354.1
		60	1,493.0
		55	1,646.0
		50	1,802.5
		45	1,985.4
		40	2,169.5
		35	2,352.8
		30	2,536.2
		25	2,767.3
		20	3,005.6
		15	3,331.7
		10	3,700.4
		5	4,209.3

Table 11. Summary of discharge and sediment loads by transport mode, particle-size range, and season, 404417108524900 Green River above Gates of Lodore, Colorado, 1999–2002.

[Instantaneous discharge from streamflow-gaging station 09234500 Green River near Greendale, Utah, 46 river miles upstream; dd mm yy, day month year; ft^3/s, cubic feet per second; tons/d, tons per day; %, percent; <, less than; >, greater than; mm, millimeter; Sand&Gvl, sand and gravel; M&C, medium and coarse; VCS & FG, very coarse sand and fine gravel; Susp Sed, suspended sediment; nd, no data]

Sample date (dd mm yy)	Instantaneous discharge (ft^3/s)	Hydrograph season	Suspended-sediment load (tons/d)	Bedload (tons/day)	Total sediment load (tons/d)	Bedload percentage of total load (%)	Total load <0.062 mm (tons/d)	Sand&Gvl load >0.062 mm (tons/d)	Suspended load <0.062 mm (tons/d)	Suspended load >0.062 mm (tons/d)	Fine sand 0.062 to <0.250 mm (tons/d)	M&C sand 0.250 to <1.00 mm (tons/d)	VCS & FG 1.00 to >8.00 mm (tons/d)	Remarks
24 May 99	4,550	Early	1,880	420	2,300	18.3	793	1,507	793	1,087	nd	nd	nd	
26 May 99	6,230	Early	17,000	726	17,726	4.1	2,193	15,533	2,193	14,807	nd	nd	nd	
26 May 99	6,230	Early	7,320	527	7,847	6.7	1,632	6,215	1,632	5,688	nd	nd	nd	
27 May 99	6,230	Early	4,140	487	4,627	10.5	1,755	2,871	1,755	2,385	nd	nd	nd	
31 May 99	6,000	Early	3,810	426	4,236	10.1	1,353	2,884	1,353	2,457	nd	nd	nd	
31 May 99	6,000	Early	6,080	386	6,466	6.0	1,192	5,274	1,192	4,888	nd	nd	nd	
1 June 99	6,000	Early	3,290	772	4,062	19.0	1,047	3,015	1,046	2,244	nd	nd	nd	Yampa peak 1 June 1999
4 June 99	8,370	Early	6,170	518	6,688	7.8	2,332	4,356	2,332	3,838	nd	nd	nd	
7 June 99	8,270	Early	10,700	304	11,004	2.8	1,487	9,517	1,487	9,213	nd	nd	nd	
7 June 99	8,270	Early	5,810	718	6,528	11.0	1,621	4,907	1,621	4,189	nd	nd	nd	
8 June 99	8,270	Early	10,500	700	11,200	6.3	1,366	9,835	1,365	9,135	nd	nd	nd	
15 June 99	10,200	Late	5,890	533	6,423	8.3	1,673	4,750	1,673	4,217	nd	nd	nd	Daily peak June 12–20, 1999
15 June 99	10,200	Late	6,170	657	6,827	9.6	1,505	5,321	1,505	4,665	nd	nd	nd	Daily peak June 12–20, 1999
17 June 99	10,200	Late	24,300	310	24,610	1.3	13,268	11,341	13,268	11,032	nd	nd	nd	Daily peak June 12–20, 1999
17 June 99	10,200	Late	7,630	331	7,961	4.2	3,289	4,672	3,289	4,341	nd	nd	nd	Daily peak June 12–20, 1999
18 June 99	10,250	Late	7,970	617	8,587	7.2	2,024	6,562	2,024	5,946	nd	nd	nd	Daily peak June 12–20, 1999
22 June 99	8,730	Late	3,180	337	3,517	9.6	999	2,519	999	2,181	nd	nd	nd	
23 June 99	7,140	Late	2,310	453	2,763	16.4	822	1,941	822	1,488	nd	nd	nd	
04 Apr 00	2,350	Early	362	196	558	35.1	221	337	221	141	255	202	100	
18 Apr 00	1,920	Early	373	336	709	47.4	317	392	317	56	318	281	54	
02 May 00	2,220	Early	270	248	518	47.9	188	330	188	82	226	149	143	Daily peak 24 May 2000
01 June 00	4,830	Late	2,060	666	2,726	24.4	631	2,095	630	1,430	1,045	1,525	156	Yampa peak 31 May 2000
06 July 00	1,340	Late	98	114	212	53.8	72	140	72	26	72	77	37	
15 May 01	2,980	Early	4,390	1,034	5,424	19.1	1,141	4,283	1,141	3,249	nd	nd	nd	No Susp Sed size data
16 May 01	3,340	Early	10,200	812	11,012	7.4	2,040	8,972	2,040	8,160	nd	nd	nd	No Susp Sed size data
24 May 01	4,300	Late	1,730	426	2,156	19.8	554	1,602	554	1,176	381	1,090	132	Yampa Peak 18 May 2001
25 May 01	3,660	Late	4,750	580	5,330	10.9	428	4,903	428	4,323	143	3,400	220	
28 May 01	2,270	Late	478	372	850	43.8	167	683	167	311	33	523	126	
03 Apr 02	916	Early	92	59	151	39.2	82	68	82	9	nd	nd	nd	No Susp Sed size data
15 May 02	811	Early	31	93	124	75.2	21	103	21	10	nd	nd	nd	No Susp Sed size data
21 May 02	3,930	Early	2,980	283	3,263	8.7	1,579	1,684	1,579	1,401	807	791	79	
05 June 02	859	Late	216	188	404	46.5	28	376	28	188	2	282	83	Yampa Peak 2 June 2002

