SEDIMENT DISCHARGE IN FORTIFICATION CREEK AND THE EFFECT OF SEDIMENTATION RATE ON THE PROPOSED RAMPART RESERVOIR, NORTHWESTERN COLORADO

By David L. Butler, Richard O. Hawkinson, and Robert W. Boulger, Jr.

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CONVERSION FACTORS

Multiply inch-pound unit	*By*	*To obtain metric unit*
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
acre-foot per square mile per year [(acre-ft/mi^2)/yr]	476.1	cubic meter per square kilometer per year
cubic foot per second (ft^3/s)	0.02831 7	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	25.40	millimeter (mm)
mile (mi)	1.609	kilometer
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter
square mile (mi^2)	2.590	square kilometer
ton	0.9074	metric ton
ton per day (ton/day)	0.9074	metric ton per day
ton per year (ton/yr)	0.9074	metric ton per year

Multiply metric unit	*By*	*To obtain inch-pound unit*
gram (g)	453.5	pound
millimeter (mm)	.03937	inch

Temperature in degree Celsius (°C) may be converted to degree Fahrenheit (°F) by use of the following formula: °F = 9/5(°C) + 32.

The following term and abbreviation also is used in this report: milligram per liter (mg/L).

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ABSTRACT

Sediment deposition needs to be considered when designing a reservoir. This report presents estimates of the sediment discharge in Fortification Creek and the sedimentation rate of the proposed Rampart Reservoir located about 20 miles north of Craig in northwestern Colorado. Suspended- and bedload-sediment data collected on 31 days during water years 1986 and 1987 were used to estimate sediment discharge from stream discharge for the proposed reservoir site. Regression relations for suspended-sediment discharge to stream discharge were determined for snowmelt runoff and base-flow periods.

Stream discharge was recorded only during water years 1985-87 at the Fortification Creek streamflow-gaging station where the sediment data were collected. Because a longer term estimate of sediment discharge in Fortification Creek was needed to determine the sedimentation rate of the proposed reservoir, a record-extension technique was used to simulate stream discharge for Fortification Creek for water years 1954-84. The estimated mean annual suspended-sediment discharge in Fortification Creek at the gaging station was 17,800 tons for water years 1954-87. Bedload discharge was estimated to account for 2 percent of the total-sediment discharge; therefore, the estimated mean annual total-sediment discharge for the same period was about 18,200 tons. The 95-percent confidence interval for that estimate was 9,820 to 35,300 tons per year.

The gaging station is downstream from the proposed damsite; the mean annual total-sediment discharge used to compute the sedimentation rate of the reservoir was assumed to be equal to 90 percent of the mean annual total-sediment discharge at the gaging station, or 16,400 tons. The reservoir storage capacity would decrease from an initial storage capacity of 12,133 acre-feet to about 11,000 acre-feet after 100 years at 100-percent trap efficiency. Using the 95-percent confidence interval of the mean annual total-sediment discharge, the storage capacity would range from 9,900 to 11,500 acre-feet after 100 years.

INTRODUCTION

Sediment deposition in a reservoir needs to be considered in dam and reservoir design and operation and the potential effect to water-quality conditions. Because of its effect on reservoir storage capacity, the sedimentation rate will affect the useful life of a reservoir. Therefore, the sedimentation rate needs to be considered when developing reservoir operating plans that will maximize benefits derived from the reservoir. Sedimentation rate at a proposed reservoir location can be determined from the following information: (1) Stream discharge, (2) total-sediment discharge, (3) particle-size distribution of sediment, and (4) operation plans and dimensions of the proposed reservoir.

The site of a proposed reservoir, about 20 mi north of Craig along Fortification Creek in east-central Moffat County, Colorado (fig. 1), was investigated by the U.S. Geological Survey in cooperation with the Colorado River Water Conservation District to determine total-sediment discharge in Fortification Creek. This investigation was the fourth in a series of sediment studies done since 1984 by the U.S. Geological Survey for proposed reservoir sites in western Colorado. The sites previously studied were Una Reservoir on the Colorado River (Butler, 1986), Rock Creek Reservoir (Butler, 1987), and Wolford Mountain Reservoir on Muddy Creek (Ruddy, 1987). The proposed Rampart Reservoir would have a capacity of 12,133 acre-ft (Western Engineers, Inc., 1984); the reservoir would be built as part of the Great Northern Project of the Colorado River Water Conservation District for the purpose of providing irrigation water to lands north of Craig. Preliminary water-supply studies of the proposed reservoir (Western Engineers, Inc., 1984) indicated that monthly storable flows ranged from 0 to 5,183 acre-ft during water years 1956-70. These studies did not include the effect of sedimentation rate on the long-term water-storage capacity of Rampart Reservoir.

