EFFECTS OF A LANDSLIDE COMPLEX ON SEDIMENT DISCHARGES AND LOADS IN THE MUDDY CREEK DRAINAGE BASIN AND DEPOSITION INTO PAONIA RESERVOIR, WEST-CENTRAL COLORADO, 1986-87

By Cynthia L. Appel and David L. Butler

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 90-4173

Prepared in cooperation with the

U.S. BUREAU OF RECLAMATION and the

COLORADO RIVER WATER CONSERVATION DISTRICT

Denver, Colorado
1991

U.S. DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Box 25046, Mail Stop 415
Federal Center
Denver, CO 80225-0046

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Box 25425
Federal Center
Denver, CO 80225-0425

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS

Multiply	*By*	*To obtain*
acre	4,047	square meter
acre-foot	1,233	cubic meter
cubic foot	0.02832	cubic meter
cubic foot per second	0.02832	cubic meter per second
foot	0.3048	meter
foot per day	0.3048	meter per day
inch	25.40	millimeter
mile	1.609	kilometer
pound, avoirdupois	0.4536	kilogram
square mile	2.590	square kilometer
ton	.9072	metric ton or megagram
tons per day	.9072	metric ton or megagram per day

The following terms also are used in this report:

gram
liter
milligram
milligram per liter
millimeter

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

EFFECTS OF A LANDSLIDE COMPLEX ON SEDIMENT DISCHARGES AND LOADS IN THE MUDDY CREEK DRAINAGE BASIN AND DEPOSITION INTO PAONIA RESERVOIR, WEST-CENTRAL COLORADO, 1986-87

By Cynthia L. Appel and David L. Butler

ABSTRACT

Total-sediment load upstream from and downstream from a landslide complex in the Muddy Creek drainage basin in Gunnison and Delta Counties was estimated by using stream-discharge and sediment data collected from June 1986 through July 1987. The relation of suspended-sediment discharge and bedload discharge to stream discharge was determined by using logarithmic regression analysis and analysis of covariance. The combined total-sediment load of East Muddy Creek, Spring Creek, and West Muddy Creek represents the total-sediment load of Muddy Creek upstream from the landslide complex and is assumed to be representative of the total-sediment load before movement of the landslide complex. The total-sediment load was estimated to be 101,000 tons during a 216-day period. The total-sediment load of Muddy Creek downstream from the landslide complex, but upstream from Paonia Reservoir, included sediment contributed by the landslide complex and was estimated to be 147,000 tons for the 216-day period. During a 483-day period, the total-sediment load of Muddy Creek upstream from Paonia Reservoir was estimated to be 293,000 tons. The total-sediment load of Muddy Creek downstream from Paonia Reservoir was estimated to be 14,900 and 51,100 tons during the 216- and 483-day periods; the trap efficiencies of the reservoir were estimated to be 90 and 83 percent.

The total-sediment load of East Muddy Creek, Spring Creek, and West Muddy Creek during the 216-day period was estimated to be about 400 tons per day, and is assumed to be representative of the sediment load deposited into Paonia Reservoir prior to movement of the landslide complex. There was a loss of about 2,100 acre-feet of water-storage capacity in the reservoir prior to movement of the landslide complex. The land-surface elevation in a ponded reach of East Muddy Creek upstream from the central slide of the landslide complex increased an average of 7.5 feet between August 1985 and June 1986. The volume of material necessary to increase the elevation of the land surface by 7.5 feet is about 2 million cubic feet. Some of the increase in the elevation of the land surface is a result of deposition of sediment by East Muddy Creek and some may be from deformation of the land surface as a result of movement of the landslide complex.

Four channel cross sections of Muddy Creek near the upstream reach of Paonia Reservoir were resurveyed to determine changes in the volumes of sediment since 1962, when Paonia Dam was completed. The maximum change in

sediment volume in a cross section between May 1962 and September 1987 was more than 2,700 cubic feet. Much of the sediment deposited in the upper reaches of Paonia Reservoir is scoured from this area and redeposited farther downstream in the reservoir.

INTRODUCTION

Rapid movement of the central lobe of a landslide complex in the Muddy Creek drainage basin about 1.5 miles upstream from Paonia Reservoir began in April 1986. Suspended sediment and bedload sediment from the landslide complex were transported downstream into Paonia Reservoir by Muddy Creek (fig. 1). The landslide complex damaged Colorado State Highway 133, and subsequent highway repairs also have added sediment to the reservoir. Water stored in Paonia Reservoir is used for irrigation in the North Fork of the Gunnison River valley. Sediment deposition in the reservoir decreases the available water-storage capacity. Also of concern are the changes in channel geometry and location of affected stream reaches as a result of the landslide and related highway reconstruction.

The quantity of sediment discharges and loads in the Muddy Creek drainage basin and the possible effects of sediment deposition on Paonia Reservoir are needed by managers to determine long-term effects of the landslide and related activities and to provide information about other slides that may affect streams and roads in western Colorado. Therefore, in 1986, the U.S. Geological Survey began a study in cooperation with the U.S. Bureau of Reclamation and, in 1987, with the Colorado River Water Conservation District to determine sediment discharges and loads in the Muddy Creek drainage basin, the quantity of sediment deposited into Paonia Reservoir, and the trap efficiency of the reservoir. Also, any general changes in channel geometry and location of East Muddy and Muddy Creeks as a result of the landslide and related highway reconstruction were to be determined.

Purpose and Scope

This report describes: (1) Total-sediment discharges and loads in the Muddy Creek drainage basin upstream from and downstream from Paonia Reservoir and trap efficiency of the reservoir, (2) the increase in total-sediment discharge in Muddy Creek as a result of the landslide complex and road-reconstruction activities, and (3) sediment deposition in the upstream reach of Paonia Reservoir. These determinations were made using existing information from geologic and topographic maps of the landslide area before and after the landslide and from stream-discharge records from streamflow-gaging stations upstream and downstream from Paonia Reservoir for 1986-87. During these years, two temporary streamflow-gaging stations were established on East and West Muddy Creeks to collect additional data. Total-sediment loads were estimated for East and West Muddy Creeks, Spring Creek, and Muddy Creek upstream and downstream from Paonia Reservoir for a 216-day period when the temporary gages were in operation. Sediment samples were collected and water-discharge measurements were made approximately biweekly at the gaging stations and at Spring Creek.

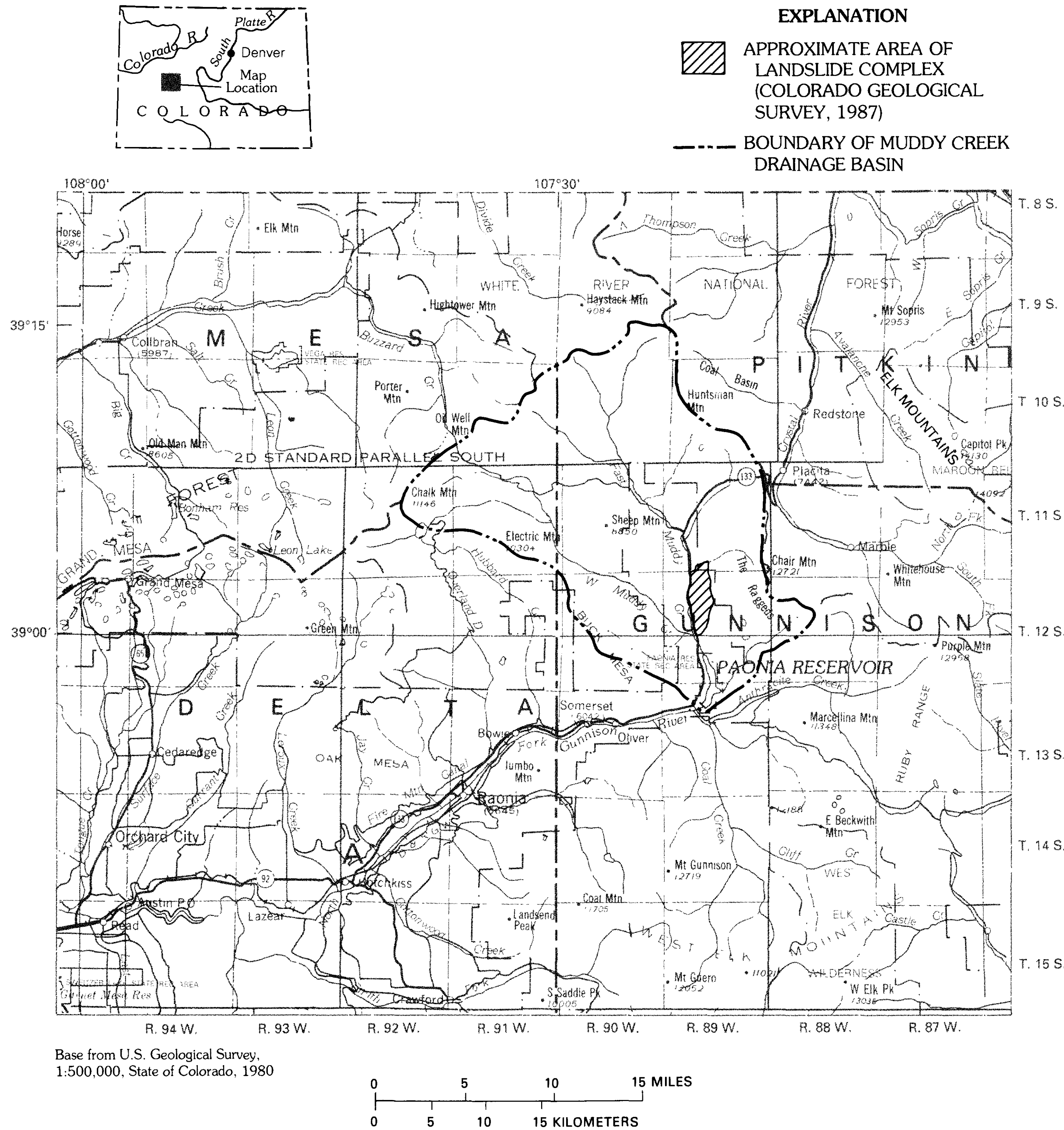


Figure 1.--Location of the Muddy Creek drainage basin.

The combined total-sediment load of East Muddy Creek, Spring Creek, and West Muddy Creek represents the total-sediment load of Muddy Creek upstream from Paonia Reservoir before movement of the landslide complex. The total-sediment load of Muddy Creek at the gaging station upstream from Paonia Reservoir includes contribution of sediment from the landslide complex. Because all bedload was assumed to be trapped in Paonia Reservoir, the suspended-sediment load of Muddy Creek downstream from Paonia Reservoir was used to estimate the trap efficiency of the reservoir. Total-sediment loads also were estimated for a 483-day period when stream-discharge records were available for the gaging stations upstream and downstream from the reservoir. This information was used to estimate the trap efficiency of Paonia Reservoir for the 483-day period.

Cross sections of the stream channel upstream from Paonia Reservoir, which originally were surveyed in 1962, were resurveyed during 1986-87 to determine the quantity of sediment deposition since completion of the reservoir and occurrence of the slide. Data from these cross sections also were used to determine general changes in stream channels and locations in the resurveyed reach.

Location and Physiography

The Muddy Creek drainage basin consists of 249 square miles in Gunnison and Delta Counties (fig. 1). The Raggeds form the eastern boundary of the drainage basin, and Grand Mesa forms the northwestern boundary. Elevations within the drainage basin range from about 6,280 feet near the base of Paonia Dam to more than 12,700 feet in The Raggeds. The major streams in the study area are East Muddy Creek and West Muddy Creek, which join to form Muddy Creek about 1.5 miles upstream from Paonia Reservoir. Muddy Creek joins Anthracite Creek to form the North Fork of the Gunnison River about 0.5 mile downstream from Paonia Dam.

Paonia Dam is about 7 miles upstream from Somerset. Paonia Dam was constructed by the U.S. Bureau of Reclamation to store water for irrigation use in the North Fork of the Gunnison River valley. Construction of the dam was completed in 1962. The surface area of Paonia Reservoir at full pool is about 0.6 square mile (about 385 acres), and the reservoir is about 3.2 miles long. The design water-storage capacity of Paonia Reservoir was 20,950 acre-feet when the water level in the reservoir was at 6,447.5 feet, the elevation of the upper spillway (Ed Warner, U.S. Bureau of Reclamation, written commun., 1986).

Climate

Although there are no climatic stations within the study area, there are several climatic stations nearby at elevations similar to those in the Muddy Creek drainage basin. Data from these climatic stations were used to estimate the distribution of precipitation in the Muddy Creek drainage basin. Precipitation in the Muddy Creek drainage basin increases with elevation and ranges from about 20 to 40 inches per year (fig. 2). Most precipitation falls as snow between December and April. Precipitation has been greater than the

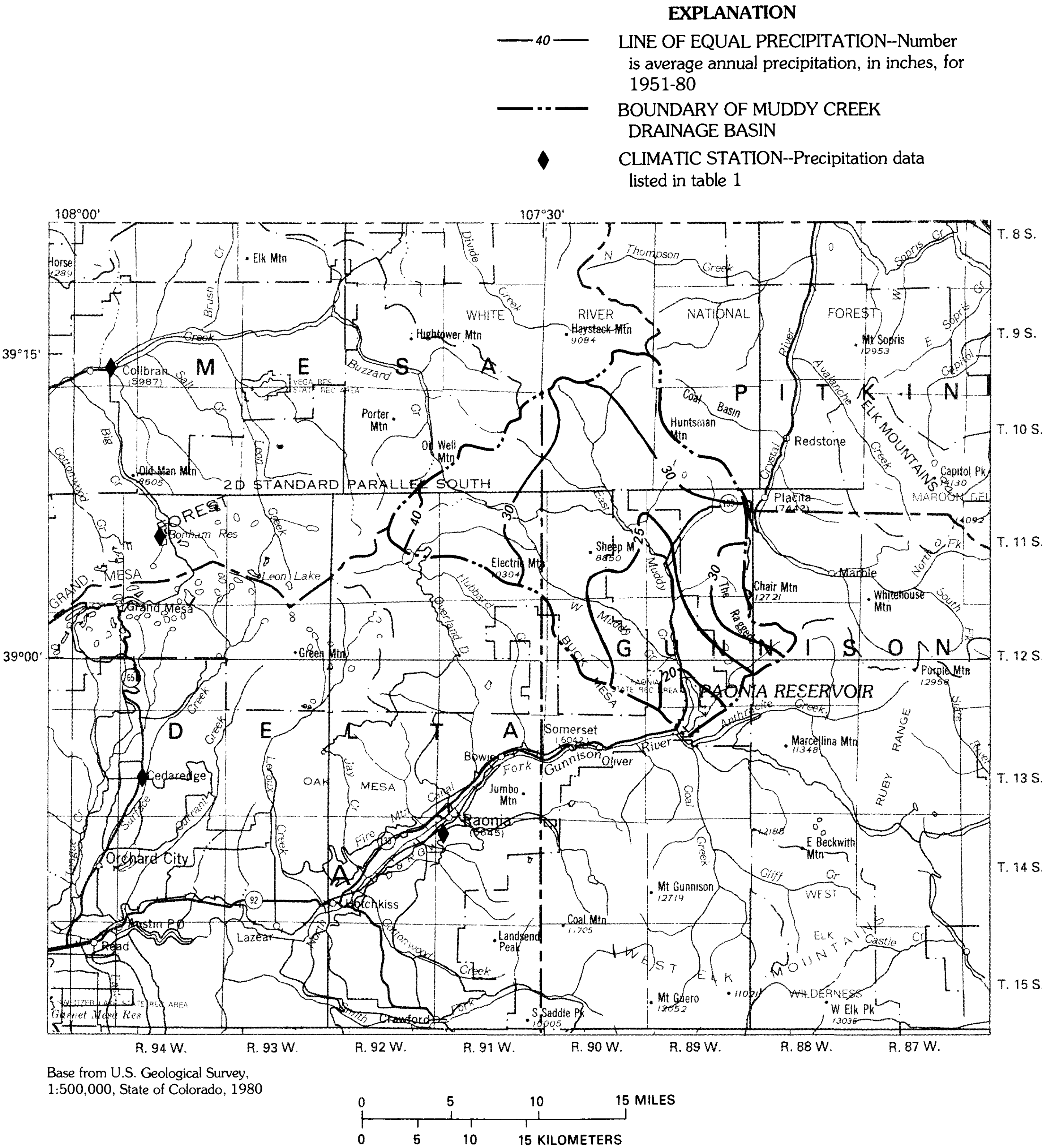


Figure 2.--Location of climatic stations near the Muddy Creek drainage basin and average annual precipitation in the drainage basin.

average for 1955-86 nearly every year since 1980 at the climatic stations listed in table 1. In 1986, precipitation at climatic stations near the Muddy Creek drainage basin ranged from 2.48 to 7.90 inches greater than the average for the period of record or the 1955-86 period (National Climatic Data Center, 1955-86). In 1986, the average precipitation at all climatic stations within the Colorado River drainage basin was 3.23 inches greater than the average. Greater than average precipitation for several consecutive years probably saturated the landslide complex, which increased the pore-water pressure within the complex and enabled the complex to move more easily.

Table 1.--*Average annual precipitation at climatic stations near the Muddy Creek drainage basin and in the Colorado River drainage basin, 1980-86*

[Years of record, number of years for which annual precipitation is available since 1955 (National Climatic Data Center, 1955-86); --, missing data; na, not applicable]

Station name	Land-surface elevation (feet)	Years of record	Precipitation, in inches 1980	1981	1982	1983	1984	1985	1986	1986 departure from the 1955-86 average (inches)
Bonham Reservoir----	9,850	21	33.56	29.37	--	44.42	45.29	--	41.29	7.90
Cedaredge-----------	6,244	30	15.67	13.92	--	19.99	15.61	18.29	18.70	6.09
Collbran------------	5,980	24	15.27	15.45	14.29	21.28	17.88	18.91	16.80	2.48
Paonia 1 SW---------	5,580	29	16.35	15.64	15.75	19.18	--	21.55	23.75	7.88
Stations in Colorado River drainage basin.	na	29	16.61	17.64	17.22	22.22	20.13	19.98	19.50	3.23

Previous Investigations

Miscellaneous streamflow and water-quality data have been collected in the North Fork of the Gunnison River drainage basin including East Muddy Creek, West Muddy Creek, and Muddy Creek (Norris and Maura, 1985). Several streamflow-gaging stations have been operated by the U.S. Geological Survey within the study area; however, none of these stations has been in operation since 1974. Personnel of the Colorado Department of Natural Resources, Division of Water Resources, Office of the State Engineer, maintain two streamflow-gaging stations on Muddy Creek, one upstream from and one downstream from Paonia Reservoir. Personnel of the U.S. Forest Service measured stream discharge and collected sediment samples on West Muddy Creek from 1984 to 1987. The U.S. Bureau of Reclamation surveyed channel cross sections of Muddy Creek in 1962 and 1969. The U.S. Bureau of Reclamation also collected suspended-sediment samples from Muddy Creek before construction of Paonia Dam.

Personnel of the Colorado Geological Survey surveyed profiles of the landslide complex in August 1985, before the greatest movement of the complex in 1986, and again in May and June 1986, after movement of the complex. Geologic hazards in the valley along the North Fork of the Gunnison River were mapped by Junge (1982).

Acknowledgments

The authors wish to thank Jack Osburn of the Colorado River Water Conservation District, who helped measure stream discharge and collect sediment samples during 1987. The cooperation of landowners who allowed streamflow-gaging stations to be installed on their property also is greatly appreciated.

GEOLOGIC SETTING AND DESCRIPTION OF LANDSLIDE COMPLEX

The Muddy Creek drainage basin is at the eastern edge of the Colorado Plateau physiographic province and adjacent to the western edge of the Southern Rocky Mountain physiographic province (Fenneman, 1946). The southern extent of the northwest-trending axis of the Piceance Basin is near the confluence of East Muddy Creek and West Muddy Creek.

Geologic units exposed in the drainage basin include the Mesaverde Group of Cretaceous age, which is composed of interbedded sandstone, shale, and coal; intrusive rocks of Tertiary age; the Wasatch Formation of Tertiary age, which is composed of claystone, mudstone, shale, sandstone, and conglomerate; and alluvium, glacial deposits, and landslide deposits of Quaternary age (fig. 3). Most of these units are subject to slope failure, landslides, and debris avalanches. The area north of Paonia Reservoir where the Wasatch Formation is exposed at land surface is considered to be an area of geologic hazard (Junge, 1982). There are several landslides within the Muddy Creek drainage basin.