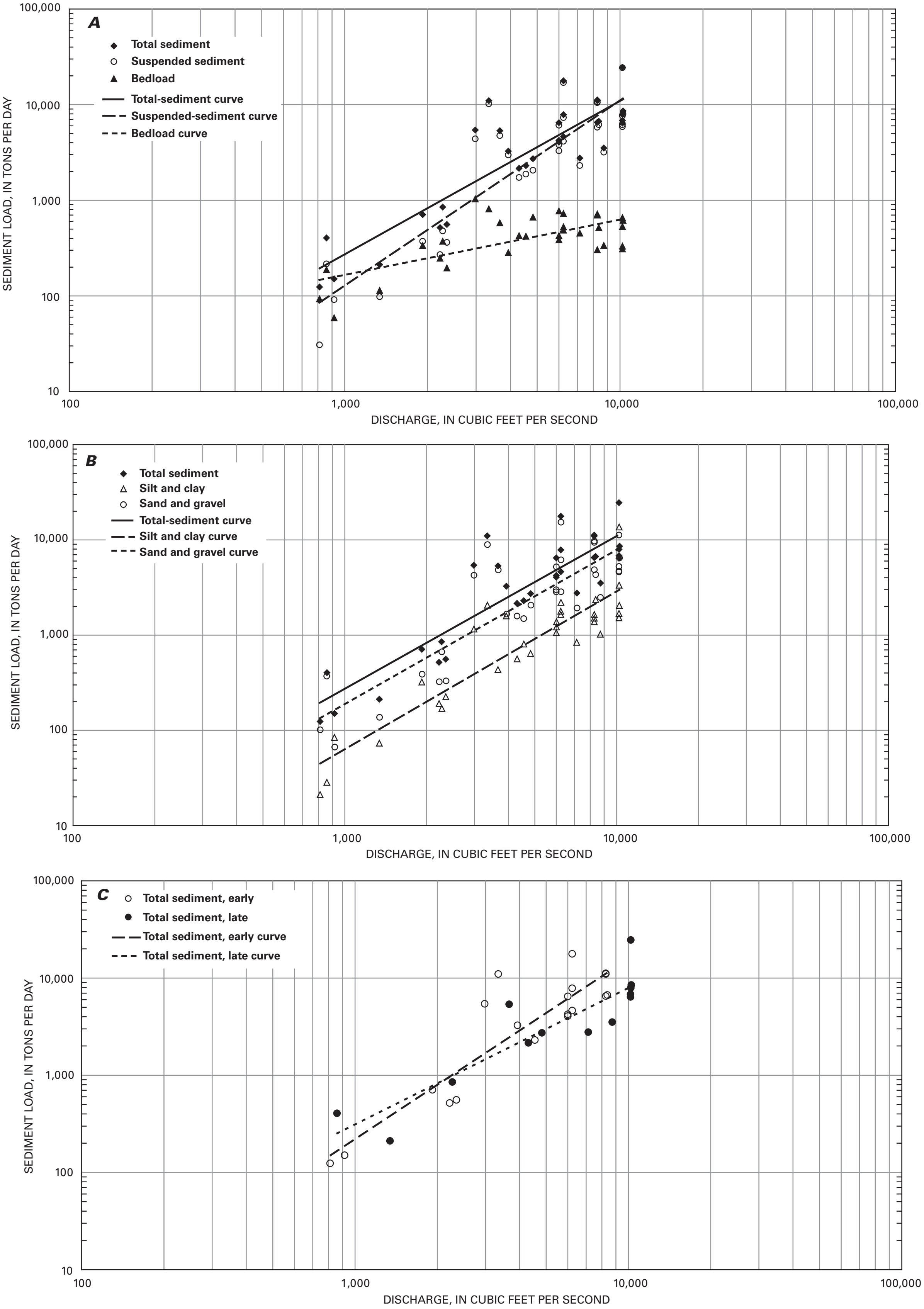

Figure 9. Relation of sediment load at 404417108524900 Green River above Gates of Lodore, Colorado, 1999–2002, *A*, to water discharge; *B*, by particle size to water discharge; and *C*, by season to water discharge.

Sediment and water-discharge measurements were made 46 river miles downstream from the dam and streamflow-gaging station in 1999 through 2002 (table 11). Annual instantaneous discharge peaks for the years when sediment measurements were made ranged from 4,050 ft^3/s in 2002 to 11,200 ft^3/s in 1999 (Crowfoot and others, 2002). Suspended and bedload sediment was measured 32 times at discharges ranging from 811 to 10,250 ft^3/s. There is little hydrograph seasonality at this site because main-stem streamflow is almost completely regulated by Flaming Gorge Reservoir. However, to test for possible seasonal hysteresis in sediment loads originating upstream from the dam and in tributaries entering downstream from the dam in the 46-mi reach upstream from the Lodore Ranger Station, the data were subdivided into "early" and "late" periods based on the rising-limb and falling-limb seasons of the Yampa River at Deerlodge Park. This subdivision resulted in 19 early season and 13 late season sediment measurements at the Gates of Lodore site.