Purpose and Scope

This report presents estimates of the total-sediment discharge in Fortification Creek at the proposed Rampart Reservoir site and the sedimentation rate of the reservoir. Sediment (suspended and bedload) and stream-discharge data collected at streamflow-gaging station 09246920, Fortification Creek near Fortification (hereinafter referred to as the Fortification Creek gage), during water years 1985-87 were used to estimate the total-sediment discharge at the proposed reservoir site. Locations of the Fortification Creek gage and the reservoir site are shown in figure 1. The Fortification Creek gage is located about 1 mi downstream from the damsite.

Description of Study Area

Fortification Creek drains 31 mi^2 of northwestern Colorado upstream from the proposed Rampart Reservoir (fig. 1). The stream heads in the western part of the Elkhead Mountains then flows west and south to the confluence with the Yampa River about 1 mi south of Craig. Drainage area of the entire Fortification Creek basin is 330 mi^2. Elevation in the drainage basin ranges from about 6,200 ft at the confluence with the Yampa River to about 11,000 ft

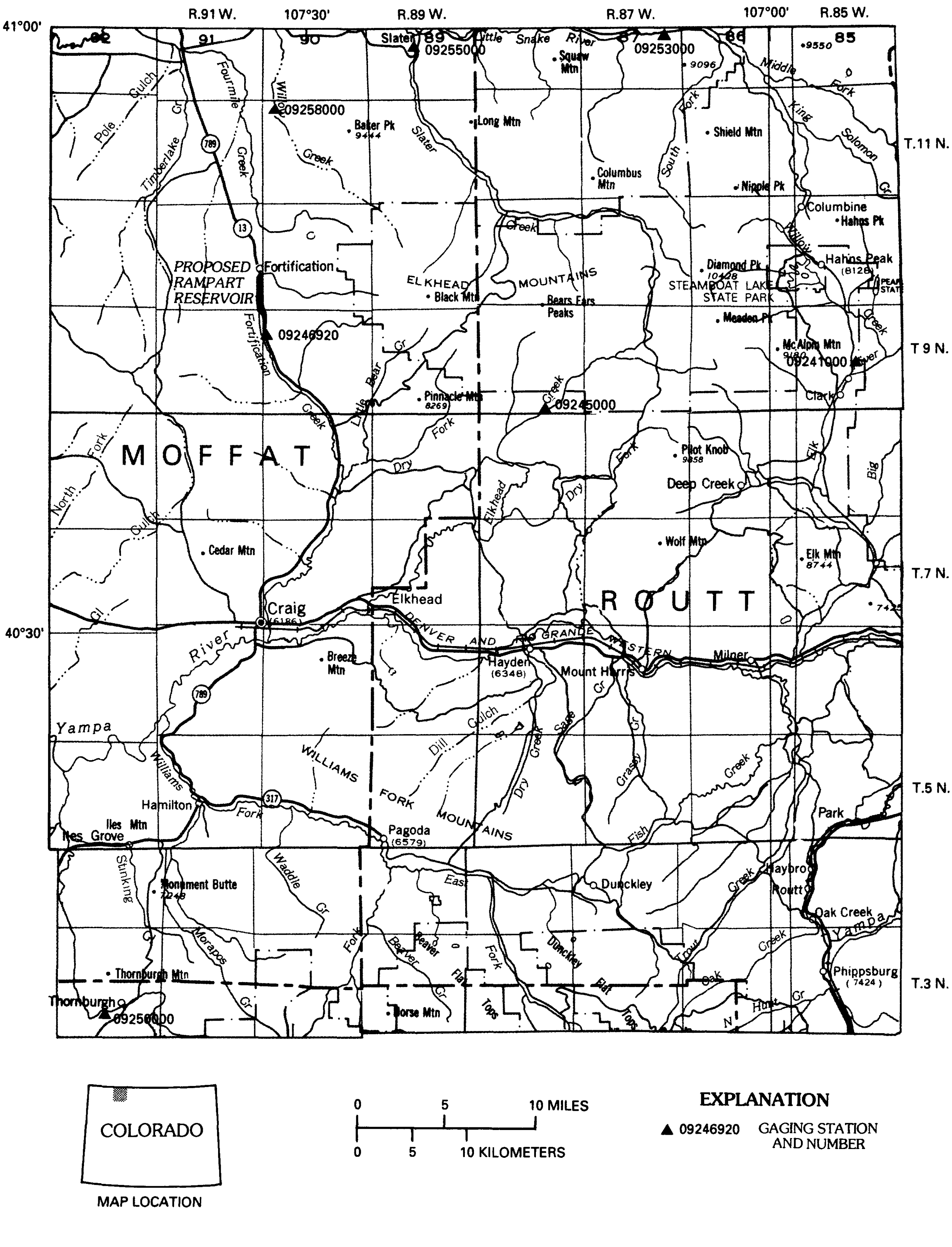

Figure 1.--Location of the study area, including the proposed Rampart Reservoir and data-collection sites.