The Muddy Creek landslide complex, which probably was caused by the physiographic instability of the landform combined with a substantial increase in precipitation since 1980 (Colorado Geological Survey, 1987) is about 13,000 feet long and 7,000 feet wide and is at the base of The Raggeds (fig. 4). The landslide complex is adjacent to East Muddy Creek, and the downstream end of the complex is about 0.5 mile upstream from Paonia Reservoir. The landslide complex originally was part of the Wasatch Formation. The active part of the landslide complex includes three parts--the northern, central, and southern slides. Movement of the landslide complex became apparent to the Colorado Geological Survey as early as 1974, and by 1983, all three slides exhibited movement (Colorado Geological Survey, 1987). On April 26, 1986, the northern and central slides of the complex began moving westward 9 to 12 feet per day, and movement continued until June 1986 (Colorado Geological Survey, 1987). The total lateral displacement of the central slide was 230 feet, whereas the northern slide was displaced 75 feet (Colorado Geological Survey, 1987). This movement raised the elevation of the streambed of East Muddy Creek as much as 30 feet immediately upstream from the confluence with West Muddy Creek. Movement of the landslide complex also damaged Colorado State Highway 133 in this area. Large quantities of material were dredged out of the East Muddy Creek channel by the State Highway Department when the landslide complex was moving. The dredging of this material changed the gradient and the sediment-carrying capacity of East Muddy Creek in this area. Lateral displacement of the landslide complex was much less in 1987 than in 1986.

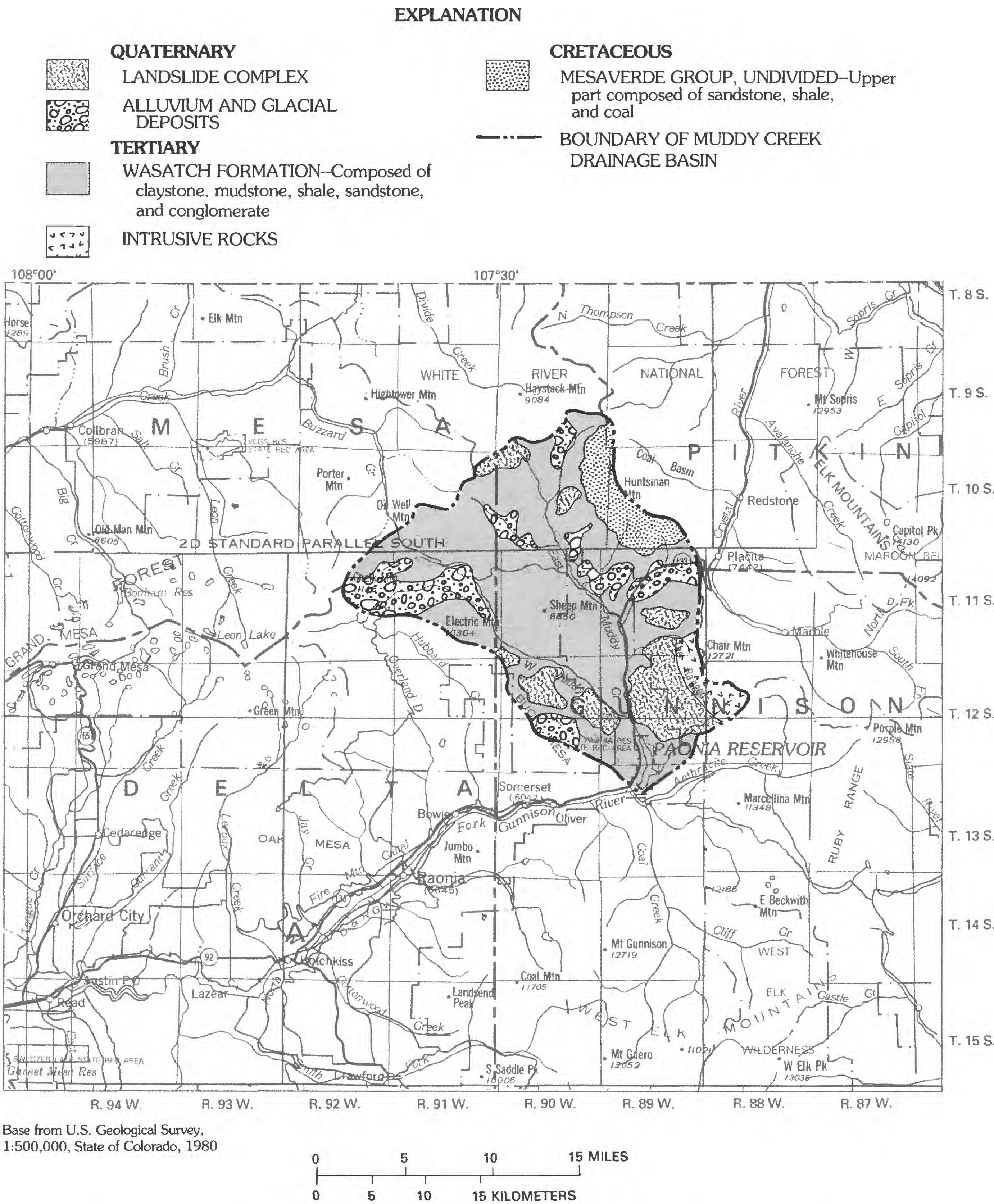
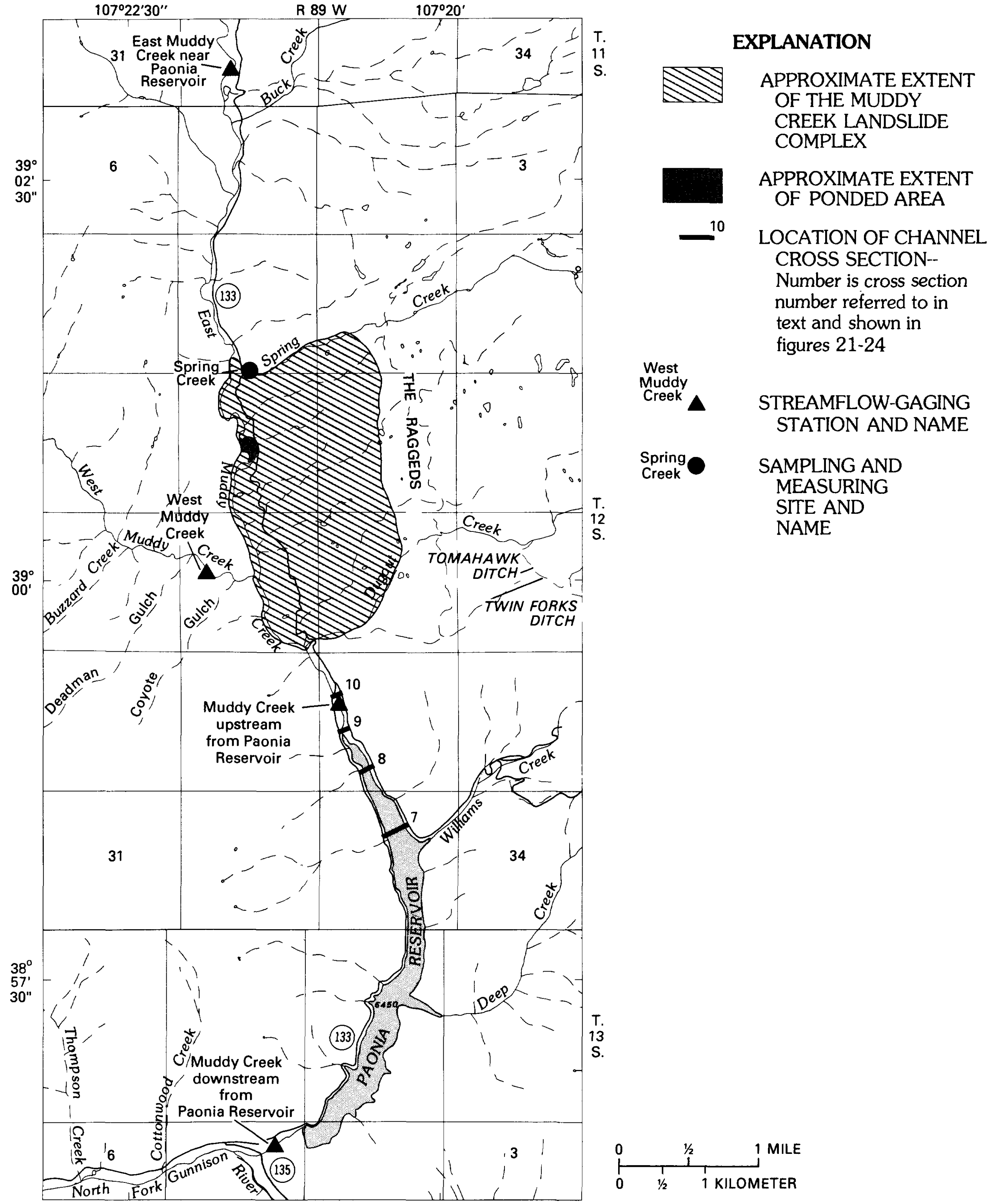


Figure 3.--Generalized geology of the Muddy Creek drainage basin (modified from Tweto, 1979).



Base from U.S. Geological Survey 1:24,000, Paonia Reservoir, 1964, Chair Mountain, 1978, Bull Mountain, 1982, and Somerset, 1978

Figure 4.--Approximate extent of the Muddy Creek landslide complex and locations of streamflow-gaging stations, ponded area, and channel cross sections.

In April 1986, the westward movement of the central part of the landslide complex constricted the channel of East Muddy Creek. A pond formed upstream from the constriction and adjacent to the northern part of the landslide complex (figs. 4-5). The velocity and, thus, the sediment-carrying capacity of East Muddy Creek were decreased in this area. Sediment settled in this pond, which covered about 0.01 square mile (about 6.4 acres) during spring runoff in 1986 and 1987. This area was surveyed by the Colorado Geological Survey in August 1985 and May and June 1986. A comparison of the two surveys indicates that the elevation of the land surface increased in the pond during this period. The increase ranged from 0 to 14.6 feet and averaged 7.5 feet. This increase in land-surface elevation is, in part, a result of sediment settling out of East Muddy Creek. The increase in elevation also is partially due to deformation of the land surface resulting from movement of the landslide complex. The volume of material necessary to increase the elevation of the land surface an average of 7.5 feet in an area of 0.01 square mile is about 2 million cubic feet. Additional sediment probably accumulated in the pond during 1987.

Figure 5.--Sediment accumulation in ponded reach of East Muddy Creek upstream from the central part of the landslide complex, September 6, 1987.

STREAM DISCHARGE

Streamflow-gaging stations were installed on East Muddy Creek and West Muddy Creek in July 1986. The streamflow-gaging station on East Muddy Creek is about 2 miles upstream from the landslide complex (fig. 4). Spring Creek drains the northern part of the landslide complex and is a tributary to East Muddy Creek. No streamflow-gaging station was installed on Spring Creek but stream discharge was measured or estimated several times during this study. The stream discharges of Buck Creek and Dugout Creek were estimated at the beginning of the study. The combined discharges of Buck and Dugout Creeks were estimated to be less than 5 cubic feet per second. Throughout the remainder of the study, the water in these streams was clear and it is assumed that the streams contribute an insignificant quantity of sediment to East Muddy Creek and Muddy Creek. The streamflow-gaging station on West Muddy Creek is about 0.2 mile upstream from the confluence with East Muddy Creek, which is immediately downstream from the central slide of the landslide complex. The streams become Muddy Creek at their confluence. Personnel of the Colorado Department of Natural Resources, Division of Water Resources, Office of the State Engineer operate streamflow-gaging stations on Muddy Creek upstream from and downstream from Paonia Reservoir. Streamflow records were available for most of water years 1986 and 1987 for these stations. Stream discharge was measured and streamflow records were computed using methods described in Rantz and others (1982). Estimates of stream discharge were made by measuring the stream width and depth and by estimating the velocity of the streamflow.

East Muddy Creek

The East Muddy Creek drainage basin consists of 135 square miles. The drainage basin upstream from the streamflow-gaging station on East Muddy Creek consists of 115 square miles. The daily mean discharge of East Muddy Creek near Paonia Reservoir is shown in figure 6 for the periods during which gage-height records were available. Gage-height records were available for 216 days from July 11 through November 5, 1986, and April 7 through July 13, 1987. According to gage-height records for the station Muddy Creek upstream from Paonia Reservoir, the maximum streamflow in 1986 occurred in May (fig. 7), before installation of the streamflow-gaging station on East Muddy Creek. The measured instantaneous discharges of East Muddy Creek ranged from 17.3 to 222 cubic feet per second in 1986. The largest instantaneous discharge was measured on June 23, before the streamflow-gaging station was installed. During the period for which gage-height records were available in 1986, the daily mean discharge of East Muddy Creek ranged from 19 to 155 cubic feet per second. In 1987, the measured instantaneous discharges ranged from 26.5 to 364 cubic feet per second. During the period for which gage-height records were available in 1987, the daily mean discharge ranged from 20 to 733 cubic feet per second.

Spring Creek

Spring Creek flows into East Muddy Creek about 2 miles downstream from the streamflow-gaging station on East Muddy Creek and 2.5 miles upstream from the streamflow-gaging station on Muddy Creek upstream from Paonia Reservoir

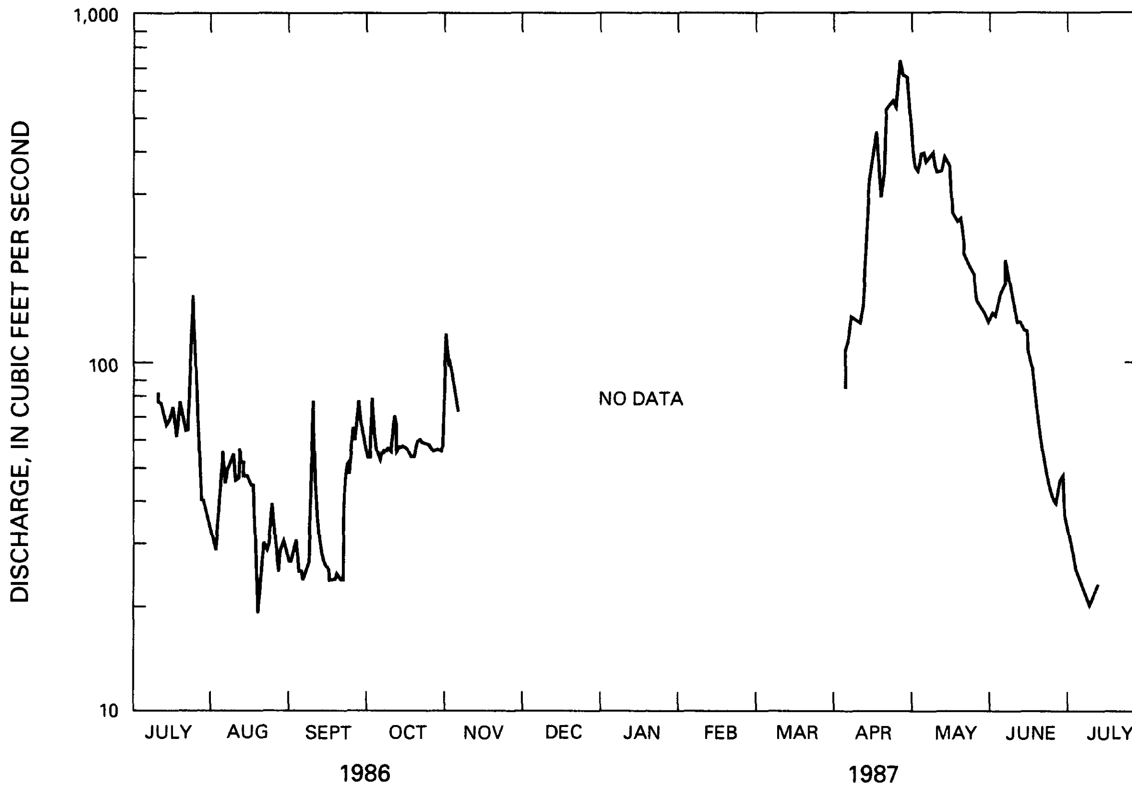


Figure 6.--Daily mean discharge of East Muddy Creek near Paonia Reservoir during parts of water years 1986 and 1987.

(fig. 4). The Spring Creek drainage basin consists of about 4.5 square miles. The channel of Spring Creek is composed of boulders, and the gradient is steep. The streamflow and sediment concentrations of Spring Creek were monitored because it was the only tributary contributing substantial quantities of sediment to East Muddy Creek. Seven measurements and six estimates of instantaneous stream discharge of Spring Creek ranged from 4 to 20 cubic feet per second. The maximum discharge of 20 cubic feet per second was an estimated discharge. The maximum stream discharge of Spring Creek occurs later in the year than those of East Muddy Creek and West Muddy Creek. The daily mean discharge of Spring Creek was estimated to be 10 cubic feet per second during the 216 days for which gage-height records were available for East Muddy Creek and West Muddy Creek.

West Muddy Creek

The West Muddy Creek drainage basin consists of 94 square miles. The drainage basin upstream from the streamflow-gaging station on West Muddy Creek consists of 92 square miles. The daily mean discharge of West Muddy Creek during 1986-87 is shown in figure 8. Gage-height records were available for West Muddy Creek for the same 216 days that they were available for East Muddy

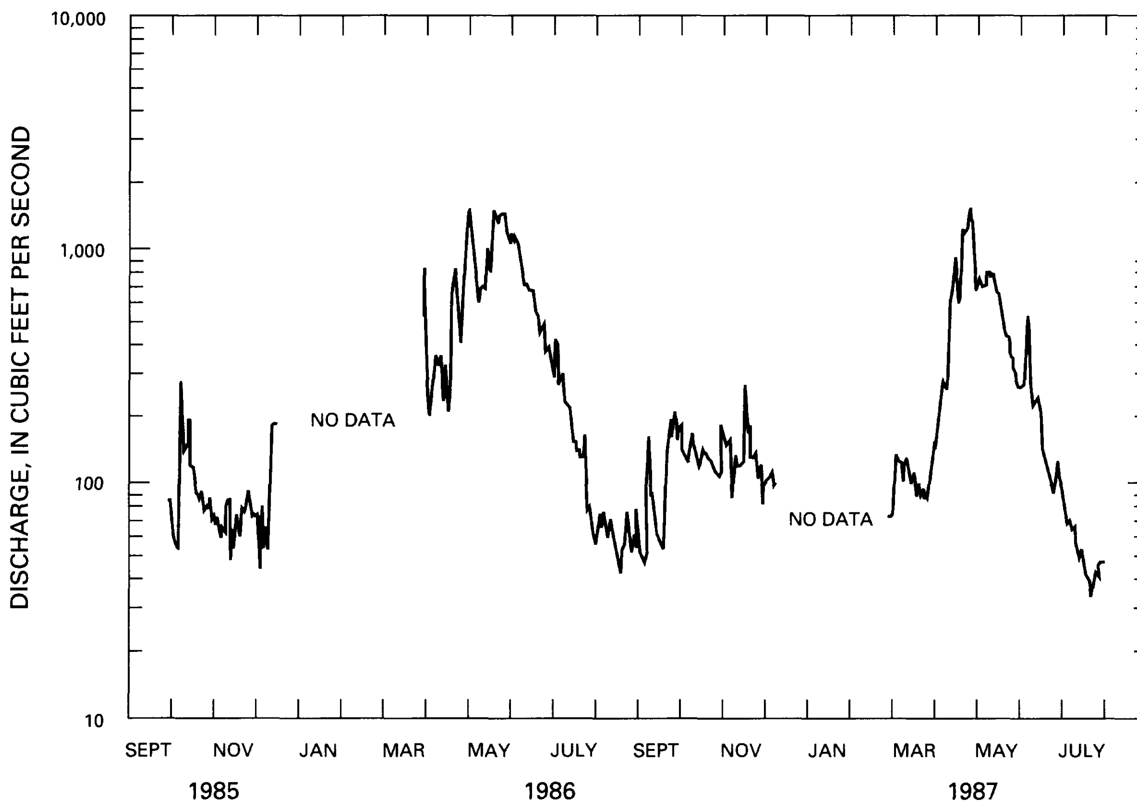


Figure 7.--Daily mean discharge of Muddy Creek upstream from Paonia Reservoir during parts of water years 1986 and 1987.