Bedload as a percentage of total-sediment load ranged from 1.3 to 75.2 percent with the higher percentages generally occurring at lesser discharges and averaged 19.9 percent. Bedload was greater than suspended-sediment load for two of eight measurements made at discharges less than about 2,400 ft^3/s. The wide range in bedload as a percentage of total load may be a reflection of the widely different streamflow magnitudes occurring when sediment was sampled. Water discharge and, consequently, suspended- and total-sediment loads, were much greater in 1999 than in other years.

Sediment-transport equations for total-sediment load, suspended-sediment load, silt-and-clay load, and sand-and-gravel load had R^2 values of 0.74 or greater (table 12) and indicate that these transport equations may be useful for annual load estimation or sediment budget calculations for discharges ranging from about 800 to 10,000 ft^3/s. The equation for bedload had an R^2 value of 0.47, possibly due to a relatively small range in bedload magnitude typical of river reaches with a limited supply of transportable bed material, such as rivers downstream from dams. The seasonal transport equations (early and late) had R^2 values of 0.81 but were based on small numbers of samples and, therefore, may not accurately reflect true seasonal conditions. One-half of the sediment measurements were made at discharges greater than 6,000 ft^3/s (fig. 9), streamflows that occur less than 5 percent of the time at this site (table 10). Additional sediment measurements made at less than about 3,000 ft^3/s or greater than 10,000 ft^3/s in both the early and late seasons would make the seasonal transport equations more representative of conditions at this site. Additional measurements also might result in a better understanding of the variation in dominant transport mode (bedload compared to suspended load) for a wide range of streamflows.

Table 12. Sediment-transport equations derived from sediment discharges measured at station 404417108524900 Green River above Gates of Lodore, Colorado, 1999–2002.

[Q_s, sediment discharge in tons per day; Q, water discharge in cubic feet per second; R^2, coefficient of determination; MSE, mean square error; n, number of samples; early and late hydrograph seasons at this site arbitrarily based on the rising and falling hydrograph seasons at Yampa River at Deerlodge Park]

Type of sediment discharge	Regression equation	R^2	MSE	n
Total	$Q_s = 0.00419\ Q^{1.60}$	0.78	0.434	32
Suspended	$Q_s = 0.000198\ Q^{1.94}$	0.80	0.584	32
Bedload	$Q_s = 3.04\ Q^{0.578}$	0.47	0.230	32
Silt and clay	$Q_s = 0.000689\ Q^{1.65}$	0.81	0.378	32
Sand and gravel	$Q_s = 0.00259\ Q^{1.62}$	0.74	0.548	32
Total, early	$Q_s = 0.000620\ Q^{1.85}$	0.81	0.432	19
Total, late	$Q_s = 0.0190\ Q^{1.40}$	0.81	0.360	13

Green River near Jensen, Utah

Site Description

Streamflow was recorded at streamflow-gaging station 09261000 Green River near Jensen, Utah. The gage is located at latitude 40°24'34", longitude 109°14'05", in sec. 5, T. 5 S., R. 24 E., Uintah County, 300 ft upstream from the county road bridge, 6.5 mi northeast of Jensen. Sediment measurements were made from the county road bridge or from the cableway at the gage in 1996 and 1998. During 1999 through 2002, all sediment measurements were made from a boat at a site approximately 1 mi upstream from the gage. The sampling site is in a broad alluvial valley just downstream from the mouth of Split Mountain Canyon, a steep, confined reach (figs. 1, 2). Drainage area at the gaging station is approximately 29,660 mi^2.

Streamflow data have been collected at gaging station 09261000 Green River near Jensen, Utah, since October 1946. Streamflow at the Jensen site has been partly regulated by Flaming Gorge Reservoir, 93 river miles upstream, since November 1962; however, the streamflow of the Yampa River, which joins the Green River 28 mi upstream from the Jensen site, has remained largely unregulated and has a strong effect on the hydrograph at the Jensen site.

Streamflow and Sediment Data

Streamflow characteristics from discharge data collected at the streamflow-gaging station since completion of Flaming Gorge Dam in 1962 are presented in table 13, and sediment-load data are presented in table 14. Plots of the sediment-load data are presented in figure 10.

Analysis

Representative peak-flow or streamflow-duration statistics for both the pre-dam period (1947–62) and the post-dam period (1963–present) are presented in table 13. Annual instantaneous discharge peaks ranged from 11,900 ft^3/s in 1955 to 36,500 ft^3/s in 1957 during the pre-dam period.

Table 13. Streamflow characteristics at streamflow-gaging station 09261000 Green River near Jensen, Utah, 1947–62 and 1963–2002.