in the Elkhead Mountain headwaters. The mean elevation of the drainage basin upstream from the Fortification Creek gage is about 8,000 ft. Numerous intermittent and ephemeral streams are tributary to Fortification Creek in the western part of the study area; several ephemeral washes discharge into Fortification Creek between the proposed damsite and the Fortification Creek gage.

Fortification Creek is within the Middle Rocky Mountain physiographic province (Hunt, 1974). The proposed reservoir site is underlain by the Wasatch Formation of Eocene age, which is composed primarily of mudstone and sandstones. The reservoir site is located in the Elkhead Mountain volcanic field and the Sand Wash structural basin (Western Engineers, Inc., 1984). Alluvium as great as 50 ft thick has been deposited in the stream valley at the reservoir site. The alluvium is composed of sand, silt, clay, and small quantities of gravel. Soils that overlie the alluvium in the vicinity of the reservoir site predominantly are Havre fine, sandy loam. Havre soils are characterized by minimal shear strength and large erosion potential. The Colorado Land Use Commission (1974) reported sediment yields of 0.2 to 0.5 (acre-ft/mi^2)/yr from rangelands in the central and western parts of the basin. Smaller yields of 0.1 to 0.2 (acre-ft/mi^2)/yr are typical of forested lands, irrigated croplands, and other areas that have sufficient vegetative cover. The drainage area upstream from the proposed reservoir site is characterized by fields and rolling hills, which are used for hay production and grazing, and forests that contain scrub oak, willow, fir, spruce, and aspen depending on elevation and exposure.

Climate in the study area is continental and is controlled locally by mountains. Summers vary from temperate to warm depending on locale in the basin, and winters are cold. Annual precipitation ranges from about 14 in. in the western part of the basin to about 40 in. in the mountains. Rainstorms occur throughout the warmer months but occur most often in the early spring and fall months. These storms cause short periods of runoff. Substantial snowfall in the mountains results in snowmelt runoff during spring.

STREAM DISCHARGE

Daily stream discharge was recorded for only 3 years, water years 1985-87, at the Fortification Creek gage. The drainage area upstream from the Fortification Creek gage is 40 mi^2. The mean annual stream discharge for this period was 17.6 ft^3/s (about 12,750 acre-ft). The maximum recorded peak discharge was 465 ft^3/s on March 25, 1985; the minimum daily stream discharge was 0.01 ft^3/s on August 5, August 19 through 22, and September 1 through 4, 1987. The monthly mean stream discharge for Fortification Creek gage for water years 1985-87 is shown in figure 2. During the period of record, 84 percent of the stream discharge occurred during March through June. There are water diversions in the basin upstream from the Fortification Creek gage to meet irrigation demands. These diversions affect stream discharge during the summer.

Stream discharge for a longer period for Fortification Creek was simulated using a record-extension technique described by Hirsch (1982). The goal of the record extension is to produce a stream-discharge record with properties such as variance and extreme-order statistics that are believed to be