Creek. The maximum discharge in 1986 occurred in May, before installation of the streamflow-gaging station on West Muddy Creek. The measured instantaneous discharges ranged from 5.70 to 174 cubic feet per second in 1986. The greatest measured instantaneous discharge was on June 23, 1986, before installation of the streamflow-gaging station. The daily mean discharge of West Muddy Creek during the period for which gage-height records were available during 1986 ranged from 5.5 to 131 cubic feet per second. The measured instantaneous discharges ranged from 10.6 to 324 cubic feet per second in 1987. The daily mean discharge during the period for which gage-height records were available in 1987 ranged from 9.0 to 772 cubic feet per second.

Muddy Creek Upstream From Paonia Reservoir

The drainage basin gaged by the streamflow-gaging station on Muddy Creek upstream from Paonia Reservoir consists of 234 square miles. The gage is about 0.3 mile upstream from Paonia Reservoir when the reservoir is full. Gage-height records were available for 483 days, including October 1 through December 15, 1985, April 1 through December 10, 1986, and March 1 through July 31, 1987 (fig. 7). This period of record includes the 216 days for which gage-height records were available for East Muddy Creek and West Muddy Creek.

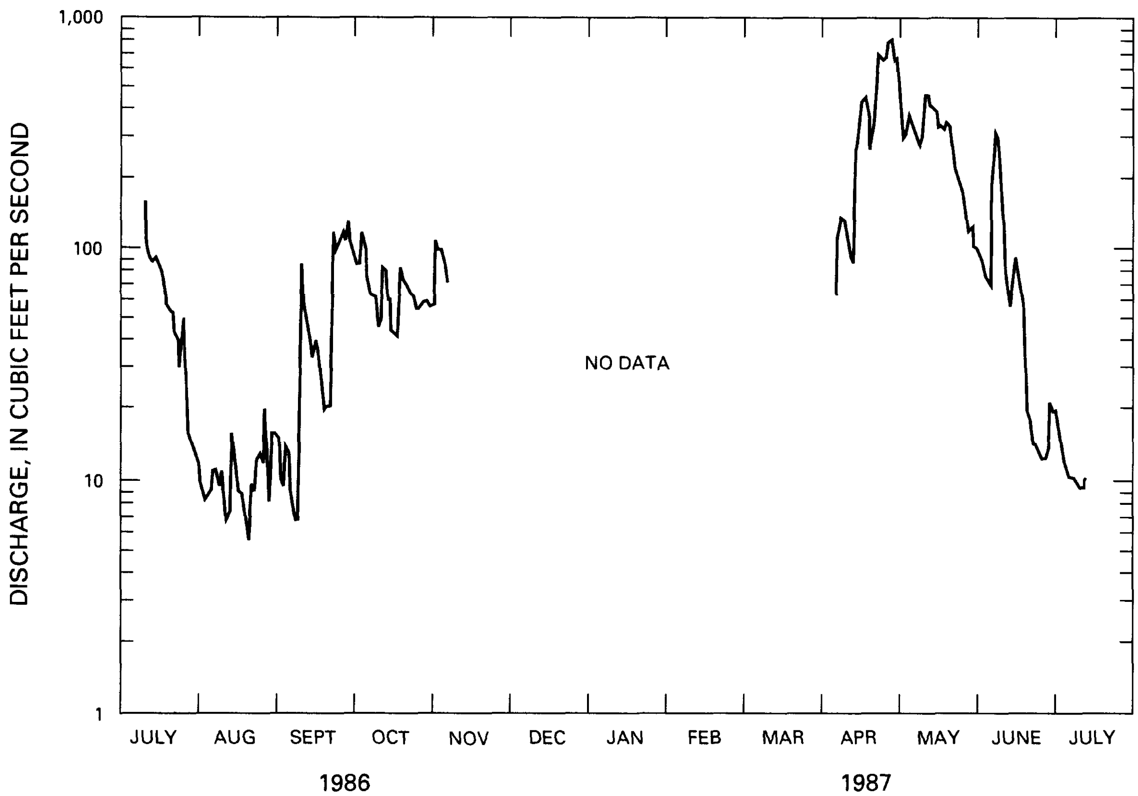


Figure 8.--Daily mean discharge of West Muddy Creek near Paonia Reservoir during parts of water years 1986 and 1987.

This period also includes the time when the rate of movement of the landslide complex was greatest. The instantaneous discharge measured by the U.S. Geological Survey ranged from 34.5 to 444 cubic feet per second in 1986. An instantaneous discharge of 1,120 cubic feet per second was measured by personnel of the Colorado Department of Natural Resources, Division of Water Resources, Office of the State Engineer on May 29, 1986. During water year 1986, the daily mean discharge ranged from 40 to 1,480 cubic feet per second (fig. 7). The maximum daily mean discharge occurred on May 4. However, gage-height records generally were poor for periods of high streamflow because the intakes to the gage were buried by a gravel bar, which developed as a result of movement of the landslide complex. The gravel bar was removed from the channel in June 1986. Measured instantaneous discharge ranged from 61.1 to 736 cubic feet per second in 1987. During water year 1987, the daily mean discharge ranged from 33 to 1,520 cubic feet per second. The maximum daily mean discharge occurred on April 29, 1987.

Muddy Creek Downstream From Paonia Reservoir

The drainage basin area for the streamflow-gaging station on Muddy Creek downstream from Paonia Reservoir is 249 square miles. The gage is 0.2 mile downstream from Paonia Dam and 0.2 mile upstream from the confluence with

Anthracite Creek. The discharge of Muddy Creek downstream from Paonia Reservoir (fig. 9) is controlled by releases from Paonia Dam. During the nonirrigation season, the lower outlet works are left open so that stream discharge being released from the reservoir is nearly equal to the stream discharge flowing into Paonia Reservoir. Once the reservoir fills in the spring, additional water spills over the upper spillway on the north side of the dam. Gage-height records were available for the same 483 days that gage-height records were available for Muddy Creek upstream from Paonia Reservoir. Measured instantaneous discharge ranged from 82.0 to 528 cubic feet per second in 1986. During water year 1986, the daily mean discharge ranged from 18 to 1,470 cubic feet per second. During water year 1987, measured instantaneous discharge ranged from 24.6 to 1,130 cubic feet per second, and daily mean discharge ranged from 18 to 1,210 cubic feet per second. The maximum instantaneous discharge measured (1,130 cubic feet per second) was about 77 percent of the maximum daily mean discharge (1,470 cubic feet per second) for the period of record.

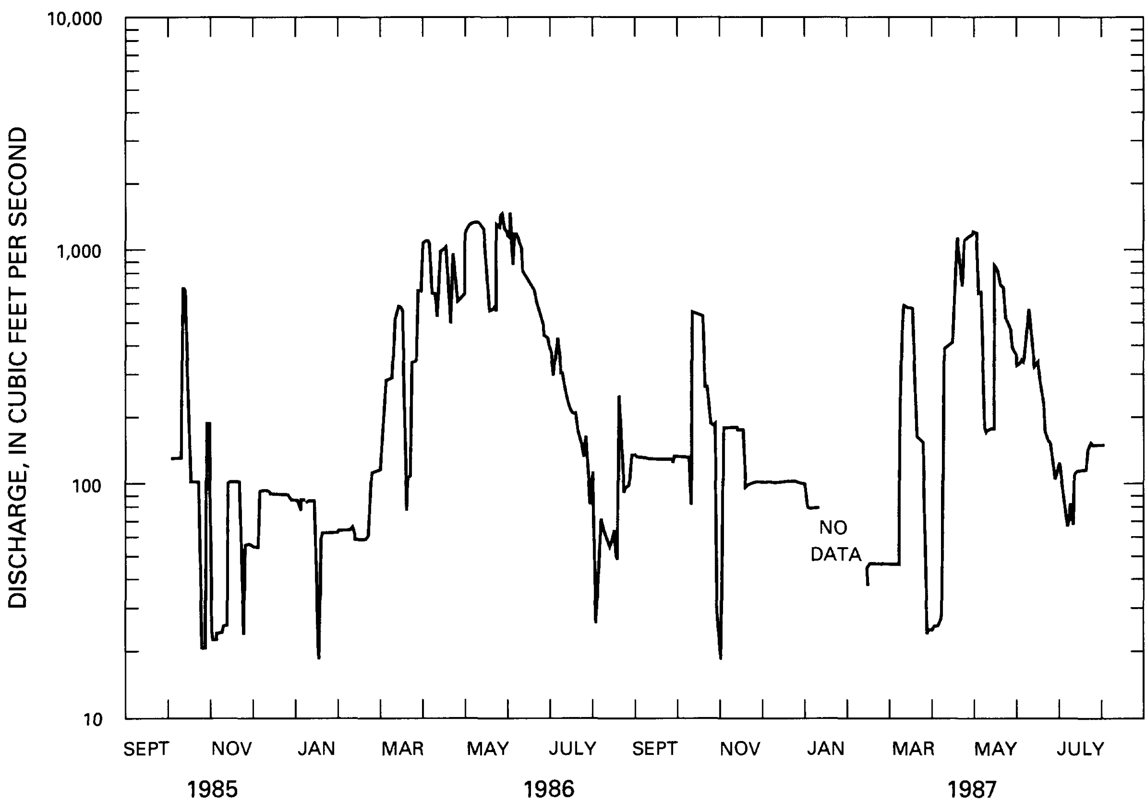


Figure 9.--Daily mean discharge of Muddy Creek downstream from Paonia Reservoir, water year 1986 and part of water year 1987.

When stream discharge was more than 300 cubic feet per second, measurements were made from the bridge 0.05 mile downstream from the gage. Because stream discharge in this cross section was difficult to measure accurately, the stream-discharge measurements were as much as 20 percent greater than the stream discharge computed from the stream-gage height and the rating curve. The rating curve is the relation of stream-gage height to stream discharge derived from all the stream-discharge measurements made by the Colorado Department of Natural Resources, Division of Water Resources, Office of the State Engineer at this gaging station.

SEDIMENT DISCHARGES AND LOADS

Suspended sediment is transported in suspension in the water by turbulence in the stream, and its weight is supported by the water. Bedload sediment is transported on or near the streambed by rolling, sliding, or saltation, and its weight is supported by the streambed. Suspended-sediment concentration, in milligrams per liter, is the mass of sediment (milligrams) per unit volume of water (liters) in a sample collected from a stream. Suspended-sediment discharge and bedload discharge are the rates (tons per day) at which a mass of sediment (tons) passes a stream transect during a unit of time (day). Suspended-sediment load is the total mass of suspended material, in tons, transported past a stream transect. Bedload is the total mass of bedload material, in tons, transported past a stream transect. The total-sediment load is the sum of the suspended-sediment load and bedload, in tons.

Sediment data were collected by the U.S. Geological Survey from June through November 1986 and from April through July 1987 at the streamflow-gaging stations and at Spring Creek (fig. 4). Suspended-sediment samples were collected by using the equal-width-increment method (Guy and Norman, 1970). Bedload samples were collected using Helley-Smith samplers and techniques described in Emmett (1980). Stream discharge was measured for each sediment sample collected. These data were used to estimate the total-sediment load of East Muddy Creek, Spring Creek, West Muddy Creek, and Muddy Creek upstream from and downstream from Paonia Reservoir. The combined total-sediment load of East Muddy Creek, Spring Creek, and West Muddy Creek represents the total-sediment load upstream from the landslide complex and is assumed to represent the total-sediment load of Muddy Creek upstream from Paonia Reservoir before movement of the landslide complex. The total-sediment load of Muddy Creek at the streamflow-gaging station upstream from Paonia Reservoir includes any contribution of sediment by the landslide complex. The suspended-sediment load of Muddy Creek downstream from Paonia Reservoir was used to estimate the trap efficiency of the reservoir.

Collection of sediment samples began in late June 1986, about 3 weeks after movement of the landslide complex ceased, and no sediment samples were collected during peak runoff. The stream discharge and the sediment concentrations, and thus the sediment discharge, probably were greater while the landslide complex was moving 9 to 12 feet per day than when samples were actually collected. Sediment concentrations probably were greater when the stream discharge was higher. Thus, the sediment discharges presented in this report probably are less than those that actually occurred during peak runoff and when the landslide complex was moving rapidly. Therefore, the sediment discharges and sediment loads presented in this report need to be considered as estimates only.

The suspended-sediment concentrations were converted to suspended-sediment discharge, in tons per day, by the equation:

$$Qs = 0.0027\ QC \tag{1}$$

where Qs = the suspended-sediment discharge, in tons per day;
0.0027 = the factor that converts the sediment concentration, in milligrams per liter, to the sediment discharge in tons per day [assuming 1 cubic foot of water-sediment mixture weighs 62.4 pounds (Porterfield, 1972)];
Q = the stream discharge, in cubic feet per second; and
C = the suspended-sediment concentration, in milligrams per liter.

The suspended-sediment discharge is computed by using equation (1), in which the entire stream discharge is multiplied by the depth-integrated suspended-sediment concentration. That computation involves several inherent assumptions. The bottom 0.3 foot of the stream was not sampled by the equipment used to collect suspended-sediment samples. Therefore, the extrapolation of the sampled suspended-sediment concentration to the bottom 0.3 foot is implied in the computation. Such extrapolation can cause underestimation of the actual suspended-sediment concentration if there is a large increase in sediment concentration at the bottom of the stream, which often is true for streams with sand channels. The streams in the Muddy Creek basin are not sand channels, and the streams also have fairly rough streambeds that cause turbulence and mixing in the stream. Therefore, it was assumed that the sampled suspended-sediment concentration was representative of the sediment concentration for the entire stream discharge. Bedload samplers may collect a small amount of suspended sediment in the bottom 0.3 foot of the stream. Adding the suspended-sediment discharge computed by using equation (1) to the bedload discharge may overestimate the total-sediment discharge because part of the suspended sediment was accounted for in both sediment discharge computations. After examination of the particle-size distributions of suspended sediment and bedload sediment and of the magnitude of the bedload discharge compared to the suspended-sediment discharge, it appears that the quantity of suspended sediment collected by the bedload sampler generally was small. Therefore, it was assumed that the error induced by adding the suspended-sediment discharge to the bedload discharge was not significant.

The relation of instantaneous suspended-sediment discharge to instantaneous stream discharge is approximately linear when the data are transformed logarithmically, which results in a regression equation (modified from Glysson, 1987, p. 15) of the form:

$$\log(Qs) = a+b[\log(Q)]+c(F) \tag{2}$$

where log = the base 10 logarithm;
Qs = the suspended-sediment discharge, in tons per day, derived from equation 1;
a = the regression intercept, in base 10 logarithm units;
b = the regression slope, in base 10 logarithm units;
Q = the stream discharge, in cubic feet per second;

c = the coefficient used in the regressions for East Muddy Creek, West Muddy Creek, and Muddy Creek upstream from Paonia Reservoir if rainfall had recently occurred in these basins, and used in the regression equation for Muddy Creek downstream from Paonia Reservoir when the lower spillway of Paonia Dam was being used to release water; and

F = the factor set equal to 1 when rainfall had recently occurred in the drainage basins or when the lower spillway was being used to release water, so that the coefficient (c) has value when it is applied to the regression; otherwise, the factor is set equal to 0.

Least-squares analysis of covariance was used to estimate the relation of stream discharge to suspended-sediment discharge during rainfall and nonrainfall periods. The suspended-sediment concentrations for East Muddy Creek, West Muddy Creek, and Muddy Creek upstream from Paonia Reservoir were greater in samples collected when rainfall had recently occurred in the drainage basins than were concentrations in samples collected when no rain had recently fallen. The suspended-sediment concentrations also were greater in samples collected at Muddy Creek downstream from Paonia Reservoir when the lower spillway was being used to release water than were those concentrations in samples collected when the upper spillway was being used. Coefficient (a) is the regression intercept and is used in estimating the suspended-sediment discharge for rainfall and nonrainfall periods. Coefficient (b) is the regression slope and also is used in estimating the suspended-sediment discharge for rainfall and nonrainfall periods.

Coefficient (c), which is used in the regression relations for East Muddy Creek, West Muddy Creek, and Muddy Creek upstream from Paonia Reservoir, estimates the effect of rainfall on the suspended-sediment discharge when the suspended-sediment concentration was increased in response to rainfall in the respective drainage basins. The rainfall factor, through the product of (c) and (F), was included in the regression relations and applied to the stream discharge only for days or parts of days when discharge was increasing in response to rainfall. For all other days, variable (F) was set equal to zero and, therefore, the product of (c) and (F) also was zero. The regression relation used for rainfall periods has the same slope as the regression relation for nonrainfall periods, but the intercept is shifted by coefficient (c) in base 10 logarithm units. In using analysis of covariance, it is assumed that rainfall in the drainage basins upstream from the reservoir did not affect the variance of $\log(Qs)$ with $\log(Q)$. Therefore, the variance about the line of least squares for rainfall periods is assumed to be equal to the variance about the line of least squares for nonrainfall periods. Hence, analysis of covariance allows some information from the larger data subset for nonrainfall periods to be used to help define the shifted line of least squares for the smaller data subset for rainfall periods. Periods of rainfall were estimated based on daily precipitation records collected at the Paonia 1 SW climatic station and the gage-height records available for the respective streamflow-gaging stations.

In the regression relation for Muddy Creek downstream from Paonia Reservoir, coefficients (a) and (b) are used to estimate the suspended-sediment discharge when the upper or the lower spillway was being used to release water from Paonia Dam. The release factor, through the product of (c) and (F), estimates the increase in suspended-sediment discharge resulting from the scouring of sediment when the lower spillway on Paonia Dam was used to release water. This factor has an effect on the regression relation only when the lower spillway is being used to release water. The regression relation used for periods when the lower spillway was being used has the same slope as the regression relation for periods when the upper spillway was being used, but the intercept is shifted by coefficient (c) in base 10 logarithm units. In using analysis of covariance, it is assumed that use of the lower spillway did not affect the variance of $\log(Qs)$ with $\log(Q)$. Hence, analysis of covariance allows some information from the larger data subset for periods when the upper spillway was being used to help define the shifted line of least squares for the smaller data subset for periods when the lower spillway was being used. Periods when the lower spillway on Paonia Dam was being used were determined from records of the water level in Paonia Reservoir available from the U.S. Bureau of Reclamation (Ed Warner, written commun., 1987).

A least-squares regression relation was used to estimate the suspended-sediment discharge of Spring Creek during the 216-day period. No gage-height records were available at Spring Creek and, therefore, not enough data were available to determine the effect of rainfall in the drainage basin on the suspended-sediment discharge. The only independent variable used in this equation was $\log(Q)$.

When a least-squares regression equation is used to predict the value of a dependent variable, such as suspended-sediment discharge, the value predicted is a mean value and is represented by the line of least squares. One of the assumptions of least-squares regression is that the distribution of the errors of the predicted value is normal and, therefore, the estimated values of the dependent variable also are median values. In transformed data, the predicted mean value of the dependent variable also is equal to the median value. However, when the data are untransformed to nonlogarithmic mean values, the nonlogarithmic mean value is not necessarily equal to the mean of the logarithmic value. To correct for the bias resulting from the untransformation of logarithm-transformed data, a correction factor is applied to the retransformed values of the dependent variable predicted by the respective regression relations. The correction applied is the so-called "smearing estimate" of Duan (1983), and in the case of the base 10 logarithm transformation, the correction is:

$$Qs = \text{antilog}\{a+b[\log(Q)]\} \sum_{i=1}^{n} \text{antilog}(ei)/n \tag{3}$$

where Qs = the sediment discharge, in tons per day;
antilog = the inverse of the base 10 logarithm;
a = the regression intercept, in base 10 logarithm units;
b = the regression slope, in base 10 logarithm units;
$\log(Q)$ = the base 10 logarithm of the stream discharge;

$\sum_{i=1}^{n}$ antilog(ei) = the sum of all the antilogs of the true residuals;

ei = the true residual between the predicted and the actual value of suspended-sediment discharge; and

n = the number of samples.

For each regression relation, the 90-percent prediction intervals were computed for each line of least squares using the equation:

$$PI = \hat{y} \pm [t_{(1-\alpha)/2,n-2}](se) \tag{4}$$

where PI = the prediction interval;

$\hat{y}$ = the predicted value of suspended-sediment or bedload discharge for a given stream discharge;

$t_{(1-\alpha)/2}$ = the value of the student's t-distribution for quantile $(1-\alpha)/2$, and the given number of degrees of freedom (n-2);

n = the number of samples; and

se = the standard error of the regression, in logarithm units.