[Recurrence interval, in years, equals reciprocal of exceedance probability, calculated with annual instantaneous discharge peak; streamflow duration in percentage of time specific discharge is equaled or exceeded, calculated with daily mean discharge; ft^3/s, cubic foot per second; %, percentage]

Recurrence interval of peak discharge			Duration of daily mean discharge		
Recurrence interval (years)	Pre-dam discharge 1947–62 (ft^3/s)	Post-dam discharge 1963–2002 (ft^3/s)	Duration (% time)	Pre-dam discharge 1947–62 (ft^3/s)	Post-dam discharge 1963–2002 (ft^3/s)
1.05	12,320	8,184	95	722.0	1,143.7
1.11	14,390	9,673	90	831.0	1,354.8
1.25	17,190	11,740	85	923.2	1,541.4
2	23,410	16,560	80	1,006.1	1,736.7
5	30,610	22,580	75	1,095.6	1,934.9
10	34,690	26,220	70	1,187.9	2,132.7
25	39,200	30,460	65	1,301.4	2,352.5
50	42,180	33,390	60	1,434.9	2,564.2
100	44,880	36,140	55	1,599.7	2,755.7
200	47,350	38,750	50	1,780.4	2,956.2
500	50,340	42,020	45	2,024.1	3,194.0
			40	2,308.1	3,453.6
			35	2,769.5	3,791.8
			30	3,652.0	4,186.7
			25	5,116.7	4,650.7
			20	7,048.3	5,360.2
			15	9,586.6	6,936.2
			10	12,744.4	9,724.2
			5	18,021.2	13,006.6

Annual instantaneous discharge peaks since Flaming Gorge Dam was constructed have ranged from 7,090 ft^3/s in 1989 to 40,000 ft^3/s in 1984 (Crowfoot and others, 2002). Base-flow conditions since 1963 occur at discharges of less than about 3,500 to 3,800 ft^3/s and are equaled or exceeded about 35 to 40 percent of the time (table 13).

Suspended sediment was measured 218 times at gaging station 09261000 from 1948 through 1979, 161 times before October 1962, and 57 times since October 1962. Suspended sediment and bedload sediment were measured in 1996 and from 1998 through 2002 as part of this study (table 14). Annual instantaneous discharge peaks for the years when the more recent sediment measurements were made ranged from 7,570 ft^3/s in 2002 to 22,400 ft^3/s in 1996. Forty suspended-sediment and 40 bedload measurements were made at discharges ranging from 965 to 22,000 ft^3/s during the more recent sampling period beginning in 1996. These data included 18 measurements during the rising-limb hydrograph season and 18 measurements during the recessional- or falling-limb hydrograph season. Bedload as a percentage of total-sediment load ranged from 0.1 to 29.9 percent and averaged 4.0 percent.

Sediment-transport equations for total-sediment, suspended-sediment, and transport by all particle-size ranges except medium and coarse sand and very coarse sand and gravel had R^2 values of 0.75 or greater (table 15) and may be useful for annual load estimations or sediment budget calculations for discharges ranging from about 1,000 to 22,000 ft^3/s. The equation for bedload transport had an R^2 value of 0.54, the equation for medium and coarse sand had an R^2 value of 0.64, and the equation for very coarse sand and gravel had an R^2 value of 0.40. Rising-limb and falling-limb seasonal equations had R^2 values of 0.77 and 0.90, respectively, but these equations were based on relatively small numbers of samples (18 for each equation).

Andrews (1986) evaluated the earlier suspended-sediment data at the Jensen site and derived regression equations for several suspended particle-size ranges for both pre-dam and post-dam periods. Andrews' equation for "all (suspended) sizes" in the post-dam period (1963–79) was:

$$Q_s = 0.0172\, Q^{1.56} \tag{3}$$

where

Q_s is suspended-sediment discharge, in tons per day;

and

Q is water discharge, in cubic feet per second.

Andrews' equation was derived from 57 measurements and had a correlation coefficient of 0.62 (or $R^2 = 0.38$). By comparison, the suspended-sediment transport equation derived from the 40 measurements made since 1996 in this study (table 15) has a slightly steeper slope (2.00), a smaller intercept, and, based on the R^2 value, much less variance.

Possible explanations for the difference between the 1963–79 and 1996–2002 transport equations could include climate and land-use changes, a change in the availability of transportable sediment, or a change in Flaming Gorge reservoir operation between the two periods.

Table 14. Summary of discharge and sediment loads by transport mode, particle-size range, and season, 09261000 Green River near Jensen, Utah, 1996–2002.

[dd mm yy, day month year; ft^3/s, cubic feet per second; tons/d, tons per day; %, percent; <, less than; >, greater than; mm, millimeter; Sand&Gvl, sand and gravel; M&C, medium and coarse; VCS & FG, very coarse sand and fine gravel; Susp Sed, suspended sediment; nd, no data]