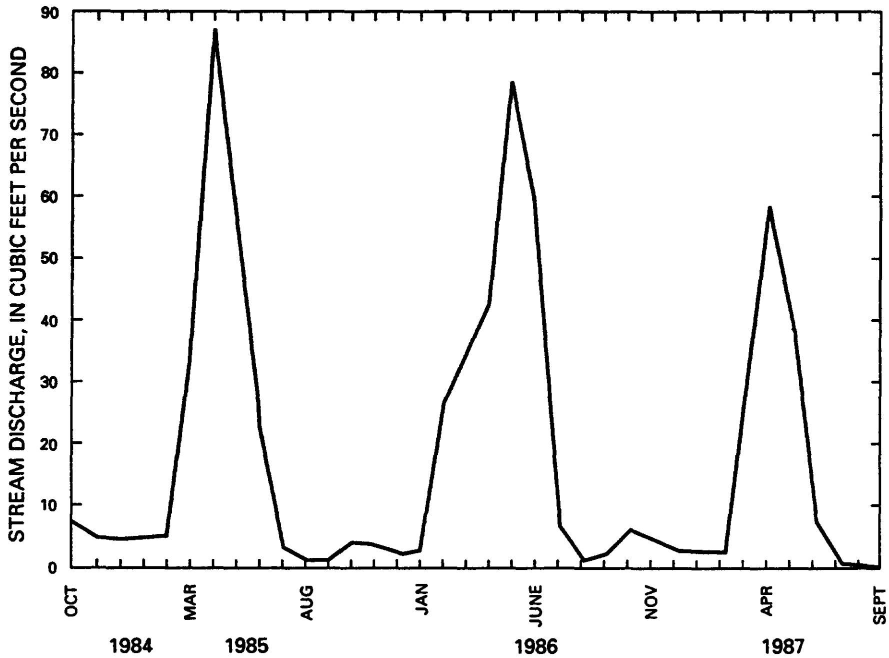

Figure 2.--Monthly mean stream discharge at gaging station 09246920, Fortification Creek near Fortification, October 1984 through September 1987.

like the actual stream-discharge record for Fortification Creek. The technique will simulate stream discharge for every day in the simulation period. The extended discharge record was used to estimate sediment discharge for the proposed reservoir site (described in "Sediment Discharge" section later in this report). Therefore, the selection of a base station was based primarily on how accurately the record-extension technique simulated the monthly distribution of stream discharge and the magnitude of simulated daily stream discharges for the snowmelt-runoff season compared to the actual stream-discharge record for Fortification Creek for water years 1985-87.

Seven streamflow-gaging stations (six of which are shown in fig. 1, not including the Fortification Creek gage), which are located in northwestern Colorado and have at least 30 years of stream-discharge records, were tested as base stations for extending the discharge record for Fortification Creek. The seventh station (09260000) is located on the Little Snake River near Lilly about 45 mi west of Craig.

Gaging station 09245000, Elkhead Creek near Elkhead (hereinafter referred to as the Elkhead Creek gage) was selected as the base station for extending the stream-discharge record for Fortification Creek. The annual mean stream discharge for water years 1985-87 at the Fortification Creek gage is compared with the long-term record (water years 1954-87) for the Elkhead Creek gage in figure 3. The drainage area upstream from the Elkhead Creek gage (fig. 1) is 64 mi^2. The mean annual stream discharge at the Elkhead Creek gage for water years 1954 through 1987 was 59.4 ft^3/s. The stream discharge was greater than average in water years 1985 and 1986 and less than average in 1987 (fig. 3). The annual mean stream discharge in water year 1986 at the Elkhead Creek gage was the second largest during water years 1954 through 1987. Because of the proximity of the drainage basins, it was assumed that stream-discharge conditions were similar in the Fortification Creek and Elkhead Creek drainages. Combining the simulated stream-discharge record for water years 1954-84 with the measured stream discharge for water years 1985-87 results in an estimated mean annual stream discharge of 15.5 ft^3/s (about 11,230 acre-ft) for water years 1954-87 at the Fortification Creek gage.

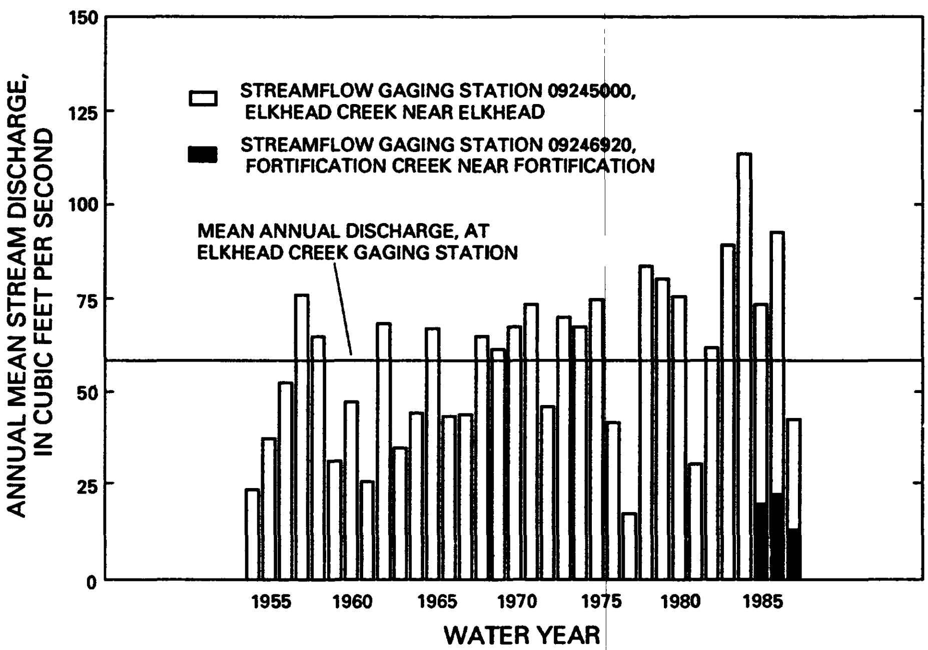

Figure 3.--Annual mean stream discharge at gaging stations 09245000, Elkhead Creek near Elkhead, and 09246920, Fortification Creek near Fortification.