The 90-percent prediction interval is the range that an individual value of suspended-sediment or bedload discharge will be within 90 percent of the time, given a certain value of stream discharge.

The mass of a bedload sample collected from a stream transect, in grams, was converted to bedload discharge, in tons per day, by the equation (William Emmett, U.S. Geological Survey, written commun., 1989, modified from Edwards and Glysson, 1987, p. 103):

$$Qb = 1.1428 \frac{(wt)\ (W)}{(nti)}$$

where Qb = bedload discharge, in tons per day;

1.1428 = factor that converts the units to tons per day.

wt = weight of the bedload sample, in grams;

W = width of the stream transect, in feet;

n = number of sampling verticals;

t = duration of sampling time at each sampling vertical, in seconds; and

i = horizontal width of the sampler intake, in inches;

Bedload discharge was estimated using least-squares regression, which results in an equation similar to equation 2. The regression equation includes coefficients (a) and (b). An insufficient number of bedload samples were collected to determine when the bedload discharge was being affected by rainfall, however, so variable (F) is not included in the equation. The smearing estimate also was used to estimate the bedload discharge for each stream.

Suspended Sediment

East Muddy Creek

Suspended-sediment samples from East Muddy Creek were collected 15 times during this study (table 2). The largest suspended-sediment concentrations sampled were 3,200 and 3,330 milligrams per liter when the stream discharge was 29.3 and 47.8 cubic feet per second. These samples were collected during or soon after rainstorms in the drainage basin. The largest concentration sampled during spring runoff was 1,240 milligrams per liter when the stream discharge was 352 cubic feet per second. The smallest suspended-sediment concentration sampled was 33 milligrams per liter when the stream discharge was 46.6 cubic feet per second.

There are several landslide deposits in the East Muddy Creek drainage basin upstream from the streamflow-gaging station on East Muddy Creek. The landslide deposits provide large quantities of material for transport as suspended-sediment and bedload by East Muddy Creek. Rainfall on the landslides or movement of the landslides may increase the total-sediment discharge of East Muddy Creek substantially; whereas, when no movement or rainfall has occurred, the total-sediment discharge probably is less. This may be one of the reasons for the variation in the suspended-sediment discharge for a given stream discharge of East Muddy Creek.

Table 2.--*Summary of sediment data collected at East Muddy Creek near Paonia Reservoir, 1986-87*

[Suspended-sediment discharge is computed by multiplying 0.0027 by stream discharge and by suspended-sediment concentration; *, sample collected during rainfall period; --, missing data]

Date of sample	Stream discharge (cubic feet per second)	Suspended-sediment concentration (milligrams per liter)	Suspended-sediment discharge (tons per day)	Bedload	
				Discharge (tons per day)	Percent of total-sediment discharge
06-23-1986	222	54	32	--	--
07-14-1986	68.3	37	6.8	--	--
07-29-1986	36.7	130	13	0.06	0.46
08-20-1986	17.3	42	2.0	--	--
08-22-1986*	29.3	3,200	253	--	--
09-23-1986*	47.8	3,330	430	.30	.07
11-18-1986	49.9	329	44	--	--
04-06-1987	62.5	668	113	28.8	20.3
04-20-1987	352	1,240	1,180	--	--
05-06-1987	364	422	415	3.73	.89
05-18-1987	353	408	389	--	--
06-01-1987	159	240	103	2.78	2.63
06-16-1987	144	46	18	--	--
07-01-1987	46.6	33	4.2	.014	.33
07-13-1987	26.5	78	5.6	--	--

A regression relation between suspended-sediment discharge and stream discharge was computed using data from the 15 samples listed in table 2. This regression relation yielded a coefficient of determination of 0.40. Using analysis of covariance, another regression relation was computed by using data for the 15 samples listed in table 2. Factor *F* was set equal to 0 for the 13 samples collected when no rainfall had recently occurred in the drainage basin; factor *F* was set equal to 1 for the 2 samples collected on August 22 and September 23, 1986, when suspended-sediment concentrations were increased because of rainfall. The latter regression relation yielded a coefficient of determination of 0.76 (table 3). The two regression curves, one for the non-rainfall periods ($F = 0$) and one for the rainfall periods ($F = 1$), for the latter regression relation are plotted in figure 10. In addition to the data points and the lines of least squares for nonrainfall and rainfall periods, the 90-percent prediction intervals for each regression line are shown in figure 10. Each of these prediction intervals spans nearly 2 orders of magnitude in suspended-sediment discharge for a given stream discharge. The correction for the bias created by transforming the dependent variable, or the smearing estimate, is 1.54. This relation may underestimate the suspended-sediment discharge when the stream discharge is greater than the largest stream discharge sampled, which was 364 cubic feet per second. The daily mean discharge was more than 364 cubic feet per second on 22 days during the 216-day period. The maximum daily mean discharge during the period for which gage-height record is available was 733 cubic feet per second.

Table 3.--*Relations of suspended-sediment discharge to stream discharge*

[*n*, number of samples; r^2, coefficient of determination; *se*, standard error of estimate in percent; log, base 10 logarithm units; *Qs*, suspended-sediment discharge, in tons per day; *Q*, stream discharge, in cubic feet per second; *F*, variable set equal to 1 so coefficient is used to estimate suspended-sediment discharge during rainfall periods for East Muddy Creek, West Muddy Creek, and Muddy Creek upstream from Paonia Reservoir, or for Muddy Creek downstream from Paonia Reservoir when the lower spillway of Paonia Dam was being used; otherwise, the variable is set equal to 0]

Stream name	Statistical values for regression of relation of suspended-sediment discharge to stream discharge			
	n	r^2	Regression relation	*se*
East Muddy Creek	15	0.76	$\log(Qs)=-1.58+1.60\log(Q)+1.58(F)$	127
Spring Creek	13	.67	$\log(Qs)=-0.65+1.91\log(Q)$	78
West Muddy Creek	14	.86	$\log(Qs)=-1.96+1.65\log(Q)+1.20(F)$	120
Muddy Creek upstream from Paonia Reservoir	15	.93	$\log(Qs)=-1.28+1.40\log(Q)+1.40(F)$	48
Muddy Creek downstream from Paonia Reservoir	12	.81	$\log(Qs)=-3.86+2.07\log(Q)+0.79(F)$	123

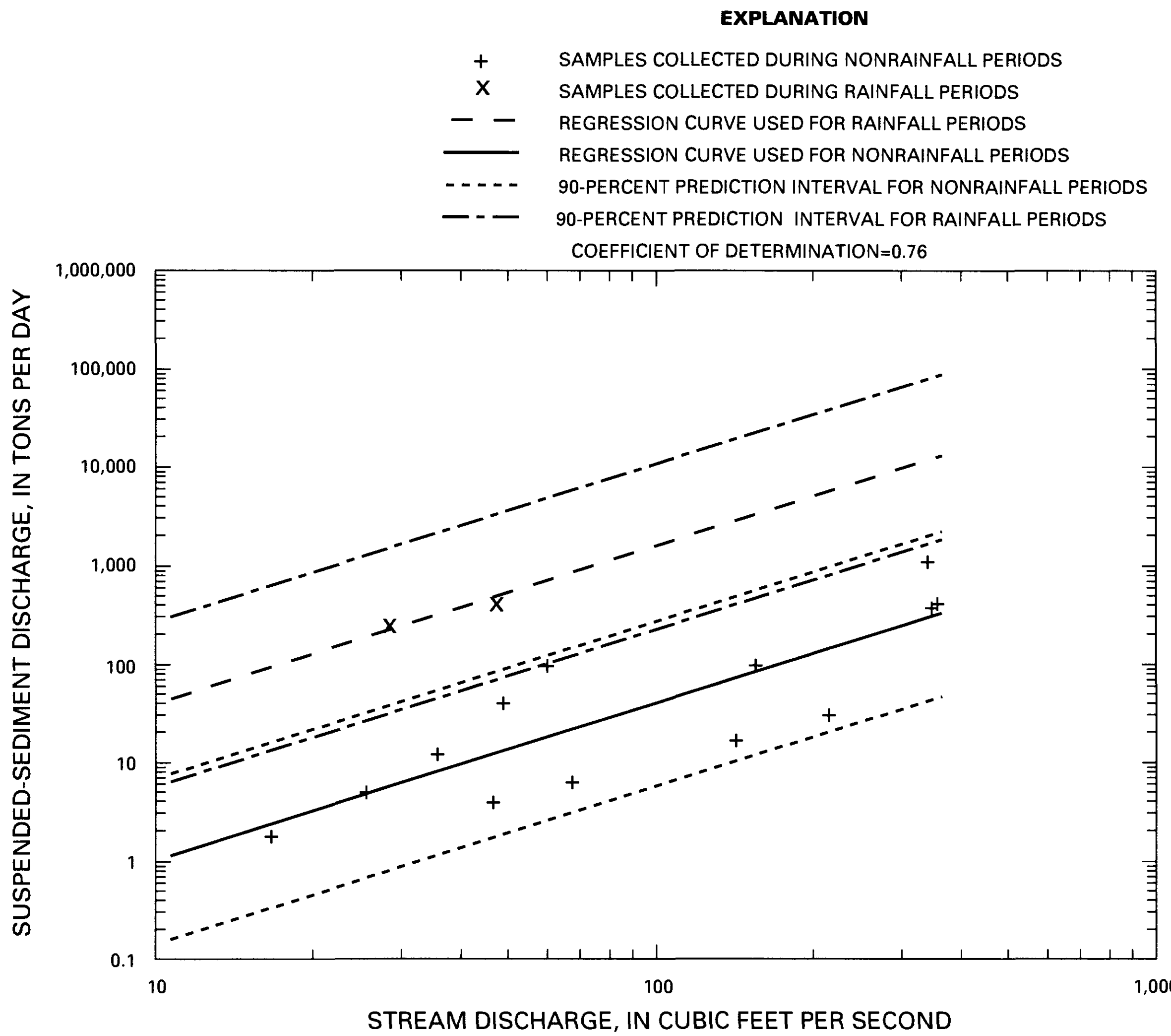


Figure 10.--Relation of suspended-sediment discharge to stream discharge for East Muddy Creek near Paonia Reservoir.

The regression relations were used to estimate the suspended-sediment discharge of East Muddy Creek for the 216 days for which gage-height records are available. During this period, the suspended-sediment load was 69,300 tons, or an average of about 320 tons per day.

The particle-size distribution of suspended sediment larger than 0.062 millimeters is listed in table 4. A larger percentage of suspended sediment is larger than 0.062 millimeters in diameter during higher streamflow than during lower streamflow.

Spring Creek

Suspended-sediment samples were collected 13 times from Spring Creek (table 5). The suspended-sediment concentration ranged from 116 milligrams per liter when the stream discharge was 5.7 cubic feet per second to 1,610 milligrams per liter when the stream discharge was estimated to be 12 cubic feet per second.

Table 4.--*Particle-size distribution of suspended-sediment samples collected at East Muddy Creek near Paonia Reservoir, 1986-87*

Date of sample	Percent finer than indicated size, in millimeters					
	2.00	1.00	0.500	0.250	0.125	0.062
06-23-1986	100	100	99.5	98.4	93.6	87.2
07-14-1986	100	100	99.9	99.8	98.0	93.9
07-29-1986	100	100	99.0	98.6	95.3	80.0
08-20-1986	100	100	95.3	91.7	78.6	54.9
08-22-1986	100	100	99.8	99.6	99.4	99.0
09-23-1986	100	100	99.2	96.0	94.5	88.5
11-18-1986	100	100	98.9	93.1	84.6	77.7
04-06-1987	100	100	99.5	95.2	86.8	71.6
04-20-1987	100	100	95.4	76.0	53.8	33.5
05-06-1987	100	99.2	97.4	93.2	84.0	66.1
05-18-1987	100	100	94.7	83.6	70.3	50.5
06-01-1987	100	100	99.9	96.1	93.0	80.9
06-16-1987	100	100	100	88.3	85.8	73.0
07-01-1987	100	100	100	99.1	96.4	83.4
07-13-1987	100	100	100	99.6	98.5	96.7

A regression relation of suspended-sediment concentration to stream discharge was computed by using data from all 13 samples listed in table 5. Because gage-height records were not available for Spring Creek, it is not known when the suspended-sediment concentration was being affected by rainfall. The regression relation had a coefficient of determination of 0.67. The results of the regression analysis are listed in table 3 and plotted in figure 11. The correction for the bias created by transformation of the dependent variable, or the smearing estimate, is 1.21. The 90-percent prediction interval consists of about 1 order of magnitude for the predicted value of suspended-sediment discharge for a given stream discharge.

Table 5.--*Summary of sediment data collected at Spring Creek near Paonia Reservoir, 1986-87*

[Suspended-sediment discharge is computed by multiplying 0.0027 by stream discharge and by suspended-sediment concentration; *e*, denotes stream discharge estimated]

Date of sample	Stream discharge (cubic feet per second)	Suspended-sediment concentration (milligrams per liter)	Suspended-sediment discharge (tons per day)
07-17-1986	20 *e*	1,490	80
07-29-1986	11	790	23
08-20-1986	5.7	116	1.8
09-23-1986	10 *e*	1,360	37
11-18-1986	5.3	599	8.6
04-06-1987	4 *e*	807	8.7
04-20-1987	5	327	4.4
05-06-1987	5 *e*	151	2.0
05-18-1987	12	986	32
06-01-1987	12 *e*	1,610	52
06-16-1987	13	505	18
07-01-1987	15	467	19
07-13-1987	10 *e*	824	22

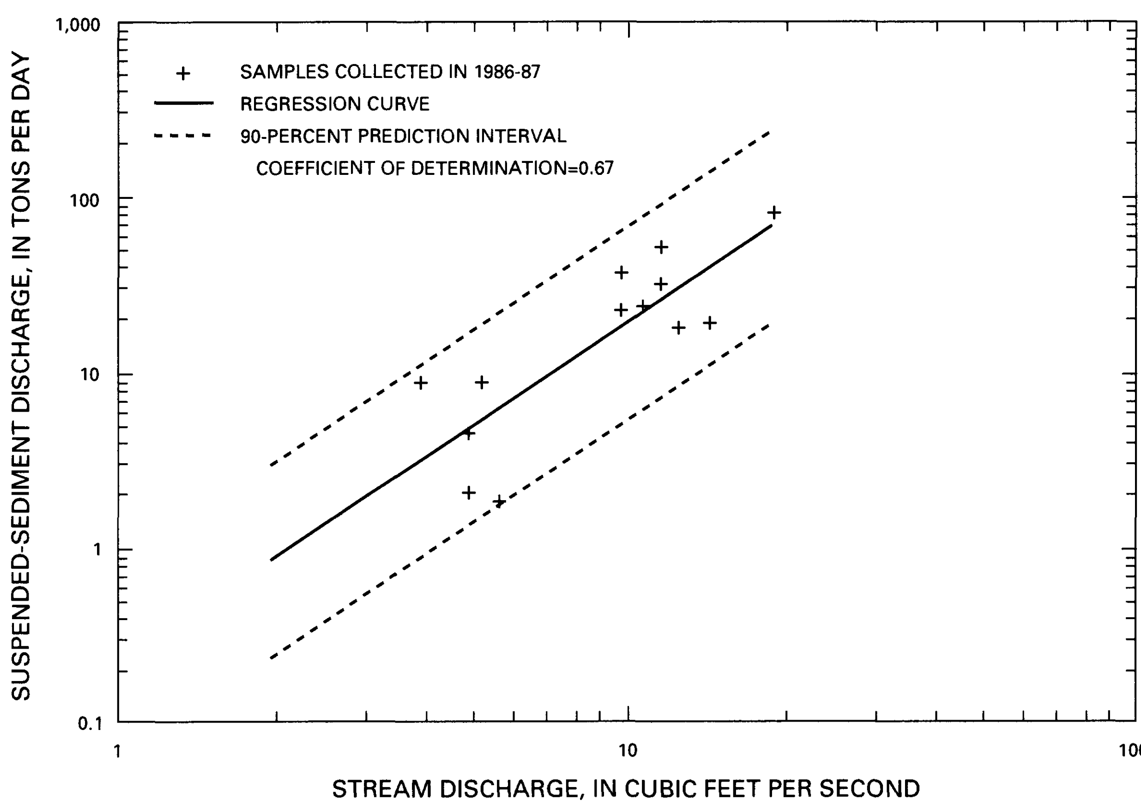


Figure 11.--Relation of suspended-sediment discharge to stream discharge for Spring Creek near Paonia Reservoir.

The mean daily stream discharge of Spring Creek was estimated to be 10 cubic feet per second during the 216-day period. Measured and estimated instantaneous discharges ranged from 4 to 20 cubic feet per second. Applying a daily mean discharge of 10 cubic feet per second to the regression relation results in a suspended-sediment discharge of 22 tons per day. The estimated suspended-sediment load from Spring Creek was 4,770 tons during the 216-day period. The estimated suspended-sediment discharge of Spring Creek varies substantially with stream discharge as listed below:

Stream discharge (cubic feet per second)	Suspended-sediment discharge (tons per day)
5	5.9
10	22
15	48
20	83

Particle-size distribution of suspended sediment from Spring Creek is listed in table 6. A larger percentage of the suspended sediment from Spring Creek is larger in diameter than the suspended sediment from the other drainages. The source of this material may be the landslide complex.

Table 6.--*Particle-size distribution of suspended-sediment samples collected at Spring Creek near Paonia Reservoir, 1986-87*

Date of sample	Percent finer than indicated size, in millimeters					
	2.00	1.00	0.500	0.250	0.125	0.062
07-17-1986	100	94.9	89.2	77.6	62.1	57.3
07-29-1986	100	94.7	86.0	73.8	61.5	52.3
09-23-1986	100	88.2	78.5	56.5	44.9	36.1
11-18-1986	100	100	92.5	80.5	68.7	57.7
04-06-1987	100	100	94.9	87.8	79.0	68.7
04-20-1987	100	100	93.6	80.5	63.7	50.1
05-06-1987	100	100	98.7	89.6	72.4	56.4
05-18-1987	100	100	94.5	82.5	66.1	51.3
06-01-1987	96.9	94.6	89.0	79.4	64.5	48.9
06-16-1987	100	88.4	84.2	69.9	50.5	37.8
07-01-1987	100	87.8	80.2	66.1	51.3	38.5
07-13-1987	100	97.1	89.4	74.5	57.2	39.7

West Muddy Creek

During this study, 14 suspended-sediment samples were collected from West Muddy Creek during 1986-87 (table 7). Samples also were collected by the U.S. Forest Service at a streamflow-gaging station 12 miles upstream from the streamflow-gaging station installed by the U.S. Geological Survey. The largest suspended-sediment concentration sampled by the U.S. Geological Survey was 1,490 milligrams per liter when the stream discharge was 97.1 cubic feet per second. This sample was collected September 23, 1986, when the suspended-sediment concentration increased in response to rainfall in the drainage basin. The sample collected on July 1, 1987, also was collected when the suspended-sediment concentration increased in response to rainfall. The largest suspended-sediment concentration sampled during spring runoff was 565 milligrams per liter when the stream discharge was 324 cubic feet per second. The smallest suspended-sediment concentration sampled was 9.5 milligrams per liter when the stream discharge was 12.3 cubic feet per second.