Sample date (dd mm yy)	Instantaneous discharge (ft^3/s)	Hydrograph season	Suspended-sediment load (tons/d)	Bedload (tons/d)	Total sediment load (tons/d)	Bedload percentage of total load (%)	Total load <0.062 mm (tons/d)	Sand&Gvl load >0.062 mm (tons/d)	Suspended load <0.062 mm (tons/d)	Suspended load >0.062 mm (tons/d)	Fine sand 0.062 to <0.250 mm (tons/d)	M&C sand 0.250 to <1.00 mm (tons/d)	VCS & FG 1.00 to >8.00 mm (tons/d)	Remarks
30 Apr 96	9,580	Rising	14,100	nd	nd	nd	nd	nd	6,768	7,332	nd	nd	nd	No bedload sample 30 April 1996
07 May 96	12,000	Rising	26,300	98	26,398	0.7	14,729	11,669	14,728	11,572	8,093	3,572	5	Mean of 7 suspended measurements
10 May 96	14,900	Rising	31,900	780	32,680	2.4	17,545	15,135	17,545	14,355	9,912	5,082	140	Mean of 7 suspended measurements
16 May 96	18,500	Rising	32,800	519	33,319	1.6	20,008	13,311	20,008	12,792	9,856	3,388	67	All 1996 measurements from bridge
20 May 96	22,000	Falling	41,200	477	41,677	1.1	25,132	16,545	25,132	16,068	11,138	5,340	67	Mean of 7 suspended measurements
23 May 96	16,000	Falling	20,100	285	20,385	1.4	9,648	10,737	9,648	10,452	7,448	3,263	26	
03 June 96	12,800	Falling	8,020	199	8,219	2.4	4,331	3,888	4,331	3,689	2,889	971	28	Mean of 7 suspended measurements
27 June 96	9,380	Falling	5,930	121	6,051	2.0	2,906	3,145	2,906	3,024	2,377	758	11	
01 July 96	6,610	Falling	3,030	41	3,071	1.3	1,576	1,495	1,576	1,454	1,243	250	2	
13 Aug 96	1,770	Base flow	64.0	1.4	65.4	2.2	nd	nd	nd	nd	nd	nd	nd	No suspended sand break analysis
07 May 98	15,700	Rising	44,900	25	44,925	0.1	28,736	16,189	28,736	16,164	nd	nd	nd	No suspended size fractions, 1998
20 May 98	13,700	Rising	24,400	285	24,685	1.2	15,860	8,825	15,860	8,540	nd	nd	nd	8 measurements made from bridge
28 May 98	13,400	Falling	16,000	263	16,263	1.6	8,800	7,463	8,800	7,200	nd	nd	nd	Peak 24 May 1998
01 June 98	14,700	Falling	15,600	188	15,788	1.2	8,268	7,520	8,268	7,332	nd	nd	nd	
04 June 98	14,400	Falling	12,700	178	12,878	1.4	8,001	4,877	8,001	4,699	nd	nd	nd	
09 June 98	11,200	Falling	9,560	886	10,446	8.5	5,832	4,615	5,832	3,728	nd	nd	nd	Bedload sampled 0.5 mile upstream
11 June 98	11,100	Falling	8,480	190	8,670	2.2	4,664	4,006	4,664	3,816	nd	nd	nd	
18 June 98	10,300	Falling	27,000	144	27,144	0.5	23,490	3,654	23,490	3,510	nd	nd	nd	Snowmelt
30 June 98	8,010	Falling	3,500	94	3,594	2.6	1,960	1,634	1,960	1,540	nd	nd	nd	
31 Mar 99	5,520	Rising	6,100	402	6,502	6.2	3,111	3,391	3,111	2,989	1,963	1,424	4	All 1999 measurements from boat
20 May 99	10,800	Rising	9,650	413	10,063	4.1	5,404	4,659	5,404	4,246	2,836	1,778	45	
25 May 99	18,300	Rising	46,000	1,145	47,145	2.4	29,900	17,245	29,900	16,100	12,040	4,998	206	Sedigraph analysis
28 May 99	19,700	Rising	37,200	788	37,988	2.1	20,832	17,156	20,832	16,368	9,735	7,326	95	Sedigraph analysis
02 June 99	20,400	Falling	29,200	597	29,797	2.0	16,060	13,737	16,060	13,140	9,672	3,928	137	Sedigraph analysis, peak 2 June 2000
24 June 99	13,800	Falling	10,600	140	10,740	1.3	4,452	6,288	4,452	6,148	5,101	1,175	13	
06 Apr 00	3,360	Rising	735	18	753	2.4	623	130	623	112	113	16	0.4	
20 Apr 00	6,270	Rising	15,659	108	15,767	0.7	9,693	6,074	9,693	5,966	5,067	1,006	0.2	
03 May 00	8,910	Rising	15,733	1,500	18,733	8.0	8,891	9,842	8,889	6,844	3,834	4,489	20	
02 June 00	16,000	Falling	22,939	1,783	24,722	7.2	10,300	14,422	10,300	12,639	7,558	6,432	431	Daily mean peak 1 June 2000
05 July 00	2,160	Base flow	321	39	360	10.9	188	172	188	133	74	94	4	
26 Mar 01	3,500	Rising	11,700	56	11,756	0.5	10,296	1,460	10,296	1,404	nd	nd	nd	Questionable bedload size
05 Apr 01	4,170	Rising	nd	59	nd	nd	nd	nd	nd	nd	nd	nd	nd	Susp Sed sample contaminated
17 Apr 01	2,600	Rising	878	14	892	1.6	834	58	834	44	nd	nd	nd	No Susp Sed size data
13 June 01	4,650	Falling	1,160	115	1,275	9.0	684	591	684	476	245	221	44	
19 June 01	2,590	Falling	266	114	380	29.9	218	161	218	48	nd	nd	nd	No Susp Sed size data
02 Apr 02	2,470	Rising	3,550	128	3,678	3.5	3,408	270	3,408	142	112	153	5	
23 Apr 02	3,080	Rising	3,680	106	3,786	2.8	1,509	2,277	1,509	2,171	75	1,779	19	
14 May 02	2,700	Rising	561	64	625	10.2	544	81	544	17	18	55	8	
22 May 02	6,960	Rising	15,200	272	15,472	1.8	5,776	9,696	5,776	9,424	3,667	5,383	38	
04 June 02	4940	Falling	2,650	234	2,884	8.1	1,935	950	1,935	716	571	367	12	
03 July 02	965	Base flow	37	3	40	8.1	33	6	33	3	nd	nd	nd	No Susp Sed size data