SEDIMENT DISCHARGE

Sediment discharge in a stream is comprised of suspended sediment and bedload sediment. Suspended-sediment particles are transported in suspension in the water by the turbulence of the stream. Suspended sediment primarily is derived from overland runoff, streambank erosion, and streambed erosion. Bedload sediment consists of sediment particles transported on or near the streambed by rolling, sliding, or saltation. A distinction between suspended sediment and bedload sediment is that the weight of bedload particles primarily is supported by the streambed, whereas the weight of suspended-sediment particles is supported by the water.

Suspended-Sediment Discharge

Suspended-sediment samples for this study were collected at the Fortification Creek gage from December 1985 through September 1987. All samples were collected using the equal-width-increment method and a DH-48 sampler (Guy and Norman, 1970). During eight visits, a second suspended-sediment sample was collected immediately after the first sample for verification of sediment concentrations or because stream discharge was changing. Six of the duplicate samples were collected at relatively stable stream discharges, one sample was collected during changing stream discharge, and the other sample was collected near the peak stream discharge of the day. Stream discharge was measured in conjunction with sediment sampling using methods described by Rantz and others (1982). All sediment samples and stream-discharge measurements were done by wading the stream. The streambed at the gage is comprised primarily of cobbles and sand.

Suspended-sediment samples were collected on 31 days from December 1985 to September 1987 (table 1). For the 8 days on which two suspended-sediment samples were collected, the average suspended-sediment concentration is listed because differences between suspended-sediment concentrations of duplicate samples were not large. For 7 of the 8 days, the difference in suspended-sediment concentrations between the 2 samples was 8 percent or less. The second sample collected on May 27, 1986, had a suspended-sediment concentration 17 percent less than the first sample.

Suspended-sediment discharge is computed from suspended-sediment concentration and stream discharge (Porterfield, 1972) by the equation:

$$Qs = 0.0027(QC) \qquad (1)$$

where Qs = suspended-sediment discharge, in tons per day;
0.0027 = conversion factor;
Q = stream discharge, in cubic feet per second; and
C = suspended-sediment concentration, in milligrams per liter.

Equation (1) can be used with either instantaneous or daily mean stream discharges and suspended-sediment concentrations to compute suspended-sediment discharge. It was assumed that it was appropriate to use the stream discharges and suspended-sediment concentrations listed in table 1, which are instantaneous values, to compute the daily suspended-sediment discharge for each sample. Although the errors inherent with that assumption are not known, the assumption needs to be used if the sediment discharge of Fortification Creek and the sedimentation rate of the proposed Rampart Reservoir are to be estimated.

Table 1.--*Stream-discharge and sediment data collected at gaging station 09246920, Fortification Creek near Fortification, water years 1986 and 1987*

[--, no data; <, less than; total sediment discharge is the sum of the suspended-sediment and bedload discharges]

Date of sample	Instantaneous stream discharge (cubic feet per second)	Instantaneous suspended-sediment concentration (milligrams per liter)	Computed suspended-sediment discharge (tons per day)	Computed bedload discharge (tons per day)	Computed total-sediment discharge (tons per day)
12-03-85	3.8	42	0.43	--	--
01-17-86	3.2	39	.34	--	--
02-18-86	38	680	70	0.92	71
[1]02-21-86	19	267	14	.01	14
[1]02-26-86	66	1,170	208	.81	209
[1]03-04-86	75	2,010	407	.32	407
[1]03-11-86	105	3,100	879	.71	880
03-27-86	14	275	10	--	--
[1]04-07-86	42	685	78	.10	78
04-30-86	42	491	56	.37	56
05-06-86	56	662	100	.52	101
[1]05-20-86	77	1,150	239	1.9	241
[1]05-27-86	81	580	127	3.3	130
07-22-86	2.3	51	.32	<.01	.32
07-30-86	.65	27	.05	--	--
09-09-86	.88	37	.09	--	--
11-10-86	2.6	59	.41	--	--
[1]03-05-87	78	821	173	2.5	176
03-17-87	11	526	16	--	--
04-08-87	38	1,230	126	.51	127
04-24-87	52	1,420	199	3.0	202
04-27-87	72	1,670	325	6.1	331
05-18-87	33	331	29	3.8	33
05-21-87	26	260	18	--	--
06-04-87	10	144	3.9	--	--
06-10-87	21	709	40	--	--
07-15-87	.66	39	.07	--	--
07-28-87	.30	65	.05	--	--
08-19-87	.01	52	<.01	--	--
09-09-87	.02	13	<.01	--	--
09-17-87	1.2	54	.17	--	--

[1]Two suspended-sediment samples were collected on this date. Suspended-sediment discharge was determined from mean values of stream discharge and suspended-sediment concentration.