Table 7.--*Summary of sediment data collected at West Muddy Creek near Paonia Reservoir, 1986-87*

[Suspended-sediment discharge is computed by multiplying 0.0027 by stream discharge and by suspended-sediment concentration; *, sample collected during rainfall period; --, missing data]

Date of sample	Stream discharge (cubic feet per second)	Suspended-sediment concentration (milligrams per liter)	Suspended-sediment discharge (tons per day)	Bedload	
				Discharge (tons per day)	Percent of total-sediment discharge
06-23-1986	174	23	11	--	--
07-14-1986	89.5	12	2.9	--	--
07-29-1986	12.3	9.5	.32	0.0025	.78
08-20-1986	5.70	22	.34	--	--
09-23-1986*	97.1	1,490	391	.25	.06
11-18-1986	42.4	58	6.6	--	--
04-07-1987	48.0	206	27	.32	1.17
04-20-1987	324	565	494	--	--
05-06-1987	312	286	241	4.52	1.84
05-18-1987	310	248	208	--	--
06-01-1987	96.1	54	14	.51	3.51
06-16-1987	88.4	97	23	--	--
07-01-1987*	19.7	388	21	.003	.01
07-13-1987	10.6	27	.77	--	--

A regression relation of suspended-sediment discharge to stream discharge was computed by using all the suspended-sediment data collected on West Muddy Creek, including the data collected by the U.S. Forest Service. This relation yielded a coefficient of determination of 0.71. Another regression relation was computed using only the data collected by the U.S. Geological Survey. This relation had a coefficient of determination of 0.72. Neither relation was considered suitable for estimating suspended-sediment discharge for West Muddy Creek. Using analysis of covariance, another regression relation was computed using data for the 14 samples listed in table 7. Factor F was set equal to 0 for the 12 samples collected when no rainfall had occurred in the basin for several days, and was set equal to 1 for the 2 samples collected when the sediment concentrations were greater as a result of rainfall in the drainage basin. The latter regression analysis (table 3) resulted in a coefficient of determination of 0.86. The two regression curves, one for the non-rainfall periods (F = 0) and one for the rainfall periods (F = 1), for the latter regression relation are plotted in figure 12. The correction for the bias created by transforming the dependent variable, or the smearing estimate, is 1.38. The 90-percent prediction intervals for nonrainfall and rainfall regression curves, both of which span nearly 2 orders of magnitude in suspended-sediment discharge for a given stream discharge, also are shown in figure 12. The regression relation may underestimate the actual suspended-sediment discharge during periods of streamflow greater than 324 cubic feet per second, which was the maximum stream discharge sampled. The daily mean discharge exceeded 324 cubic feet per second on 25 days during the 216-day period.

The regression relation listed in table 3 for West Muddy Creek was applied to the daily mean discharges computed from the gage-height record for West Muddy Creek to estimate the suspended-sediment discharge. The resulting suspended-sediment load was 25,500 tons during the 216 days, or an average of about 118 tons per day.

The particle-size distribution of suspended sediment at West Muddy Creek is listed in table 8. The data in table 8 indicate that much of the suspended sediment in West Muddy Creek is composed of silt- and clay-sized particles (less than 0.062 millimeters).

Table 8.--*Particle-size distribution of suspended-sediment samples collected at West Muddy Creek near Paonia Reservoir, 1986-87*

Date of sample	Percent finer than indicated size, in millimeters					
	2.00	1.00	0.500	0.250	0.125	0.062
06-23-1986	100	100	99.6	99.5	98.3	95.2
07-14-1986	100	100	98.3	97.7	93.6	85.3
07-29-1986	100	100	100	97.2	91.9	74.6
08-20-1986	100	100	91.3	80.7	68.5	43.5
09-23-1986	100	100	98.4	97.0	90.1	71.2
11-18-1986	100	100	96.7	91.5	83.1	72.7
04-07-1987	100	100	99.1	96.3	90.6	78.7
04-20-1987	100	99.3	97.4	92.3	84.2	73.3
05-06-1987	100	100	96.4	88.9	76.0	62.9
05-18-1987	100	96.5	90.6	86.2	78.7	70.7
06-01-1987	100	100	100	99.9	94.4	89.5
06-16-1987	100	100	98.9	94.5	87.5	76.0
07-01-1987	100	100	100	99.9	99.2	96.6
07-13-1987	100	100	100	100	100	94.3

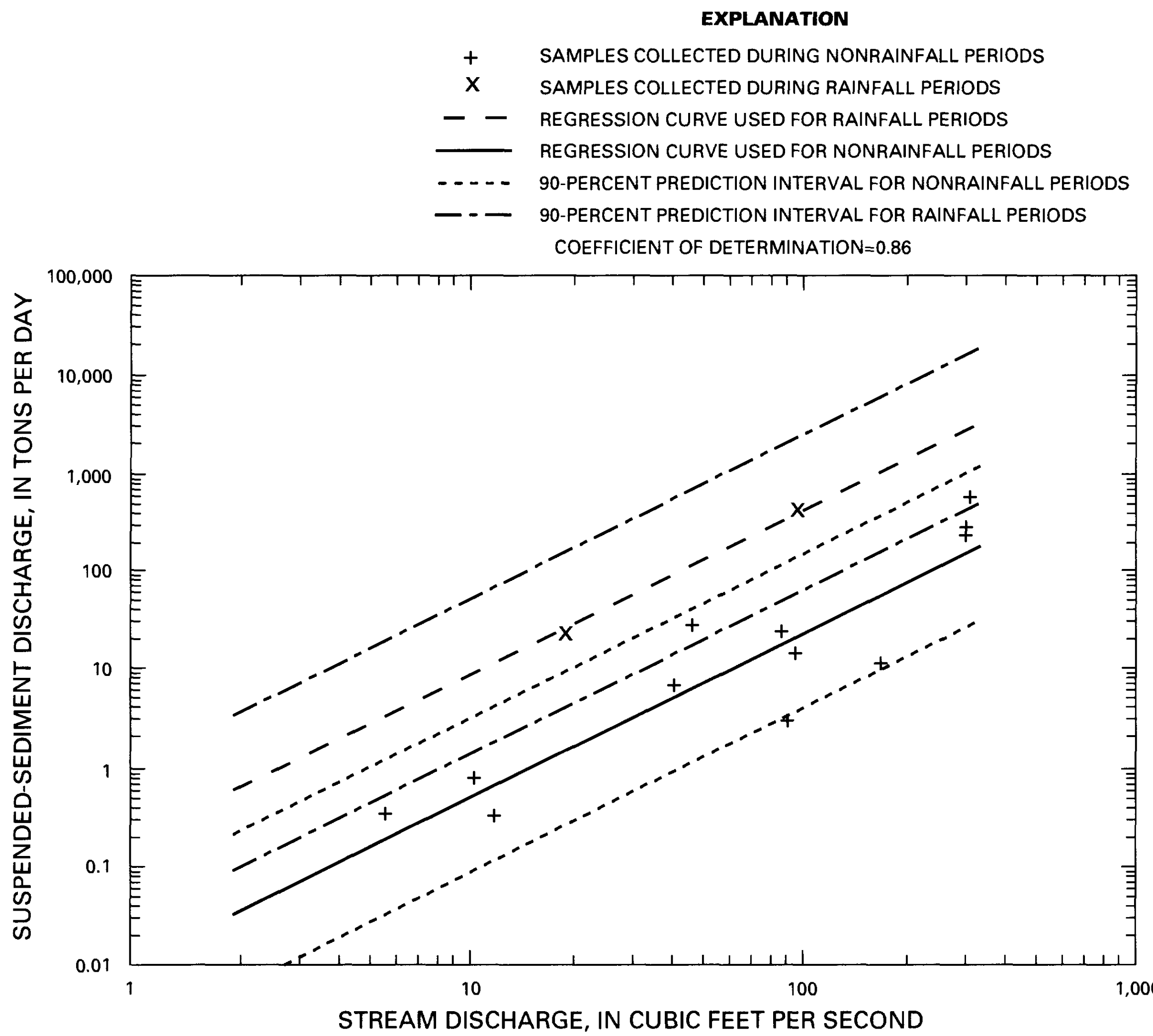


Figure 12.--Relation of suspended-sediment discharge to stream discharge for West Muddy Creek near Paonia Reservoir.

Muddy Creek Upstream From Paonia Reservoir

Suspended-sediment samples were collected 15 times in 1986-87 from Muddy Creek upstream from Paonia Reservoir (table 9). The suspended-sediment concentration ranged from 55 milligrams per liter when the stream discharge was 34.5 cubic feet per second to 4,900 milligrams per liter when the stream discharge was 57.9 cubic feet per second. The sample in which the concentration was 4,900 milligrams per liter was collected when rainfall had increased the suspended-sediment concentration. The largest concentration not affected by rainfall was 456 milligrams per liter when the stream discharge was 736 cubic feet per second.

Table 9.--*Summary of sediment data collected at Muddy Creek upstream from Paonia Reservoir, 1986-87*

[Suspended-sediment discharge is computed by multiplying 0.0027 by stream discharge and by suspended-sediment concentration; *, sample collected during rainfall period; --, missing data]

Date of sample	Stream discharge (cubic feet per second)	Suspended-sediment concentration (milligrams per liter)	Suspended-sediment discharge (tons per day)	Bedload	
				Discharge (tons per day)	Percent of total sediment discharge
06-24-1986	444	118	141	--	--
07-14-1986	196	234	124	--	--
07-29-1986	74.0	128	26	0.38	1.44
08-20-1986	34.5	55	5.1	--	--
08-22-1986*	57.9	4,900	766	--	--
09-24-1986*	140	1,770	669	37.6	5.32
11-18-1986	118	135	43	--	--
04-06-1987	145	182	71	3.78	5.05
04-21-1987	612	370	611	--	--
05-07-1987	736	456	906	55.7	5.79
05-18-1987	728	245	482	--	--
06-02-1987	288	169	131	3.91	2.90
06-16-1987	252	94	64	--	--
07-01-1987	97.8	141	37	.043	.12
07-13-1987	61.1	98	16	--	--

The U.S. Bureau of Reclamation collected 44 sediment samples during spring runoff in 1949, 1952, and 1953 (Robert Strand, U.S. Bureau of Reclamation, written commun., 1986). Regression analyses indicate that the two groups of samples were significantly different. Changes in the stream channel of Muddy Creek as a result of construction of Paonia Reservoir and Colorado State Highway 133 have occurred since the samples were collected during 1949, 1952, and 1953. Sampling methods also have changed since the samples were collected; therefore, the samples collected by the U.S. Bureau of Reclamation were not used in the analysis of the data collected for this study.

Using analysis of covariance, a regression relation of suspended-sediment discharge to stream discharge was computed by using data from the 15 samples listed in table 9. Factor F was set equal to 0 for the 13 samples collected when no rainfall had occurred in the Muddy Creek drainage basin for several days; factor F was set equal to 1 for the 2 samples collected on August 22 and September 24, 1986, when suspended-sediment concentrations increased because of rainfall. The results of the regression analysis are listed in table 3 and the two curves, one for non-rainfall periods ($F = 0$) and one for rainfall periods (F = 1), are plotted in figure 13. The regression relation had a coefficient of determination of 0.93. The correction for the bias created by transformation of the dependent variable, or the smearing estimate, is 1.08. The 90-percent prediction intervals for nonrainfall and rainfall regression relations span less than 1 order of magnitude in suspended-sediment discharge for a given stream discharge. This regression relation was used to estimate the suspended-sediment discharge of Muddy Creek upstream from Paonia Reservoir. The relation may underestimate the suspended-sediment discharge when the stream discharge is greater than 736 cubic feet per second (the maximum streamflow sampled) or when the landslide complex was moving. The daily mean discharge exceeded 736 cubic feet per second on 23 days during the 216-day period and on 61 days during the 483-day period.

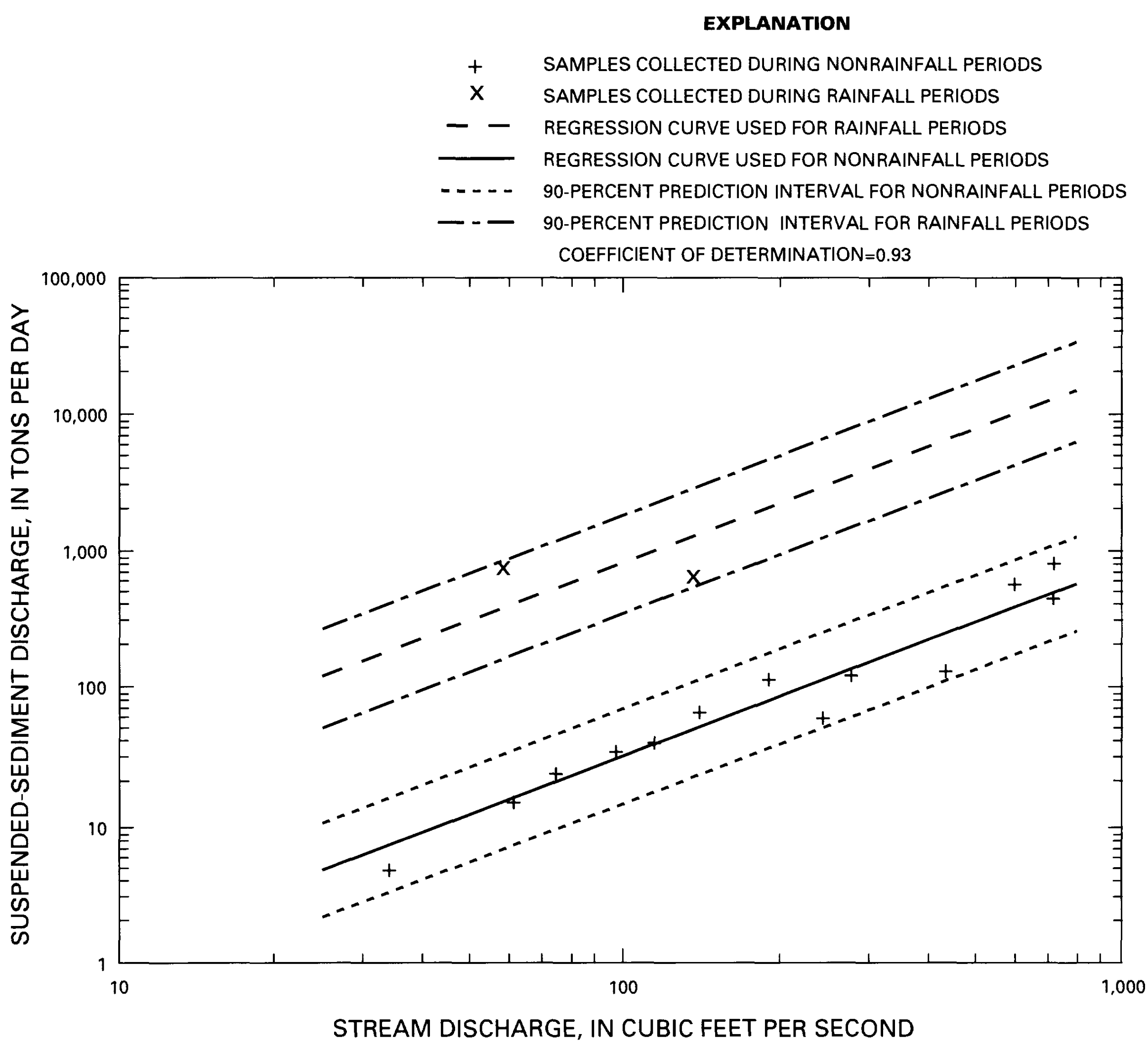


Figure 13.--Relation of suspended-sediment discharge to stream discharge for Muddy Creek upstream from Paonia Reservoir.

The regression relation was applied to the daily mean stream discharge to estimate the suspended-sediment load of Muddy Creek upstream from Paonia Reservoir. During the 216-day period, the suspended-sediment load was 140,000 tons, or an average of about 650 tons per day. During the 483-day period, the suspended-sediment load was 272,000 tons, or an average of about 560 tons per day. The combined suspended-sediment load from East Muddy Creek, Spring Creek, and West Muddy Creek for the 216-day period was about 99,600 tons, or an average of about 460 tons per day. This gain of 40,400 tons in suspended-sediment load may be caused by movement of the landslide complex. The lack of a stream-discharge record for Spring Creek means only a rough estimate of the sediment load from Spring Creek can be made. Additional suspended sediment is deposited in the pond on East Muddy Creek adjacent to the northern slide of the landslide complex. Therefore, the actual contribution of suspended-sediment load from the Muddy Creek landslide complex may be more than the estimated 40,400 tons of suspended-sediment load at Muddy Creek upstream from Paonia Reservoir.

The distribution of the particle size of suspended sediment from Muddy Creek upstream from Paonia Reservoir is listed in table 10. The distribution of the particle size of suspended sediment in Muddy Creek upstream from Paonia Reservoir is similar to that at East Muddy Creek (table 4). Generally, the percentage of suspended sediment finer than 0.062 millimeter in diameter decreases during periods of large stream discharge.

Table 10.--*Particle-size distribution of suspended-sediment samples collected at Muddy Creek upstream from Paonia Reservoir, 1986-87*

Date of sample	Percent finer than indicated size, in millimeters					
	2.00	1.00	0.500	0.250	0.125	0.062
06-24-1986	100	100	94.6	87.4	74.8	68.2
07-14-1986	100	99.7	99.5	96.1	92.8	88.4
07-29-1986	100	100	99.8	97.0	92.2	83.7
08-20-1986	100	100	99.8	99.7	98.4	95.4
08-22-1986	100	100	99.9	99.8	99.5	99.0
09-24-1986	100	100	99.2	97.5	95.1	91.7
11-18-1986	100	100	97.7	94.7	88.6	81.7
04-06-1987	100	100	98.6	95.5	92.3	88.1
04-21-1987	100	99.5	96.3	90.4	81.5	69.4
05-07-1987	100	96.0	92.1	85.1	72.2	58.5
05-18-1987	100	97.7	93.4	88.1	78.2	67.6
06-02-1987	100	100	99.7	97.8	94.1	90.0
06-16-1987	100	100	99.2	97.4	92.9	86.3
07-01-1987	100	100	100	100	98.5	95.6
07-13-1987	100	100	100	100	100	98.3

Muddy Creek Downstream From Paonia Reservoir

Twelve suspended-sediment samples were collected from Muddy Creek downstream from Paonia Reservoir during this study (table 11). The maximum suspended-sediment concentration sampled was 356 milligrams per liter; this sample was collected at the largest sampled stream discharge of 1,130 cubic feet per second. The suspended-sediment concentrations generally were greatest when the stream discharge was largest, which was when water was flowing over the upper spillway. The residence time of water flowing into the reservoir is brief; thus, the suspended sediment is not allowed to settle out when water is flowing over the upper spillway. The suspended-sediment concentration in water released through the lower spillway also is greater when the water level in the reservoir is low. The samples collected on November 18, 1986, on April 6, 1987, and on July 13, 1987, were collected when water was being released through the lower spillway. The largest stream discharge measured when the lower spillway was being used was 114 cubic feet per second.

Table 11.--*Summary of sediment data collected at Muddy Creek downstream from Paonia Reservoir, 1986-87*

[Suspended-sediment discharge computed by multiplying 0.0027 by stream discharge and by suspended-sediment concentration; *, sample collected when lower spillway was being used]

Date of sample	Stream discharge (cubic feet per second)	Suspended-sediment concentration (milligrams per liter)	Suspended-sediment discharge (tons per day)
06-24-1986	528	33	47
07-15-1986	202	13	7.1
07-29-1986	82.0	3.8	.84
11-18-1986*	101	22	6.0
04-06-1987*	24.6	74	4.9
04-21-1987	1,130	356	1,090
05-07-1987	655	131	232
05-19-1987	1,100	72	214
06-02-1987	338	24	22
06-16-1987	297	14	11
07-01-1987	118	5.0	1.6
07-13-1987*	114	13	4.0

Applying analysis of covariance to the 12 samples listed in table 11, a regression relation between suspended-sediment and stream discharge was computed. Factor F was set equal to zero for the 9 samples collected when water was flowing over the upper spillway; factor F was set equal to 1 for the 3 samples collected when the lower spillway was being used. The results of the regression analysis are listed in table 3 and plotted in figure 14.

The regression relation for the upper spillway was extended beyond the maximum discharge sampled (1,130 cubic feet per second). The daily mean stream discharge exceeded 1,130 cubic feet per second on 11 days in the 216-day period and on 30 days in the 483-day period. Stream discharge ranged from 20 to 150 cubic feet per second when the lower spillway was used during the 483-day period, which includes the 216-day period. No samples were collected outside of this range in stream discharge while the lower spillway was being used. The correction for the bias created when the dependent variable was transformed, or the smearing estimate, is 1.65. The regression relation had a coefficient of determination of 0.81. The 90-percent prediction intervals for the two regression relations also are shown in figure 14. Both intervals span about 1½ orders of magnitude.