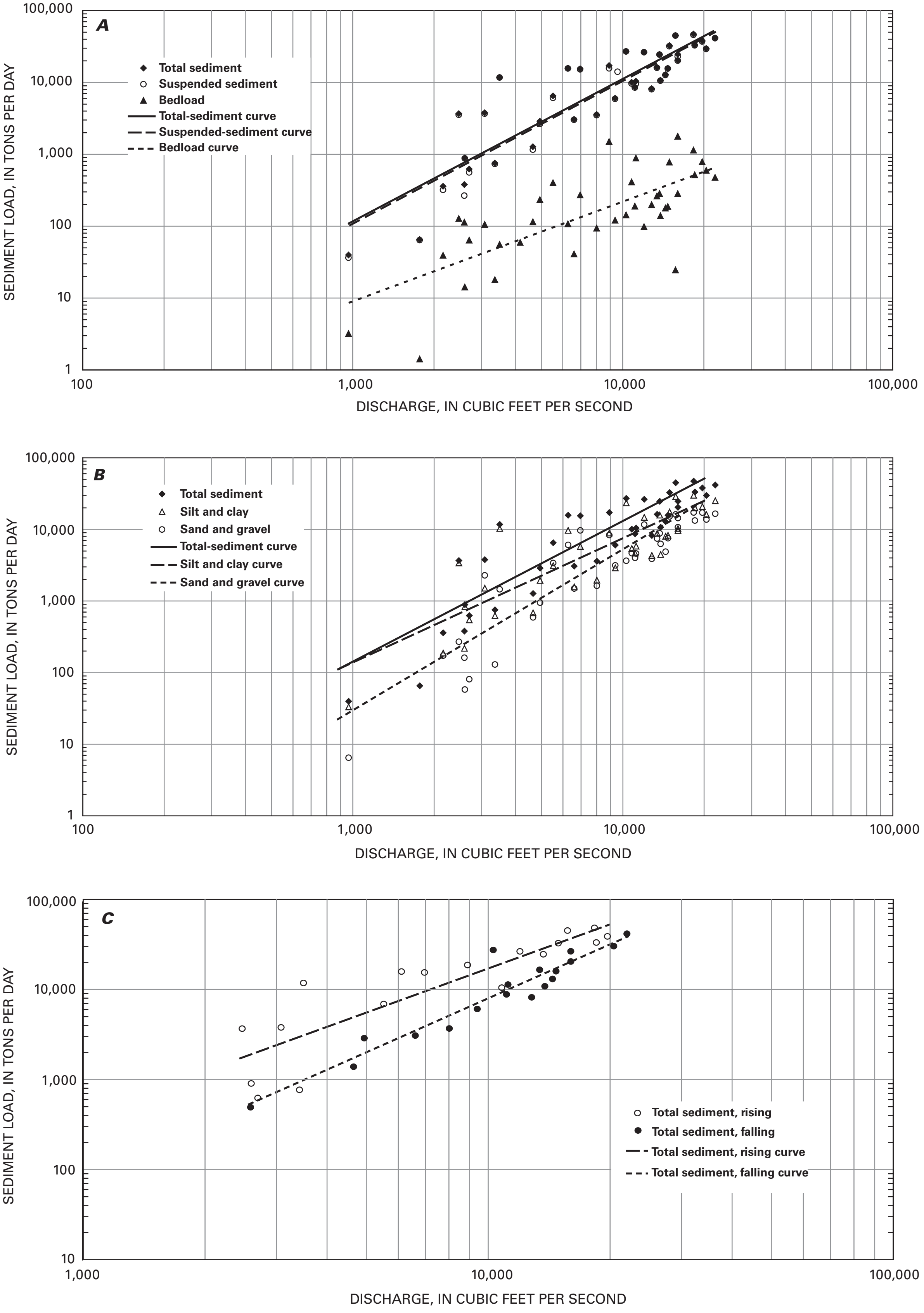

Figure 10. Relation of sediment load at 09261000 Green River near Jensen, Utah, 1996–2002, *A*, to water discharge; *B*, by particle size to water discharge; and *C*, by season to water discharge.

Table 15. Sediment-transport equations derived from sediment discharges measured at station 09261000 Green River near Jensen, Utah, 1996–2002.

[Q_s, sediment discharge in tons per day; Q, water discharge in cubic feet per second; R^2, coefficient of determination; MSE, mean square error; n, number of samples]

Type of sediment discharge	Regression equation	R^2	MSE	n
Total	$Q_s = 0.000146\ Q^{1.97}$	0.81	0.608	39
Suspended	$Q_s = 0.000104\ Q^{2.00}$	0.81	0.620	40
Bedload	$Q_s = 0.000621\ Q^{1.38}$	0.54	1.08	40
Silt and clay	$Q_s = 0.000779\ Q^{1.73}$	0.75	0.625	38
Sand and gravel	$Q_s = 0.00000438\ Q^{2.25}$	0.85	0.574	38
Fine sand	$Q_s = 0.000000377\ Q^{2.47}$	0.86	0.532	25
Medium and coarse sand	$Q_s = 0.0000739\ Q^{1.83}$	0.64	1.04	25
Very coarse sand and fine gravel	$Q_s = 0.0000110\ Q^{1.58}$	0.40	2.10	25
Total, rising	$Q_s = 0.00483\ Q^{1.64}$	0.77	0.487	18
Total, falling	$Q_s = 0.0000802\ Q^{2.00}$	0.90	0.140	18