Complete particle-size distribution was determined for 13 samples (table 2), and the percent finer than 0.062 mm was determined for 5 other samples. The particle-size distribution grouped according to sand-silt-clay classification percentages (Simons and Senturk, 1977) is listed in table 3.

The daily mean stream discharge shown in figures 4 and 5 indicate a large variability of stream discharge in Fortification Creek during snowmelt runoff in 1986 and 1987. Those variations primarily result from fluctuating weather conditions. As evident in figures 4 and 5, sediment samples were not collected during all the major runoff events. In addition, large diurnal fluctuations in stream discharge occurred, especially during the early part of the runoff period when the low-elevation snowmelt was occurring. Eight of the 20 sediment samples collected during snowmelt runoff in 1986 and 1987 were collected at stream discharges within 10 percent of the daily mean discharge for that day; five of the sediment samples were collected at stream discharges that were at least 10 percent greater than the daily mean discharge; and the other 7 samples were collected at stream discharges at least 10 percent less than the daily mean discharge of the day. The sediment samples collected March 4 and 11 in 1986 were collected near the peak stream discharge for those two days; conversely, the sediment sample collected April 24, 1987, was collected near the minimum stream discharge for that day. The maximum suspended-sediment concentration that was sampled during this study occurred on March 11, 1986. Two samples collected on that date had suspended-sediment concentrations of 3,090 and 3,100 mg/L (reported as 3,100 mg/L in table 1).

The runoff at Fortification Creek during 1986 (fig. 4) represented unusual hydrologic conditions in which the instantaneous peak stream discharge of the year was recorded in mid-February. That event was caused by unusually warm weather that was accompanied by rain, which caused considerable snowmelt at lower elevations in northwestern Colorado. The maximum suspended-sediment concentration sampled in 1987 occurred after the instantaneous peak stream discharge recorded for the year (April 1).

The instantaneous values of suspended-sediment concentration and stream discharge listed in table 1 are shown in figure 6. The points are in two groups; there is a break at about 10 ft^3/s of stream discharge. Samples collected at stream discharges greater than about 10 ft^3/s had suspended-sediment concentrations greater than 100 mg/L; samples collected at stream discharges less than 10 ft^3/s had suspended-sediment concentrations less than 100 mg/L. The grouping of the data in figure 6 indicates that suspended-sediment concentrations in Fortification Creek may vary because of seasonal effects. All the samples collected at stream discharges greater than 10 ft^3/s were collected during snowmelt runoff in 1986 and 1987.

The relation of computed suspended-sediment discharge to instantaneous stream discharge often is approximately linear for logarithm-transformed data. Such a relation is needed if the annual suspended-sediment discharge is to be estimated by using stream-discharge data. Without such a relation, suspended-sediment samples would have to be collected at least daily to compute annual suspended-sediment discharge. The regression equation (Glysson, 1987, p. 15) is:

Table 2.--*Particle-size distribution of suspended sediment in samples collected at gaging station 09246920, Fortification Creek near Fortification, water years 1986 and 1987*

[--, no data]

Date of sample	Percent finer than indicated size (millimeters)							
	0.500	0.250	0.125	0.062	0.016	0.008	0.004	0.002
02-18-86	100	100	96	92	72	66	60	54
02-21-86	100	100	100	99	89	83	73	66
02-26-86	100	100	99	98	93	84	74	61
03-04-86	100	100	100	99	94	87	75	63
03-11-86	100	100	99	98	91	85	75	64
03-27-86	--	--	--	98	--	--	--	--
04-07-86	100	100	100	97	81	70	60	48
04-30-86	--	--	--	86	--	--	--	--
05-06-86	--	--	--	76	--	--	--	--
05-20-86	100	99	83	64	42	36	30	24
05-27-86	100	97	76	65	44	38	32	25
03-05-87	100	98	96	95	92	91	90	78
03-17-87	100	100	100	99	81	66	53	42
04-24-87	100	96	88	76	52	44	36	28
04-27-87	100	85	62	43	32	--	21	16
05-21-87	--	--	--	60	--	--	--	--
06-04-87	--	--	--	79	--	--	--	--
06-10-87	100	100	98	93	71	59	50	41

$$\ln(Qs) = a + b[\ln(Q)], \tag{2}$$

where
ln = base e logarithm;
Qs = suspended-sediment discharge, in tons per day;
a = regression intercept;
b = regression slope; and
Q = stream discharge, in cubic feet per second.