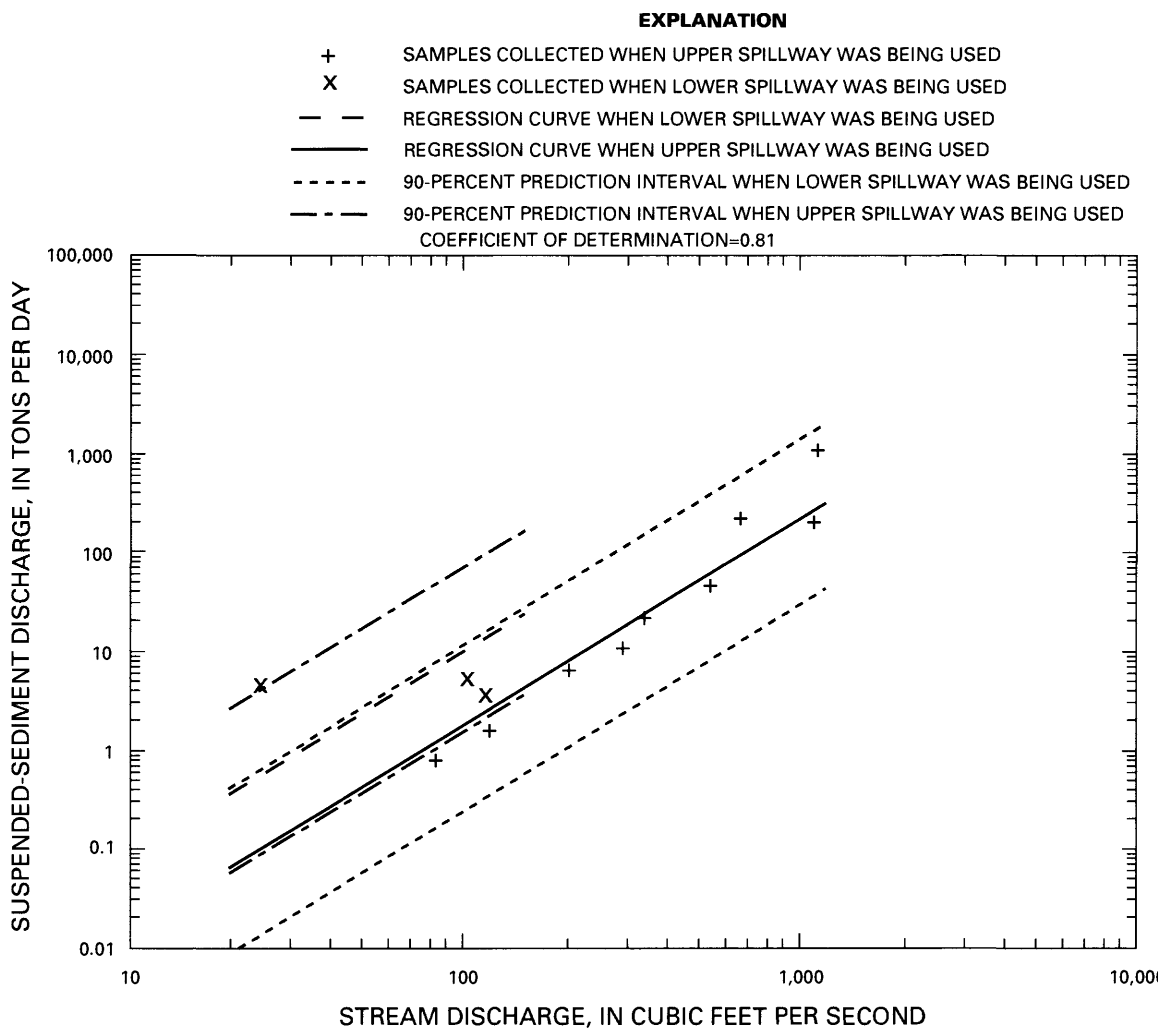


Figure 14.--Relation of suspended-sediment discharge to stream discharge for Muddy Creek downstream from Paonia Reservoir.

The regression relations were applied to the daily mean discharges for the 216- and 483-day periods. The computed suspended-sediment load for the 216-day period was 14,900 tons, or an average of about 69 tons per day. The suspended-sediment load for the 483-day period was 51,100 tons, or an average of about 106 tons per day.

The distribution of the particle size of suspended sediment in Muddy Creek downstream from Paonia Reservoir is listed in table 12. Generally, a larger percentage of the suspended sediment is finer than 0.062 millimeter than suspended sediment at the other streamflow-gaging stations. The larger suspended-sediment particles settle out in the reservoir. In 3 samples, 100 percent of the suspended sediment collected at the gaging station was smaller than 0.062 millimeter in diameter.

Table 12.--*Particle-size distribution of suspended-sediment samples collected at Muddy Creek downstream from Paonia Reservoir, 1986-87*

Date of sample	Percent finer than indicated size, in millimeters					
	2.00	1.00	0.500	0.250	0.125	0.062
06-24-1986	100	100	84.8	76.9	73.8	72.9
07-15-1986	100	100	100	99.3	97.8	97.3
07-29-1986	100	100	94.6	93.8	84.3	52.2
11-18-1986	100	100	99.8	98.9	97.9	95.8
04-06-1987	100	100	100	99.8	98.1	94.4
04-21-1987	100	100	100	100	99.5	98.9
05-07-1987	100	100	99.3	97.7	96.8	94.2
05-19-1987	94.5	91.3	91.2	88.8	86.7	86.2
06-02-1987	100	100	100	100	100	100
06-16-1987	100	100	100	100	100	100
07-01-1987	100	100	100	96.2	89.3	75.8
07-13-1987	100	100	100	100	100	100

Bedload

Bedload discharge generally was less than 6 percent of the total-sediment discharge from East Muddy Creek, West Muddy Creek, and Muddy Creek upstream from Paonia Reservoir (tables 2, 7, and 9). Bedload discharge from mountain streams, such as those in the Muddy Creek drainage basin, is variable. Because only six bedload samples were collected at each site, the bedload discharges presented in this report should be considered estimates only. No bedload samples were collected at Spring Creek or Muddy Creek downstream from Paonia Reservoir. When the trap efficiency of the reservoir was computed, it was assumed that all bedload was trapped in Paonia Reservoir and included any contribution of bedload by the landslide complex.

East Muddy Creek

Bedload discharge of East Muddy Creek ranged from 0.07 to 20.3 percent of the total-sediment discharge (table 2). The bedload sample collected on April 6, 1987, indicates bedload was 20.3 percent of the total-sediment discharge. This sample was collected in a stream reach dominated by a riffle regime. All other samples were collected in a pool regime where less bedload would be expected. This sample was not used in developing the regression relation.

The regression relation of bedload discharge to stream discharge was used to estimate the bedload discharge of East Muddy Creek during the 216-day period. The results of the regression analysis are listed in table 13 and plotted in figure 15. The regression relation had a coefficient of determination of 0.72. The correction for the bias created when the dependent variable was transformed, or the smearing estimate, is 1.68. The 90-percent prediction interval spans nearly 3 orders of magnitude for a given stream discharge, indicating that the estimates of bedload discharge has a large error. The regression relation was applied to the daily mean stream discharges to estimate the total bedload of 670 tons during the 216 days, or an average of about 3.1 tons per day.

The distribution of particle size of bedload sediment from East Muddy Creek is listed in table 14. Data in table 14 indicate that bedload particle size is larger during high stream discharge than it is during low stream discharge at East Muddy Creek. A larger percentage of the bedload sediment from East Muddy Creek is larger in diameter than is the bedload sediment at the other streamflow-gaging stations; however, data are sparse. Some bedload sediment probably is deposited in the ponded reach of East Muddy Creek, which resulted from westward movement of the landslide complex.

Table 13.--*Summary of bedload discharge regression analysis*

[*n*, number of samples; r^2, coefficient of determination; *se*, standard error of estimate, in percent; log, base 10 logarithm units; *Qb*, bedload discharge, in tons per day; *Q*, stream discharge, in cubic feet per second]

Stream name	Statistical values for regression of bedload discharge versus stream discharge			
	n	r^2	Regression equation	*se*
East Muddy Creek	5	0.72	$\log(Qb) = -4.74+2.17 \log(Q)$	223
West Muddy Creek	6	.92	$\log(Qb) = -5.27+2.44 \log(Q)$	113
Muddy Creek upstream from Paonia Reservoir	5	.76	$\log(Qb) = -5.61+2.57 \log(Q)$	229

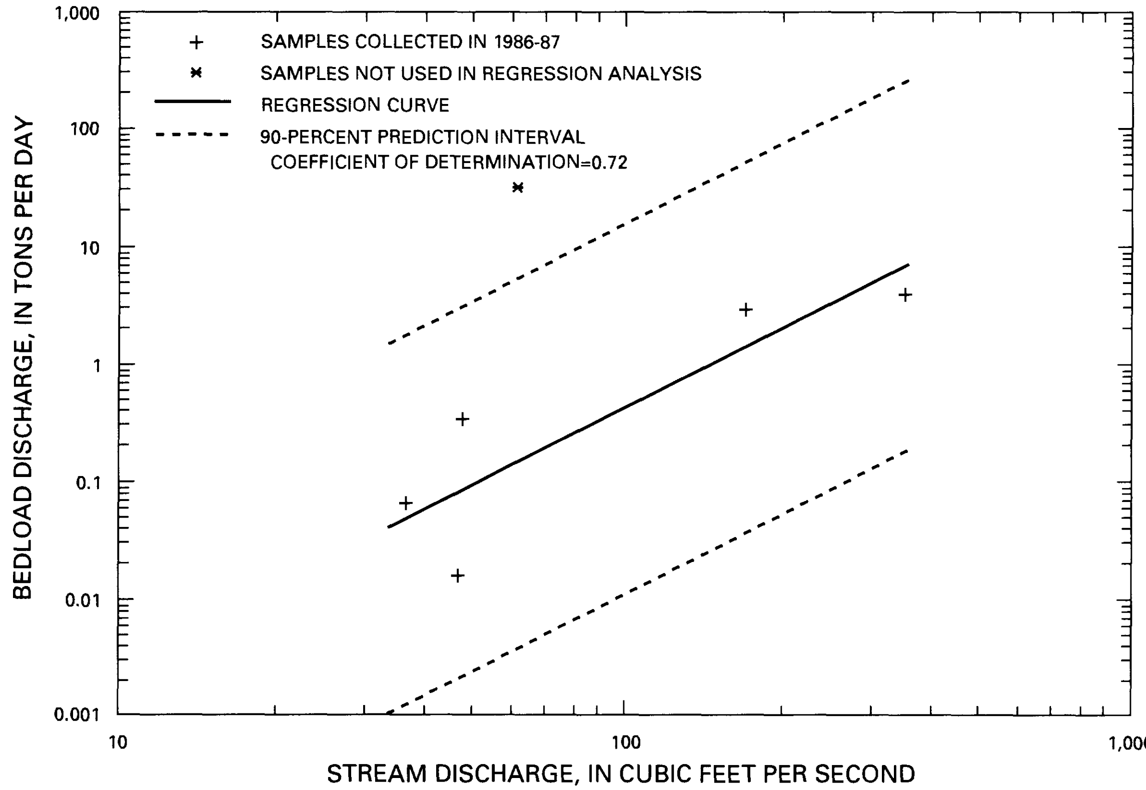


Figure 15.--Relation of bedload discharge to stream discharge for East Muddy Creek near Paonia Reservoir.

Table 14.--*Particle-size distribution of bedload samples collected at East Muddy Creek near Paonia Reservoir, 1986-87*

[--, missing data]

Date of sample	Percent finer than indicated size, in millimeters							
	19.0	9.50	4.00	2.00	1.00	0.500	0.250	0.125	0.062
07-29-1986	100	100	100	97.0	95.5	90.3	59.6	55.9	36.1
09-23-1986	100	100	100	100	100	56.7	23.4	11.8	6.0
04-06-1987	100	100	100	99.8	96.1	55.4	5.6	1.1	.5
05-06-1987	100	97.9	93.6	88.7	83.1	59.5	1.9	--	--
06-01-1987	100	98.2	92.3	80.3	49.3	21.2	1.0	.3	.2
07-01-1987	100	100	100	84.6	77.3	66.3	32.0	21.8	12.5

West Muddy Creek

Bedload discharge ranged from 0.01 to 3.51 percent of the total-sediment discharge of West Muddy Creek (table 7). The bedload discharge was a larger percentage of the total-sediment discharge during spring runoff. Sampling bedload at West Muddy Creek was difficult because the channel is partially composed of boulders that do not allow the sampler to lie completely on the channel bottom.

All of the bedload samples were used to determine the regression relation between bedload discharge and stream discharge of West Muddy Creek. The results of the regression analysis are listed in table 13 and plotted in figure 16. The regression relation had a coefficient of determination of 0.92. The correction for the bias created by the transformation of the dependent variable, or the smearing estimate, is 1.43. The 90-percent prediction interval spans less than 2 orders of magnitude; thus, estimates of bedload discharge for West Muddy Creek may be somewhat more reliable than those for East Muddy Creek but need to be considered as estimates only. This regression relation was used to estimate the bedload discharge of West Muddy Creek for the 216-day period. Total bedload was 990 tons, or an average of about 4.6 tons per day during the 216 days. The particle-size distribution of bedload sediment is listed in table 15.

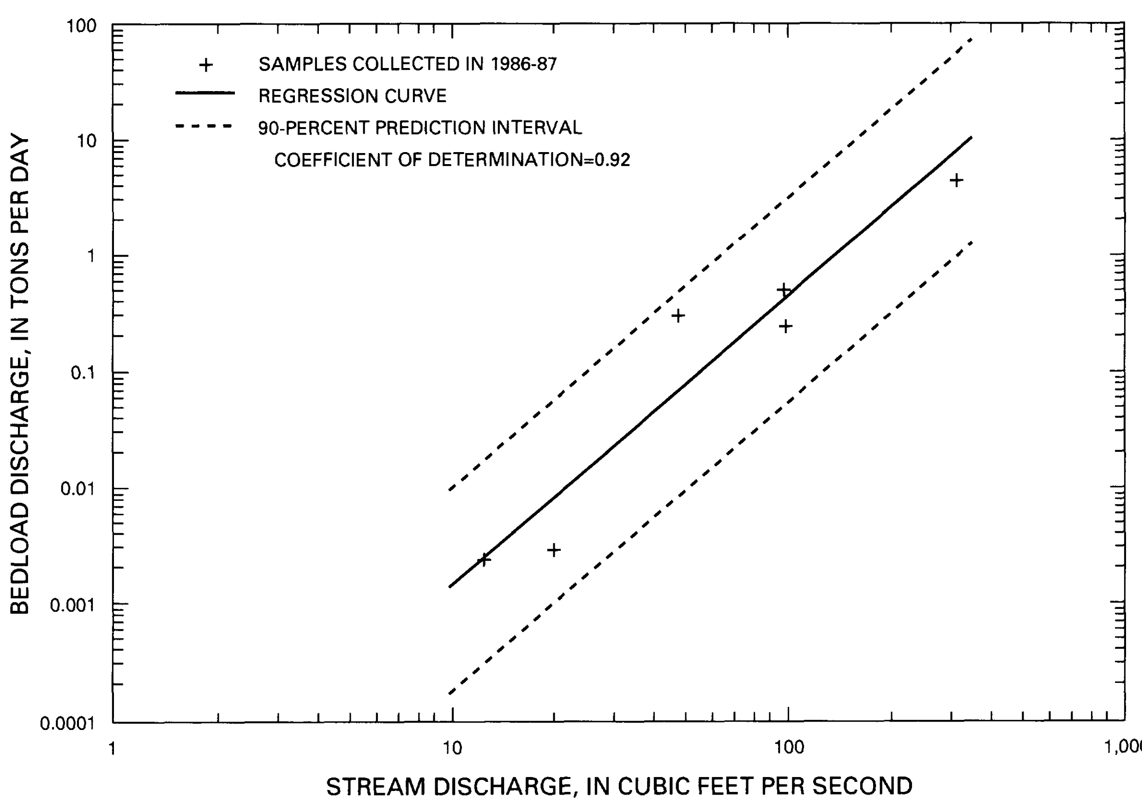


Figure 16.--Relation of bedload discharge to stream discharge for West Muddy Creek near Paonia Reservoir.

Table 15.--*Particle-size distribution of bedload samples collected at West Muddy Creek near Paonia Reservoir, 1986-87*

Date of sample	Percent finer than indicated size, in millimeters								
	19.0	9.50	4.00	2.00	1.00	0.500	0.250	0.125	0.062
07-29-1986	100	100	100	95.5	78.8	62.9	19.8	14.0	12.1
09-23-1986	100	100	100	100	100	100	11.7	5.8	2.3
04-07-1987	100	100	100	98.5	95.1	75.2	6.9	2.4	1.5
05-06-1987	100	99.4	95.7	87.9	65.6	33.8	2.0	.8	.5
06-01-1987	100	100	100	98.0	76.7	32.4	4.4	2.7	2.2
07-01-1987	100	100	100	100	92.2	61.9	11.6	9.0	8.3

Muddy Creek Upstream From Paonia Reservoir

Bedload discharge ranged from 0.12 to 5.79 percent of the total-sediment discharge of Muddy Creek upstream from Paonia Reservoir (table 9). Bedload discharge was the largest percentage of the total-sediment discharge on May 7, 1987, during spring runoff. However, this percentage of bedload discharge is not substantially larger than the percentage of bedload discharge sampled on September 24, 1986, during runoff in response to rainfall. Bedload discharge of Muddy Creek upstream from Paonia Reservoir generally is a greater percentage of the total-sediment discharge than is bedload discharge at the other streamflow-gaging stations. The landslide complex probably is contributing to the bedload sediment of Muddy Creek upstream from Paonia Reservoir.

Five of the samples collected were used to determine the regression relation of bedload discharge to stream discharge. The results of the regression analysis are listed in table 13 and plotted in figure 17. This regression relation had a coefficient of determination of 0.76. The correction for the bias created by transformation of the dependent variable, or the smearing estimate, is 1.73. The 90-percent prediction interval shown in figure 17 spans nearly 3 orders of magnitude for a given stream discharge. The estimates of bedload discharge at Muddy Creek upstream from Paonia Reservoir, therefore, need to be considered estimates only. The regression relation was used to estimate the bedload discharge for the 216- and 483-day periods. Bedload discharge was 7,200 and 21,200 tons, or an average of about 33 and 44 tons per day, respectively.

The combined bedload discharge of East Muddy Creek and West Muddy Creek for the 216-day period was 1,700 tons, or an average of about 7.9 tons per day. Comparing this bedload discharge to the bedload discharge for Muddy Creek upstream from Paonia Reservoir indicates an increase of the bedload discharge of about 5,500 tons. The 90-percent prediction intervals of the regression relations span 2 to 3 orders of magnitude, which needs to be considered when comparing the bedload discharges. These data indicate, however, that the landslide complex may contribute to the bedload discharge of Muddy Creek upstream from Paonia Reservoir.

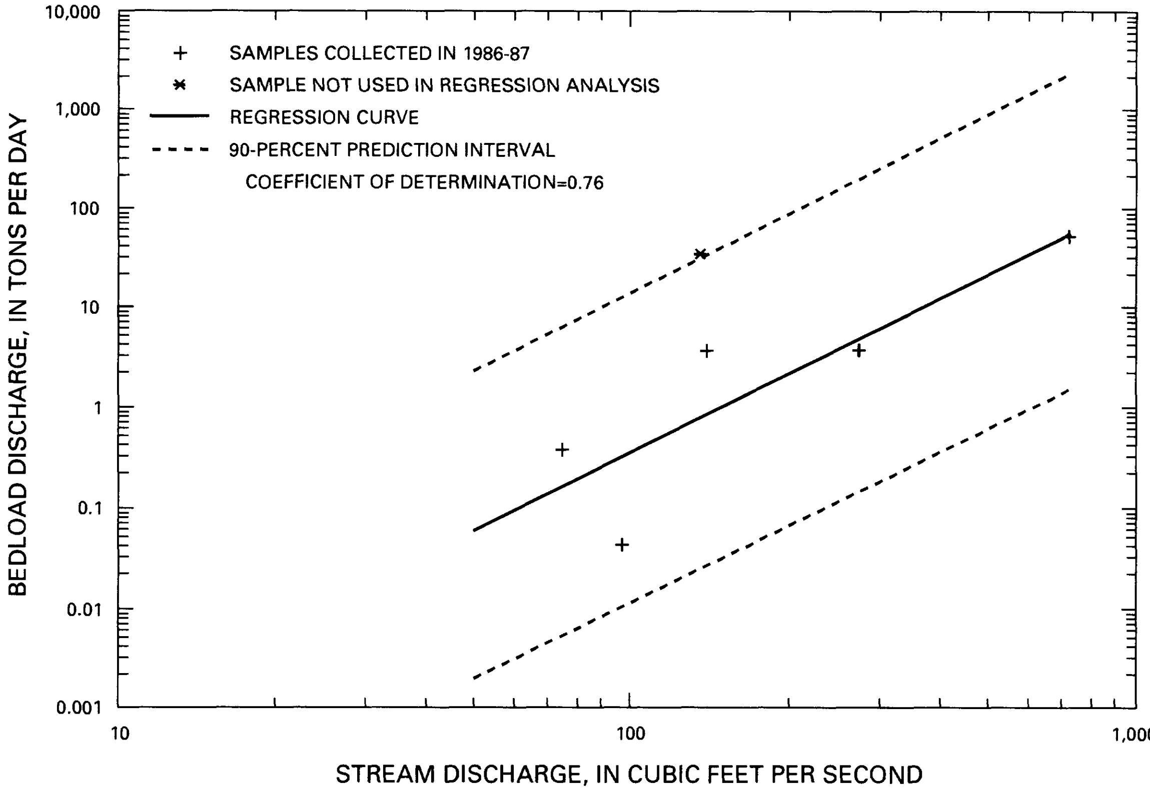


Figure 17.--Relation of bedload discharge to stream discharge for Muddy Creek upstream from Paonia Reservoir.