Summary and Conclusions

Large amounts of sediment are stored in the lower Little Snake, lower Yampa, and lower Green Rivers in the form of alluvial banks, bars, and islands. These near-channel areas may be important secondary sources of sediment that periodically are entrained by the Green River and its larger tributaries. Aerial photographs made in 1988 of the channels of the Little Snake River downstream from the Lily streamflow-gaging station 09260000, the Yampa River downstream from Cross Mountain, and the Green River from the Lodore Ranger Station to Jensen were assessed to determine the relative abundance of alluvial deposits in the banks and bars. The relative abundance of subaerial alluvial deposits in the photographs varied from river to river in the watershed and from subreach to subreach along a river. Although the flood-plain width was relatively narrow and the surface area of alluvial deposits was small, the Little Snake River, a few miles downstream from the Lily streamflow-gaging station, had a consistently high percentage of alluvial deposits along its boundaries.

The large sediment yield of the Little Snake River is reflected in the increase in relative abundance of alluvial deposits in the Yampa River immediately downstream from the Little Snake River confluence. The relative abundance of alluvial material decreases abruptly from more than 80 percent to less than 20 percent as the Yampa River flows into the steep and narrow Yampa Canyon. Alluvial deposits are relatively scarce in Yampa Canyon between river miles 45 and 21. The canyon geomorphology in this reach is dominated by the massive limestone of the Morgan Formation; also, the river is steep and the canyon floor is narrow, providing little area suitable for significant alluvial sediment storage. The Yampa River flows through the massive Weber Sandstone downstream from river mile 21 and, from here to the mouth, the canyon floor is wider and more conducive to sediment deposition.

The abundance of subaerial alluvial deposits in the Green River downstream from the Lodore Ranger Station is less uniform than in the Little Snake or Yampa Rivers. The relative abundance of alluvial deposits varies from less than 10 to more than 80 percent of the visible channel boundary between the Lodore Ranger Station and the downstream end of the study reach at river mile 194. The regional structural geology and lithology at river level may be important in determining variations in canyon-floor width and gradient, which influence the relative abundance of alluvial deposits in the Green River.

Sediment data from five sites in the Yampa River Basin and the upper Green River Basin have been collected by the USGS in cooperation with the Colorado Division of Wildlife and the U.S. Fish and Wildlife Service during an ongoing, multiyear study that began in 1998. These data were augmented with sediment data gathered at these sites in earlier years as part of other USGS studies and routine data-collection activities. The sampling sites are the Yampa River above Little Snake River, near Maybell, Colorado, 09251100; the Little Snake River, near Lily, Colorado, 09260000; the Yampa River at Deerlodge Park, 09260050; the Green River above Gates of Lodore, Colorado, 404417108524900 (nearest streamflow gage, Green River near Greendale, Utah, 09234500); and the Green River near Jensen, Utah, 09261000.

The period of record, number of samples, and type of sediment analyses differ at each of the sites. The sites with the shortest periods of record are the Yampa River above Little Snake River (1998–2002) and the Green River above Gates of Lodore (1999–2002); for both sites, data include suspended-sediment and bedload measurements. Suspended-sediment measurements were made at the Little Snake River, near Lily site in 1983, 1994–98, and 2000–2002. Bedload measurements were made in 2001 and 2002. Suspended- and bedload-sediment measurements were made at the Yampa River at Deerlodge Park site in 1982–83 and 1998–2001, and only suspended-sediment measurements were made in 1994 and 1997. Suspended-sediment measurements were made at the Green River near Jensen site from 1948–79. Suspended- and bedload-sediment measurements were made at the Green River near Jensen site in 1996 and from 1998 through 2002. Sediment load by transport mode, particle-size range, and hydrograph season also were computed for all sites.

One objective of this study was to identify future data needs for improving the accuracy of sediment-transport relations that can be used in calculating sediment budgets at the five sampling sites. Sediment-transport curves were derived by least-squares regression of logarithmic-transformed data to provide a means to estimate seasonal and annual sediment supply to the principal streams in the upper part of the watershed (the Yampa River, the Little Snake River, and the Green River upstream from the Gates of Lodore) and on the Green River just upstream from a critical spawning habitat near Jensen, Utah. These transport curves can be revised as additional data from the ongoing sampling program become available.

The relative accuracy and representativeness of the transport relations derived in this study were assessed using the coefficients of determination (R^2) and mean square error (MSE) of regression equations, the range of discharges sampled, the seasonality of the relations, and the number of samples. The transport equations in this report are considered to be reasonably representative if the R^2 is greater than about 0.70, if sediment samples are evenly distributed over the likely range of nonbase-flow discharges in a year, if the samples are distributed between the rising-limb and falling-limb hydrograph seasons, and if the number of samples is large enough to reflect the variance in the relation between sediment load and water discharge.

The sediment-transport equations presented in this report indicate that gravel, sand, silt, and clay transport in these rivers is strongly dependent on the streamflow magnitude and, to a lesser degree, on the season. The timing of annual runoff and consequently the timing of sediment entrainment, transport, and deposition affect aquatic habitat and are dependent on long-term climate and seasonal weather patterns and on the operation of upstream reservoirs. Reach-specific estimates of the timing, volume, and particle size of sediment deposited at critical aquatic-habitat sites other than at the gaged sampling sites require streamflow-routing simulation through the drainage network and are beyond the scope of this report.