An inherent, often unstated, assumption is that it is appropriate to use a regression relation such as equation (2) that was derived from instantaneous values of stream discharge and suspended-sediment discharge to estimate daily suspended-sediment discharges from daily mean stream discharge, which is done later in this report for Fortification Creek. It would be preferable to use a regression relation based on daily mean stream and suspended-sediment discharges when using daily mean stream discharges to predict suspended-sediment discharges, but the sediment data required were not available. Collection of daily sediment data was beyond the scope of this study.

Table 3.--*Particle-size distribution of suspended sediment in samples collected at gaging station 09246920, Fortification Creek near Fortification, grouped into sand-silt-clay percentages*

[Sand, particles greater than or equal to 0.0625 millimeter; silt, particles less than 0.0625 millimeter and greater than or equal to 0.004 millimeter; clay, particles less than 0.004 millimeter]

Date of sample	Percent sand	Percent silt	Percent clay
02-18-86	8	32	60
02-21-86	1	26	73
02-26-86	2	24	74
03-04-86	1	24	75
03-11-86	2	23	75
04-07-86	3	37	60
05-20-86	36	34	30
05-27-86	35	33	32
03-05-87	5	5	90
03-17-87	1	46	53
04-24-87	24	40	36
04-27-87	57	22	21
06-10-87	7	43	50

Several relations for estimating suspended-sediment discharge from stream discharge for Fortification Creek were analyzed. The simplest relation is a single regression that uses all the samples and is shown in figure 7 and listed in table 4. At first, that regression relation appears to describe the data very well and has a large coefficient of determination (0.96). However, a large coefficient of determination can be misleading when evaluating the suitability of a regression relation for its intended purpose. The regression relation that is based on all the samples is substantially affected by the samples collected at small stream discharges on August 19 and September 9, 1987 (data points represented by stream discharges of 0.01 and 0.02 ft^3/s in fig. 7). The effect of those samples is to decrease the slope of the regression line, which may cause substantial underestimation of suspended-sediment discharge at the large stream discharges. For example, at the stream discharge of 105 ft^3/s for the sample collected March 11, 1986 (table 1), the predicted suspended-sediment discharge of 279 tons/day is about 600 tons less than the computed suspended-sediment discharge. Because most of the annual suspended-sediment discharge occurs during periods of large stream discharge and the regression relation underpredicts suspended-sediment discharge at large stream discharges, the single regression relation was not considered suitable for estimating suspended-sediment discharge in Fortification Creek.

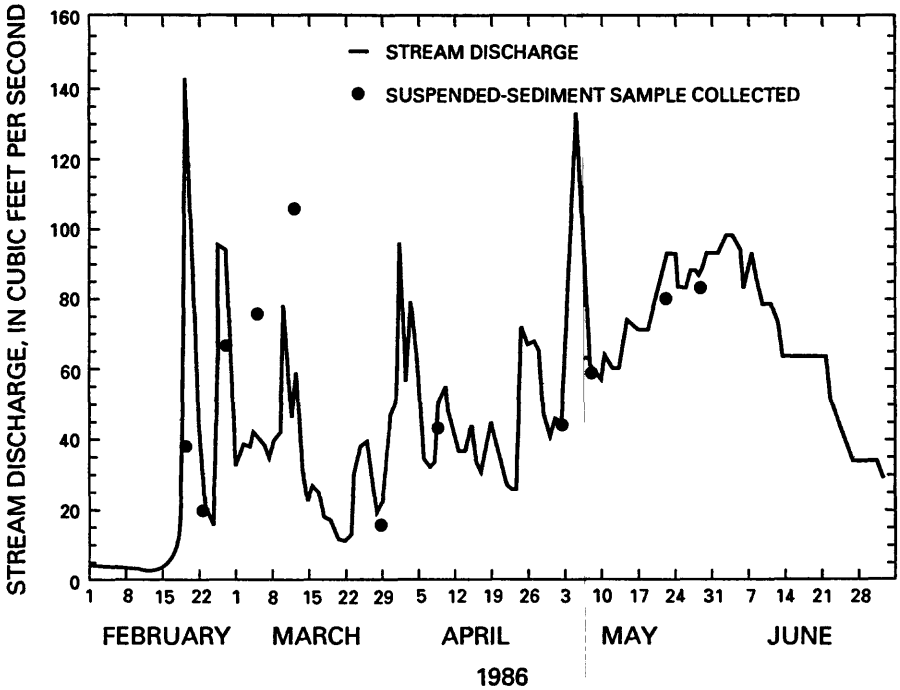

Figure 4.--Daily mean stream discharge at gaging station 09246920, Fortification Creek near Fortification, and the date and measured stream discharge of suspended-sediment samples collected from February through June 1986.