The distribution of the particle size of bedload sediment from Muddy Creek upstream from Paonia Reservoir is listed in table 16. A larger percentage of bedload sediment from this site is larger in diameter than is the bedload sediment at the other streamflow-gaging stations.

Table 16.--*Particle-size distribution of bedload samples collected at Muddy Creek upstream from Paonia Reservoir, 1986-87*

Date of sample	Percent finer than indicated size, in millimeters										
	75.0	38.1	19.0	9.50	4.00	2.00	1.00	0.500	0.250	0.125	0.062
07-29-1986	100	100	100	100	98.6	95.7	88.8	69.0	9.9	2.4	0.3
09-24-1986	100	100	100	100	82.3	50.4	33.2	16.8	2.7	1.3	.8
04-06-1987	100	100	100	98.1	83.6	60.7	43.2	25.2	2.5	.6	.4
05-07-1987	100	85.0	76.4	71.9	64.5	48.9	22.0	6.4	.6	.3	.2
06-02-1987	100	100	100	98.9	98.1	95.4	81.7	49.1	4.4	1.4	.8
07-01-1987	100	100	100	100	100	100	100	100	52.7	45.8	42.6

Total-Sediment Load

The total-sediment load of East Muddy Creek was estimated to be 70,000 tons (table 17) for the 216-day period, or an average of about 320 tons per day. No bedload discharge was estimated for Spring Creek, but the suspended-sediment load was estimated to be 4,770 tons for the same period. The total-sediment load of West Muddy Creek was estimated to be 26,500 tons for the 216-day period or an average of about 120 tons per day.

Table 17.--*Total-sediment loads in the Muddy Creek drainage basin, 1986-87*

[--, missing data]

Stream name	Suspended-sediment load (tons)	Bedload (tons)	Total-sediment load[1] (tons)
216-day period (July 11-November 5, 1986, and April 7-July 13, 1987)			
East Muddy Creek	69,300	670	70,000
Spring Creek	4,770	--	4,770
West Muddy Creek	25,500	990	26,500
Subtotal	99,600	1,700	101,000
Muddy Creek upstream from Paonia Reservoir	140,000	7,200	147,000
Muddy Creek downstream from Paonia Reservoir	14,900	0	14,900
483-day period (October 1-December 15, 1985, April 1-December 10, 1986, and March 1-July 31, 1987)			
Muddy Creek upstream from Paonia Reservoir	272,000	21,200	293,000
Muddy Creek downstream from Paonia Reservoir	51,100	0	51,100

[1]Subtotals and totals do not match because of rounding.

The combined total-sediment load of East Muddy Creek, Spring Creek, and West Muddy Creek represents the total-sediment load of Muddy Creek upstream from the landslide complex. The combined total-sediment load is assumed to represent the total-sediment load of Muddy Creek upstream from Paonia Reservoir before movement of the landslide complex. The combined total-sediment load of the three creeks was estimated to be 101,000 tons (table 17) during the 216-day period, or an average of about 470 tons per day. The total-sediment load of Muddy Creek upstream from Paonia Reservoir was estimated to be 147,000 tons (table 17) for the same period, or an average of about 680 tons per day. This gain of 46,000 tons in total-sediment load may be partially from scouring of material in the East Muddy Creek and Muddy Creek channels resulting from movement of the landslide complex. This is an average increase in sediment discharge of about 210 tons per day for the 216-day period.

The actual increase in total-sediment load in Muddy Creek due to movement of the landslide complex probably is more than the estimated gain in total-sediment load. The landslide complex probably contributed greater quantities of sediment to the streams when it was moving 9 to 12 feet per day, which occurred before the start of sample collection for this study. Also, additional sediment has been deposited in the pond on East Muddy Creek adjacent to the northern side of the landslide complex. Surveys done by the Colorado Geological Survey (1987) indicate that the land-surface elevation rose as much as 14.6 feet in the pond area. The total volume of material necessary for this increase in land surface is estimated to be about 2 million cubic feet. Some of the increase in the land-surface elevation in the pond probably is due to surface deformation and lateral displacement of the land surface resulting from movement of the landslide complex.

The total-sediment load of Muddy Creek downstream from Paonia Reservoir can be compared to the total-sediment load of Muddy Creek upstream from Paonia Reservoir to estimate the trap efficiency of the reservoir. All bedload sediment is assumed to be trapped by the reservoir. The total-sediment load upstream from Paonia Reservoir during the 216-day period was 147,000 tons, while the total-sediment load downstream from the reservoir was 14,900 tons. Therefore, about 132,000 tons of sediment was deposited in the reservoir, and the trap efficiency was about 90 percent. The average sediment deposition rate was estimated to be about 610 tons per day during the 216-day period. The total-sediment load in Muddy Creek upstream from Paonia Reservoir was 293,000 tons during the 483-day period or an average of about 610 tons per day. The suspended-sediment load from Muddy Creek downstream from Paonia Reservoir was 51,100 tons during the 483-day period (table 17) or an average of about 110 tons per day. This indicates that about 242,000 tons of sediment was deposited in Paonia Reservoir during the 483-day period, and the trap efficiency was about 83 percent. The average sediment deposition rate was estimated to be about 500 tons per day for the 483-day period. Because the trap efficiency estimated for the 483-day period was for a longer period of time, it probably is a more accurate estimate of the trap efficiency of Paonia Reservoir than is the trap efficiency estimated for the 216-day period.

The combined total-sediment load for the 216-day period of East Muddy Creek, Spring Creek, and West Muddy Creek is assumed to be representative of the long-term total-sediment load of Muddy Creek upstream from Paonia Reservoir before movement of the landslide complex. That assumption is used to estimate the sediment deposition in Paonia Reservoir prior to movement of the landslide complex since Paonia Dam was completed in 1962. The combined total-sediment load of the three streams was 101,000 tons during the 216-day period, or an average of about 470 tons per day. The total-sediment load of Muddy Creek downstream from Paonia Reservoir was 14,900 tons for the 216-day period, or an average of about 69 tons per day. Therefore, the assumed sedimentation rate into Paonia Reservoir was about 400 tons per day prior to movement of the landslide complex. If that sediment deposition rate has occurred since 1962, about 91 million cubic feet of material has been deposited in Paonia Reservoir prior to movement of the landslide complex. Therefore, the quantity of water-storage capacity lost in the reservoir is estimated to be about 2,100 acre-feet. The quantity of sediment deposited in Paonia Reservoir caused by movement of the landslide complex was not determined.

Bed Material

The distribution of the particle size of bed material was determined by doing pebble counts on East Muddy Creek, West Muddy Creek, and Muddy Creek upstream from Paonia Reservoir. The pebble counts were done in a stream reach about 10 times longer than the average stream width. The reach was divided into 10 cross sections that were equal distances apart. Ten samples of bed material were collected at equal distances across each cross section. The sampling method used is described in more detail by Wolman (1954). If the bed material was less than 8 millimeters in diameter or larger than 256 millimeters in diameter, no sample was collected but the size was noted. The three main axes of each sample collected were measured, and the average diameter was computed. The percentage of bed material in each size class was then computed. The distribution of the size of bed material is shown in figure 18.

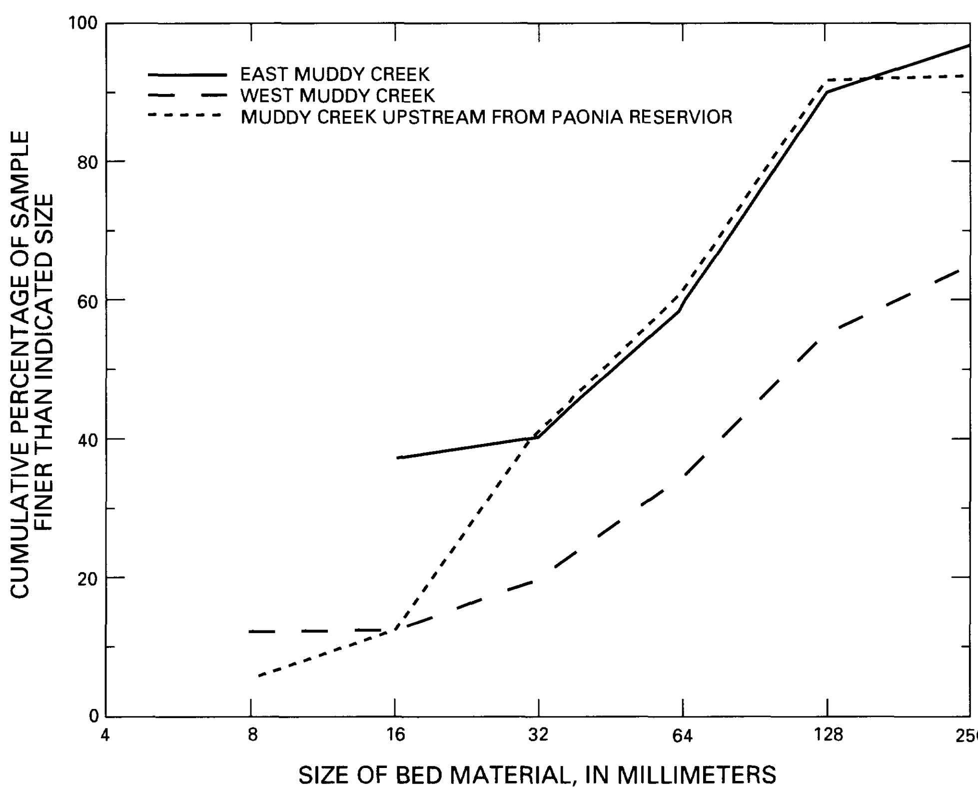


Figure 18.--Size distribution of bed material in the Muddy Creek drainage basin.

The suspended-sediment discharge and bedload discharge of these streams indicate that they transport substantial quantities of sediment. The bed-material samples were collected during fairly low streamflows but after spring runoff began. Scour of the stream channel had thus begun, and the quantity of fine-grained material observed during sampling probably was much less than if the bed-material samples had been collected in the fall when sediment deposition in the channels occurs.

Four of the cross sections from which samples were collected for the pebble count on East Muddy Creek were in a riffle regime; the other six cross sections were in a pool regime between two riffles. The reach of East Muddy Creek sampled for bed material is about 250 feet long and the average width is about 30 feet. The stream discharge of East Muddy Creek was about 60 cubic feet per second when the bed material was sampled. The view shown in figure 19 is looking upstream from the center of the channel from the downstream end of the reach. About 50 percent of the streambed material in East Muddy Creek was between 16 and 128 millimeters in diameter. Only 3 percent was larger than 256 millimeters in diameter, but about 38 percent was finer than 16 millimeters in diameter (fig. 18). The streambeds of West Muddy Creek and Muddy Creek upstream from the reservoir had less material finer than 16 millimeters in diameter than did East Muddy Creek.

Figure 19.--Reach of East Muddy Creek where pebble counts were done, April 7, 1987.

The reach of West Muddy Creek sampled for bed material is about 300 feet long, and the average width is about 30 feet. Five of the cross sections sampled were in a riffle, and five were in a pool upstream from the riffle. The riffle sampled was the control for the streamflow-gaging station on West Muddy Creek. The stream discharge was about 48 cubic feet per second when the bed-material samples were collected. The view shown in figure 20 is looking downstream and includes the reach where the pebble counts were done. About 35 percent of the bed material from West Muddy Creek was larger than 256 millimeters in diameter compared to 3 percent at East Muddy Creek and 7 percent at Muddy Creek upstream from Paonia Reservoir. Twelve percent of the bed material from West Muddy Creek was less than 8 millimeters in diameter (fig. 18).

Figure 20.--Reach of West Muddy Creek where pebble counts were done, April 7, 1987.

The reach of Muddy Creek upstream from Paonia Reservoir sampled for bed material is about 300 feet long, and the average width is about 60 feet. Eight of the cross sections sampled were in a riffle, and two were in a pool. The stream discharge was about 145 cubic feet per second when the samples were collected. About 7 percent of the bed material was larger than 256 millimeters, and 6 percent was less than 8 millimeters (fig. 18). The percentages of bed material between 32 and 256 millimeters in diameter from Muddy Creek upstream from Paonia Reservoir and East Muddy Creek were nearly the same.

SEDIMENT DEPOSITION IN THE UPSTREAM REACH OF PAONIA RESERVOIR

The U.S. Bureau of Reclamation surveyed 10 cross sections of the channel of Muddy Creek within 3.5 miles of Paonia Dam in 1962 and 1969. The four upstream cross sections (fig. 4) were resurveyed during this study to determine how much sediment has been deposited at these locations. Reference marks established by the U.S. Bureau of Reclamation were used as ends of the cross sections, where they could be found.

Based on sediment data collected at Muddy Creek upstream from Paonia Reservoir, sediment is being transported into Paonia Reservoir at an average rate of about 610 to 680 tons per day. This sediment creates a delta as it is deposited in the upper end of the reservoir when the water level in the reservoir is high. As the water level in the reservoir decreases, the sediment is transported farther downstream in the reservoir. Most of this sediment eventually is deposited at a relatively permanent location in the reservoir. An average of only about 69 to 110 tons per day of sediment is transported in Muddy Creek downstream from Paonia Dam. When the landslide complex began moving in April 1986, a large quantity of material moved into the channel of East Muddy Creek. Large quantities of this material were dredged out of the channel by the State Highway Department. Additional material was removed from the Muddy Creek channel in June 1986 to clear the buried intakes of the streamflow-gaging station upstream from Paonia Reservoir. All of this altered the gradient and, therefore, the sediment-carrying capacity of Muddy Creek.

To allow comparisons of the volume of sediment within the cross sections on different dates, the cross-sectional area of a computation rectangle consisting of the active stream channel at each location was computed (figs. 21-24). The computation rectangle includes that part of the stream channel where scour and deposition of sediment occur. The cross-sectional area occupied by sediment within this computation rectangle on different dates was then computed. To determine the volume of sediment deposited, the cross sections were assumed to be 1 foot wide. No survey was done along the longitudinal axis of the channel between cross sections 7 and 10. Therefore, the total volume of material deposited in this stream reach is unknown. To determine the total volume of sediment deposited in Paonia Reservoir, all 10 cross sections originally surveyed by the U.S. Bureau of Reclamation would need to be resurveyed.

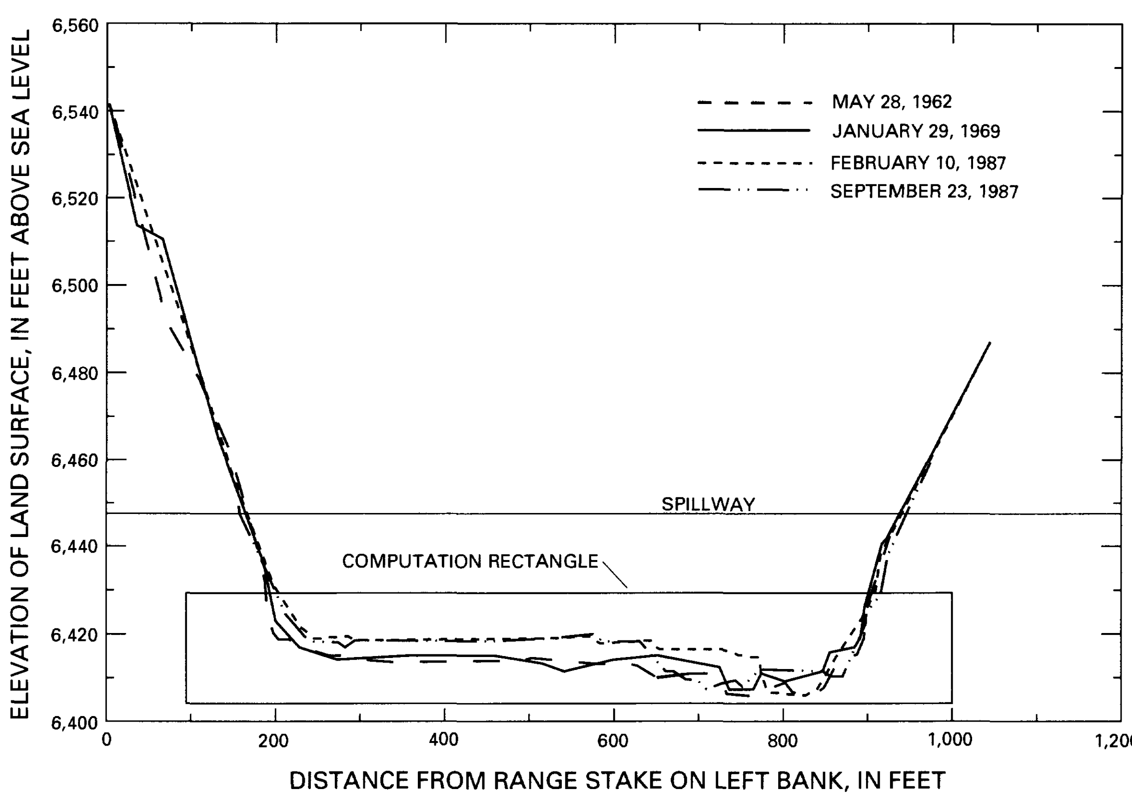


Figure 21.--Cross section 7, Muddy Creek upstream from Paonia Reservoir.

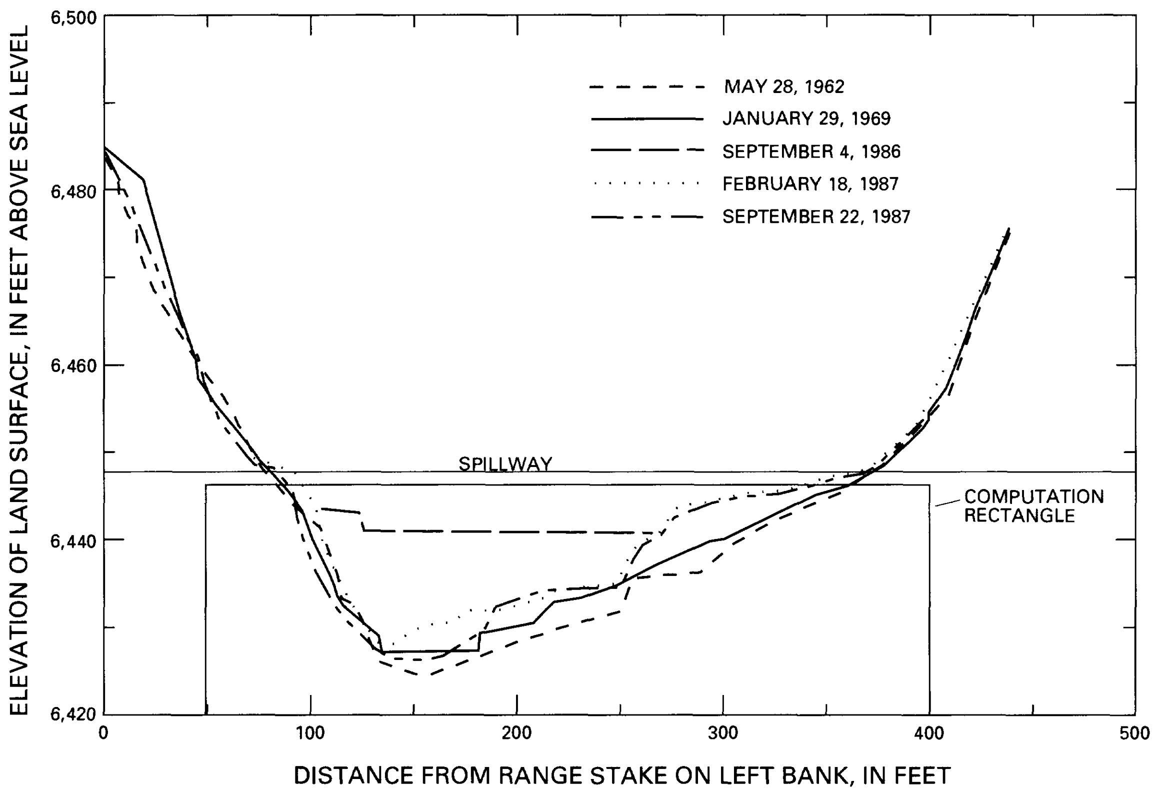


Figure 22.--Cross section 8, Muddy Creek upstream from Paonia Reservoir.