Yampa River above Little Snake River, near Maybell, Colorado

The relatively large R^2 values for all transport equations at the Yampa River above Little Snake River near Maybell (R^2 greater than or equal to 0.80) indicate that the transport equations may be useful for annual load estimation or sediment budget calculations for discharges ranging from about 500 to 10,000 ft^3/s; however, the small number of samples used to calculate the seasonal transport equations may not be representative of flow conditions. These transport equations may not adequately reflect transport conditions of higher discharges that occurred in 1997 or in the mid-1980s before the streamflow-gaging station was established. Additional measurements in the 500- to 10,000-ft^3/s range from both the rising-limb and falling-limb hydrograph seasons and any measurements exceeding about 10,000 ft^3/s would make these equations more representative of flow conditions at this site.

Little Snake River near Lily, Colorado

The suspended-sediment measurements at Little Snake River near Lily are relatively evenly distributed at streamflows from about 40 to 6,000 ft^3/s; however, sediment measurements at streamflows approaching the 1984 historical instantaneous peak discharge (16,700 ft^3/s) have not been made. Bedload measurements were made in 2001 and 2002. The transport equation for suspended-sediment load ($R^2 = 0.74$) is adequate for estimating annual suspended loads for discharges ranging from about 40 to 6,000 ft^3/s and may have some applicability for discharges ranging from about 1 to 40 ft^3/s. The suspended-sediment load transport equation must be recomputed with data from discharges greater than 6,000 ft^3/s for it to be applicable at extremely high discharges. Transport equations by suspended-particle size are applicable for discharges ranging from about 50 to 6,000 ft^3/s; however, their R^2 values are less than 0.55. Although the distribution of data indicate a seasonal sediment-load hysteresis may exist, the relatively low R^2 value for the rising-hydrograph season ($R^2 = 0.47$) could be improved with additional data collected in the appropriate season. Also, because bedload data have been collected for only 2 years at this site, neither the total-annual sediment load nor the relative portion of total-sediment load transported as bedload is well documented.

Yampa River at Deerlodge Park, Colorado

Suspended- and bedload-sediment data were collected at the Yampa River at Deerlodge Park site near the 1983 instantaneous peak discharge of 23,400 ft^3/s, but no sediment measurements were made the following year during the historical instantaneous peak discharge (33,200 ft^3/s). Data collected since 1983 at Deerlodge Park has increased the number of suspended-sediment measurements by 139 percent and has increased the number of total sediment (suspended sediment plus bedload sediment) measurements by 71 percent since 1982–83. Based only on the relative magnitudes of the R^2 value, the additional data have resulted in a slightly improved suspended-sediment transport equation, compared to a previous USGS study (0.80 compared to 0.76), and a slightly deteriorated total-load equation (0.72 compared to 0.79). The updated transport equation for suspended-sediment load may be useful for annual suspended-sediment load calculations for discharges ranging from about 40 to 18,000 ft^3/s, whereas, the updated transport equations for total-sediment load, suspended-sediment load, sand and gravel load, and fine sand load may be useful for annual load calculations for discharges ranging from about 600 to 18,000 ft^3/s.

Unless there is an opportunity to make future measurements above about 18,000 ft^3/s, additional data collection may not improve these transport equations. However, more bedload measurements made during streamflows of less than about 700 ft^3/s could improve the accuracy of both the bedload-transport and total-sediment transport equations. Additional data collection during the rising-limb and falling-limb hydrograph periods might improve the transport equations that describe seasonality.

Green River above Gates of Lodore, Colorado

Sediment-transport equations for total-sediment load, suspended-sediment load, silt and clay load, and sand and gravel load had R^2 values greater than or equal to 0.74. The equation for bedload had an R^2 value of 0.47, possibly due to a relatively small range in bedload magnitude typical of river reaches with a limited supply of transportable bed material, such as rivers downstream from dams. The seasonal transport equations had R^2 values of 0.81 but were based on small numbers of samples and, therefore, may not accurately reflect true seasonal conditions. One-half of the sediment measurements were made at discharges greater than 6,000 ft^3/s, streamflows that occur relatively infrequently. Additional sediment measurements made at less than 3,000 ft^3/s or greater than 10,000 ft^3/s in both early and late hydrograph seasons could improve the accuracy of the transport equations. Additional measurements also might result in a better understanding of the variation in dominant transport mode (bedload compared to suspended load) over a wide range of streamflows.

Green River near Jensen, Utah

Sediment-transport equations for total-sediment, suspended-sediment, and transport by all particle sizes except medium and coarse sand, and very coarse sand and fine gravel had R^2 values of 0.75 or greater and may be useful for annual load estimations or sediment budget calculations for discharges ranging from about 1,000 to 22,000 ft^3/s. No sediment measurements have been made at streamflows approaching the 1984 historical instantaneous peak discharge of 40,000 ft^3/s. The equation for bedload transport had an R^2 value of 0.54, the equation for medium and coarse sand had an R^2 value of 0.64, and the equation for very coarse sand and fine gravel had an R^2 value of 0.40. Rising-limb and falling-limb season equations had R^2 values of 0.77 and 0.90, respectively, but these equations were based on relatively small numbers of samples (18 for each equation).

The suspended-sediment transport equation derived from the 40 measurements made since 1996 has a different slope and intercept than the post-dam period (1963–79) equation and, based on the R^2 value, much less variance. Possible explanations for the difference between these two transport equations could include climate and land-use changes, a change in the availability of transportable sediment, or a change in Flaming Gorge Reservoir operation between the two periods.

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