Cross Section 7

Cross section 7 is about 2.5 miles upstream from Paonia Dam and 0.75 mile downstream from the upstream extent of the reservoir when it is at maximum capacity (fig. 4). The cross section is 1,046 feet wide (fig. 21); however, only 814 feet were resurveyed in September 1987. The lowest point in the cross section surveyed in 1962 was about 42 feet below the elevation of the upper spillway on Paonia Dam.

When cross section 7 was surveyed in May 1962, the volume of sediment within the computation rectangle, including the active channel, was 9,890 cubic feet. In January 1969, the volume of sediment within the computation rectangle was 10,770 cubic feet, indicating a change in volume of 880 cubic feet since May 1962. In February 1987, the volume of sediment within the computation rectangle was 13,590 cubic feet, indicating a change in volume of 2,820 cubic feet since January 1969. Scour of the channel may have occurred between February and September 1987, and the volume of sediment within the computation rectangle was only 12,670 cubic feet in September 1987. The water level in the reservoir was too high for cross section 7 to be surveyed in September 1986. The volume of sediment in the cross section probably was larger in September 1986 than in February 1987, as indicated by the data from cross sections 8 and 9.

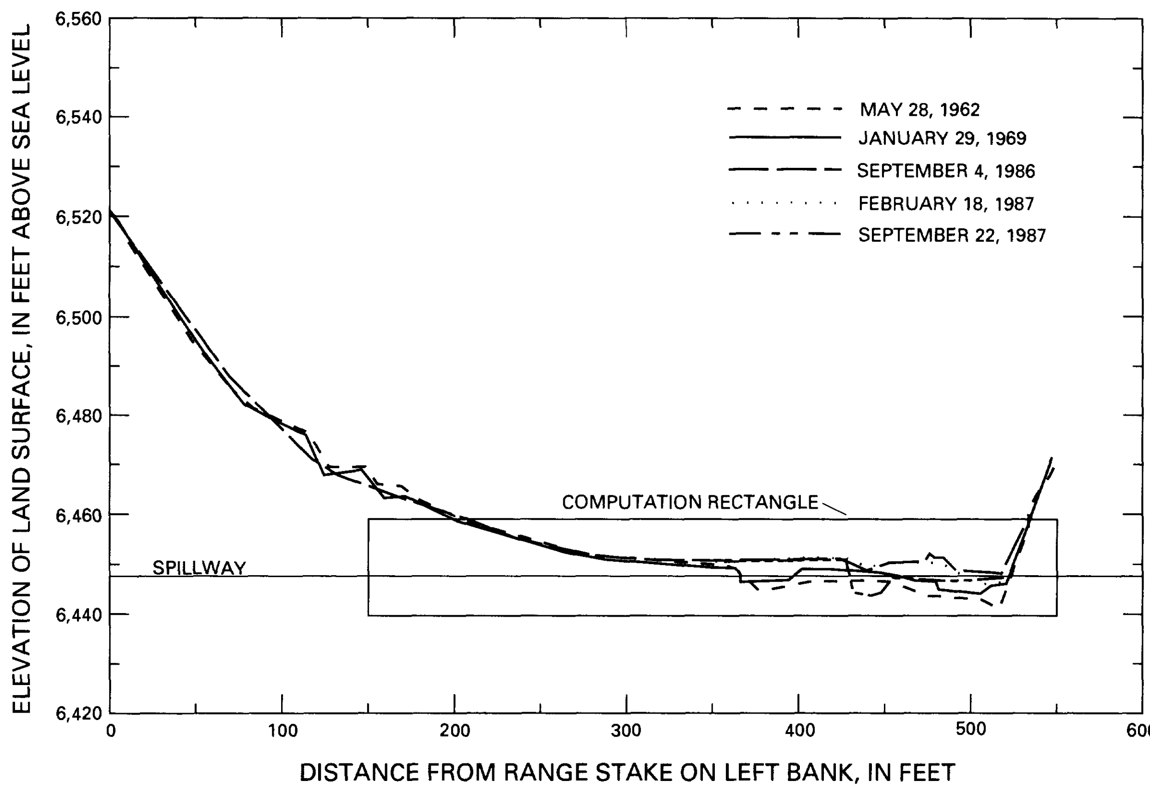


Figure 23.--Cross section 9, Muddy Creek upstream from Paonia Reservoir.

Cross Section 8

Cross section 8 is about 2.9 miles upstream from Paonia Dam and 0.3 mile downstream from the upstream extent of the reservoir when at maximum capacity (fig. 4). The cross section is 438 feet wide (fig. 22). In 1962, the lowest point in the cross section was about 22 feet below the elevation of the upper spillway on Paonia Dam.

When cross section 8 was surveyed in May 1962, the volume of sediment within the computation rectangle, including the active channel, was 5,900 cubic feet (fig. 22). In January 1969, the volume of sediment within the computation rectangle was 6,300 cubic feet, indicating a change in volume of 400 cubic feet since May 1962. In September 1986, the volume of sediment within the computation rectangle was 8,330 cubic feet, indicating an increase of about 2,000 cubic feet since January 1969. Extensive scouring of the channel may have occurred between September 1986 and September 1987; the volume of sediment within the computation rectangle was 7,000 cubic feet in February 1987 and was 6,640 cubic feet in September 1987. The change in volume of sediment between May 1962 and September 1987 was about 740 cubic feet.

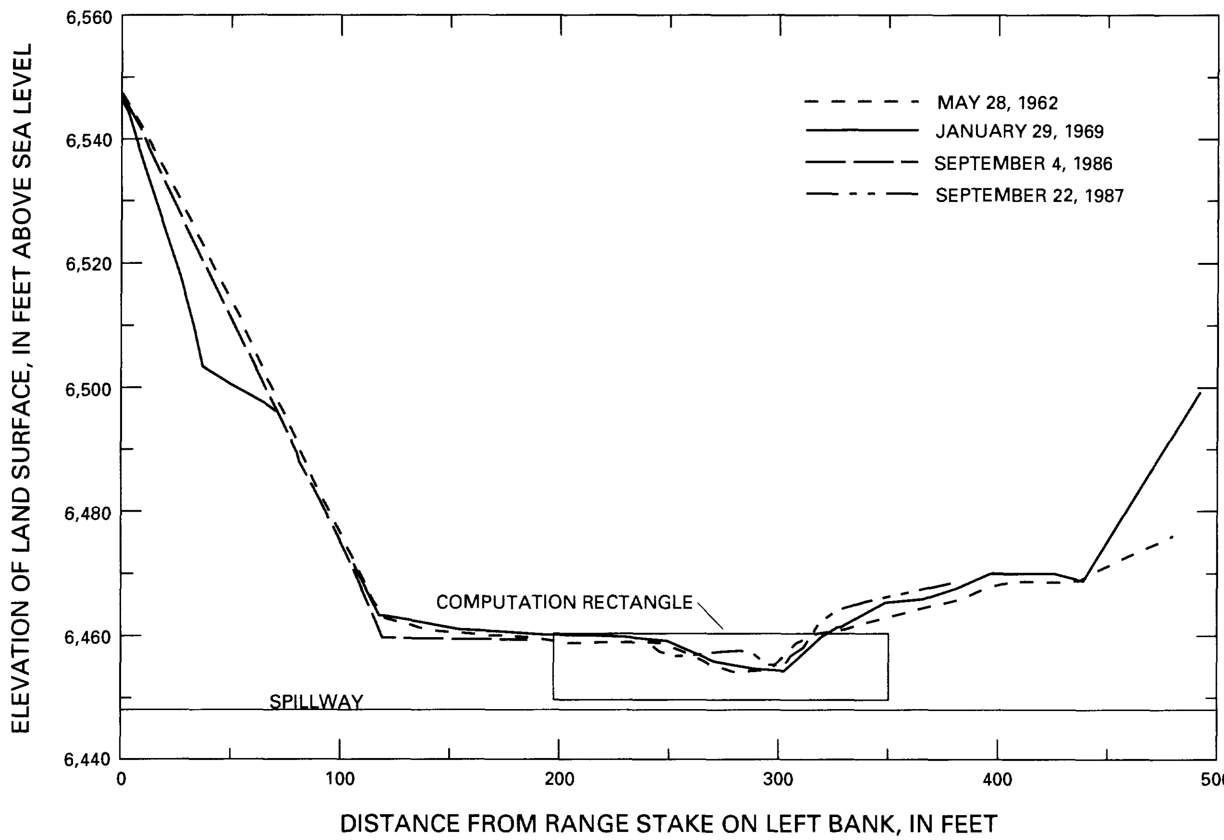


Figure 24.--Cross section 10, Muddy Creek upstream from Paonia Reservoir.

Cross Section 9

Cross section 9 is about 3.2 miles upstream from Paonia Dam and is at the upstream extent of the reservoir when it is at maximum capacity (fig. 4). The cross section is about 550 feet wide; however, only about 280 feet were resurveyed in February and September 1987 (fig. 23). The reference mark established by the U.S. Bureau of Reclamation on the right side of the channel could not be found. The resurveyed part of the cross section includes all of the active channel at this location. In 1962, the lowest point of the cross section was about 8 feet below the elevation of the upper spillway on Paonia Dam.

When cross section 9 was surveyed in May 1962, the volume of sediment within the computation rectangle, including the active channel, was 4,240 cubic feet. In January 1969, the volume of sediment within the computation rectangle was 4,560 cubic feet, indicating a change in volume of 320 cubic feet since May 1962. In September 1986, the volume of sediment within the computation rectangle was 5,190 cubic feet, indicating a change in volume of 630 cubic feet since January 1969. Some scour of the channel may have occurred between September 1986 and February 1987, and the volume of material within the computation rectangle was only 5,080 cubic feet in February 1987. This scour may have continued through September 1987, and the volume of material was only 4,770 cubic feet. These trends are consistent with those at cross section 8.

Cross Section 10

Cross section 10 is about 3.7 miles upstream from Paonia Dam and 0.5 mile upstream from the upstream extent of Paonia Reservoir when it is at maximum capacity (fig. 4). The cross section is about 490 feet wide; however, only 198 feet were resurveyed in September 1987 (fig. 24). The reference mark used by the U.S. Bureau of Reclamation on the right side of the channel could not be found. Changes in Colorado State Highway 133 since 1962 have affected the channel near this cross section and, thus, accurate comparisons between the surveys are difficult.

When cross section 10 was surveyed in May 1962, the volume of sediment within the computation rectangle, including the active channel, was 1,230 cubic feet. In January 1969, the volume of sediment in the computation rectangle was 1,250 cubic feet, indicating a change in volume of 20 cubic feet since May 1962. In September 1986, the volume of sediment within the computation rectangle was 1,280 cubic feet, indicating a change in volume of 30 cubic feet since January 1969. In September 1987, the volume of sediment was 1,290 cubic feet.

SUMMARY

The Muddy Creek drainage basin consists of 249 square miles in Gunnison and Delta Counties. Paonia Reservoir is about 3.2 miles long, and its surface area is about 0.6 square mile (about 385 acres). Paonia Dam was constructed by the U.S. Bureau of Reclamation to store water for irrigation in the North Fork of the Gunnison River valley. The dam was completed in 1962. Paonia Dam is about 7 miles upstream from Somerset. East Muddy Creek and West Muddy Creek join about 1.5 miles upstream from the reservoir to form Muddy Creek, which flows into the reservoir.

The Muddy Creek landslide complex is about 13,000 feet long and 7,000 feet wide. The complex is at the base of The Raggeds, which form the eastern boundary of the drainage basin. In April 1986, the northern and central slides of the Muddy Creek landslide complex began moving 9 to 12 feet per day. The total lateral displacement of the central slide of the landslide complex was as much as 230 feet to the west. This movement constricted the flow of East Muddy Creek immediately upstream from the confluence with West Muddy Creek and raised the stream channel as much as 30 feet. A pond formed on East Muddy Creek upstream from the constriction of the channel. The elevation of the land surface increased an average of 7.5 feet between August 1985 and June 1986 in this pond, which covered about 0.01 square mile (about 6.4 acres). The volume of material necessary to increase the elevation of the land surface an average of 7.5 feet is about 2 million cubic feet. Some of this material is sediment that settled out of East Muddy Creek, and some may be material resulting from deformation of the land surface as a result of movement of the landslide complex.

Streamflow-gaging stations were constructed by the U.S. Geological Survey on East Muddy Creek and West Muddy Creek in July 1986. Gage-height data were collected for 216 days during 1986 and 1987 at these sites. The State Division of Water Resources maintains streamflow-gaging stations on Muddy

Creek upstream from and downstream from Paonia Reservoir. Gage-height data were collected for 483 days at the streamflow-gaging stations upstream from and downstream from the reservoir during the 1986-87 water years. In addition, stream discharge was measured or estimated 13 times at Spring Creek, a tributary to East Muddy Creek.

Sediment data were collected by the U.S. Geological Survey from June through November 1986 and from April through July 1987 at East Muddy Creek, West Muddy Creek, Muddy Creek upstream from Paonia Reservoir, Muddy Creek downstream from Paonia Reservoir, and Spring Creek. Stream discharge was measured in conjunction with sediment sampling. The maximum daily mean discharge computed from gage-height records was as much as twice the instantaneous discharges measured during sampling; therefore, no sediment samples were collected during the largest streamflows. At Muddy Creek downstream from Paonia Reservoir, the largest stream discharge measured and sampled was about 75 percent of the maximum daily mean discharge recorded.

Regression relations of stream discharge to suspended-sediment discharge and bedload discharge at East Muddy Creek, West Muddy Creek, and Muddy Creek upstream from Paonia Reservoir were determined using analysis of covariance or least-squares regression analysis. No bedload samples were collected at Spring Creek and Muddy Creek downstream from Paonia Reservoir; thus, only the relation of suspended-sediment discharge to stream discharge was determined. The regression relations were used to estimate the suspended-sediment load and bedload of the streams. The suspended-sediment load and the bedload of East Muddy Creek and West Muddy Creek were estimated for 216 days using daily stream discharges. The suspended-sediment load of East Muddy Creek was 69,300 tons during the 216-day period, and bedload was 670 tons. The suspended-sediment load of Spring Creek was estimated to be 4,770 tons during the 216-day period using estimated stream discharges. At West Muddy Creek, the suspended-sediment load was 25,500 tons during the 216-day period, and bedload was 990 tons. Computed daily stream discharges were used to estimate the suspended-sediment load and bedload of Muddy Creek upstream from Paonia Reservoir for a 216-day period and for a 483-day period. The suspended-sediment loads were 140,000 and 272,000 tons during the 216- and 483-day periods, respectively; bedload was 7,200 and 21,200 tons, respectively. Computed stream discharge was used to estimate the suspended-sediment loads of Muddy Creek downstream from Paonia Reservoir for the 216- and the 483-day periods. The suspended-sediment loads were 14,900 and 51,100 tons during the two periods.

The total-sediment load of each stream during each period is the sum of the daily suspended-sediment loads and the daily bedloads. The combined total-sediment load of East Muddy Creek, Spring Creek, and West Muddy Creek is assumed to be representative of the total-sediment discharge of Muddy Creek upstream from the landslide complex. This total-sediment load was compared to the total-sediment load estimated for Muddy Creek upstream from Paonia Reservoir, which is downstream from the landslide complex. The comparison indicates an average increase of about 210 tons per day of sediment during the 216-day period, probably from the landslide complex. No samples were collected when the landslide complex was moving 9 to 12 feet per day, which occurred prior to the 216-day period, and additional sediment has been deposited in a pond on East Muddy Creek adjacent to the northern slide of the landslide complex. Therefore, the total contribution of sediment from the landslide complex is unknown.

The total-sediment discharges into the reservoir were 680 and 610 tons per day, respectively, during the 216- and 483-day periods. The difference between the sediment discharges of Muddy Creek upstream from and downstream from the reservoir was used to estimate the trap efficiency of Paonia Reservoir. During the 216-day period, 132,000 tons of sediment was deposited in the reservoir and the trap efficiency was 90 percent. During the 483-day period, 242,000 tons of sediment was trapped in the reservoir and the trap efficiency is estimated to be 83 percent. The deposition rates into the reservoir average about 610 and 500 tons per day during the 216- and 483-day periods. There may be some lag time for transport of sediment through the reservoir; thus, the trap efficiency estimated for the 483-day period may be more accurate.

The combined total-sediment load for the 216-day period of East Muddy Creek, Spring Creek, and West Muddy Creek is assumed to be representative of the long-term total-sediment load of Muddy Creek upstream from Paonia Reservoir before movement of the landslide complex. The combined total-sediment load of these streams was 101,000 tons during the 216-day period, or an average of about 470 tons per day. The total-sediment load of Muddy Creek downstream from Paonia Reservoir was 14,900 tons for the 216-day period, or an average of about 69 tons per day. Therefore, the assumed sediment deposition rate in Paonia Reservoir was about 400 tons per day prior to movement of the landslide complex. If that sediment deposition rate has occurred since Paonia Dam was built, about 91 million cubic feet of material has been deposited in Paonia Reservoir prior to movement of the landslide complex. The quantity of water-storage capacity lost in the reservoir is estimated to be about 2,100 acre-feet. The quantity of sediment deposition in Paonia Reservoir caused by the movement of the landslide complex was not determined.

Four channel cross sections on Muddy Creek in the upstream part of Paonia Reservoir were resurveyed in 1986 and 1987 to determine changes in the volume of sediment in the cross sections. These channel cross sections originally were surveyed by the U.S. Bureau of Reclamation in 1962 and 1969. The changes in the volumes of sediment deposited in the channel cross sections between May 1962 and September 1987 ranged from 60 to 2,780 cubic feet. The cross-section data indicated that channel scouring had occurred between September 1986 and September 1987.

REFERENCES CITED

Colorado Climate Center, 1984, Colorado average annual precipitation 1951-80: Ft. Collins, Colorado State University map, 1 sheet, scale 1:500,000.

Colorado Geological Survey, 1987, Atlas of topographic profiles--Muddy Creek landslide complex: Denver, Colo., 3 folios.

Duan, Naihua, 1983, Smearing Estimate--A nonparametric retransformation method: Journal of American Statistical Association, v. 78, no. 383, p. 605-610.

Emmett, W.W., 1980, A field calibration of the sediment-trapping characteristics of the Helley-Smith bed-load sampler: U.S. Geological Survey Professional Paper 1139, 44 p.

Fenneman, N.M., 1946, Physical division of the United States: Washington, D.C., U.S. Geological Survey special map.

Guy, H.P., and Norman, V.W., 1970, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, bk. 3, chap. C2, 59 p.

Junge, W.R., 1982, Geologic hazards in the North Fork Gunnison River area, Delta and Gunnison Counties, Colorado, in Southeastern Piceance Basin, western Colorado: Grand Junction, Colo., Grand Junction Geological Survey field trip summary, 1982, p. 83-86.

National Climatic Data Center, 1955-86, Climatological data, Colorado annual summary: Asheville, N.C., v. 60-90, no. 13.

Norris, J.M., and Maura, W.S., 1985, Water-quality data for streams in the upper North Fork of the Gunnison River, Colorado: U.S. Geological Survey Open-File Report 85-190, 122 p.

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water-Resources Investigations, bk. 3, chap. C3, 66 p.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow Volume 1.--Measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 284 p.

Tweto, Ogden, 1979, Geologic Map of Colorado: U.S. Geological Survey, 2 sheets, scale 1:500,000.

Wolman, M.G., 1954, A method of sampling coarse river-bed material: American Geophysical Union Transactions, v. 35, no. 6, p. 951-956.

★ U.S. GOVERNMENT PRINTING OFFICE: 1991--576-275/45140 REGION 8