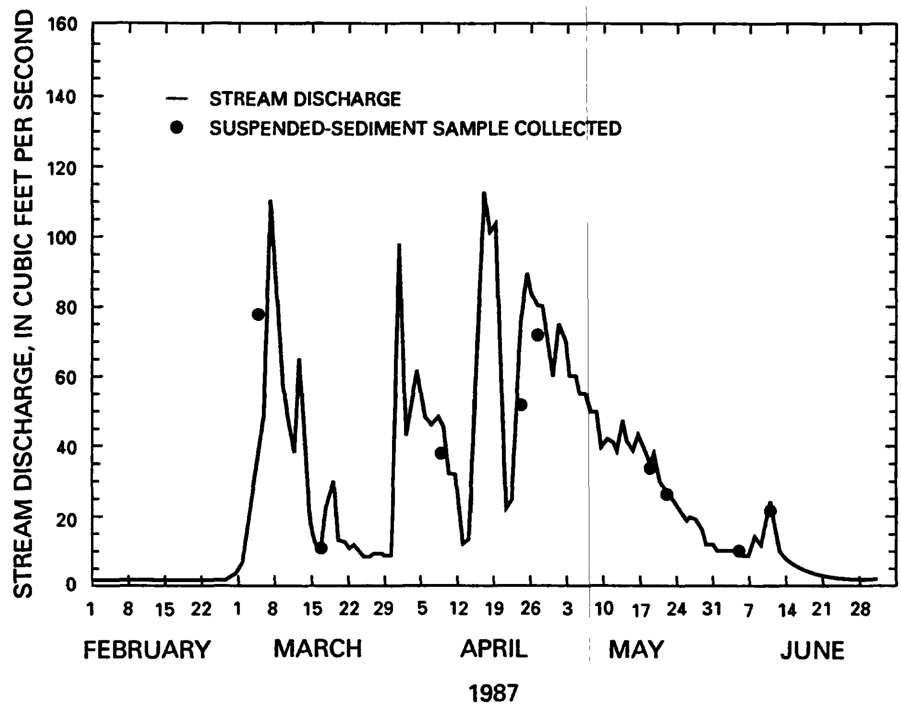

Figure 5.--Daily mean stream discharge at gaging station 09246920, Fortification Creek near Fortification, and the date and measured stream discharge of suspended-sediment samples collected from February through June 1987.

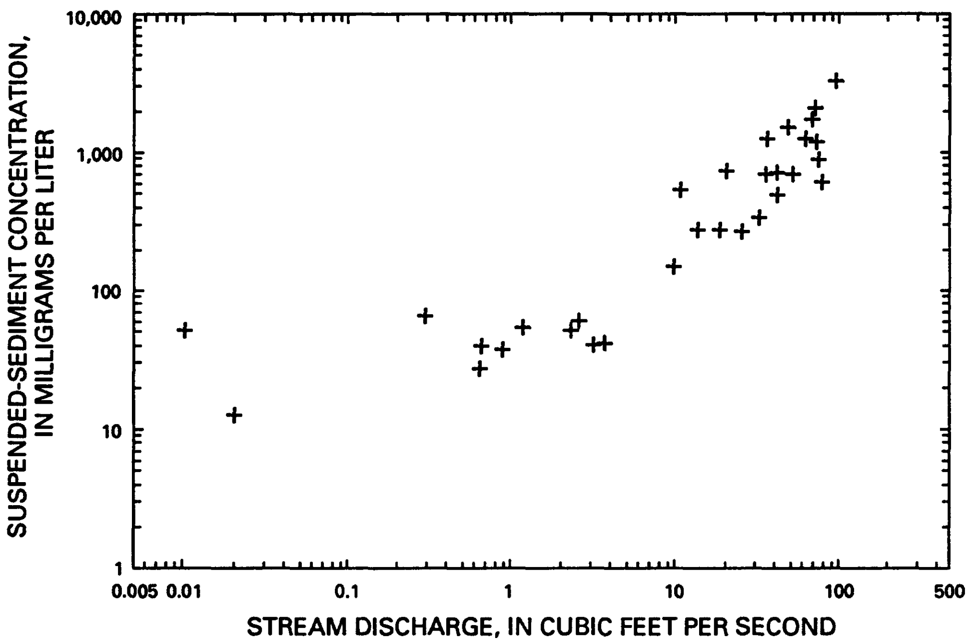

Figure 6.--Measured suspended-sediment concentration and stream discharge at gaging station 09246920, Fortification Creek near Fortification.

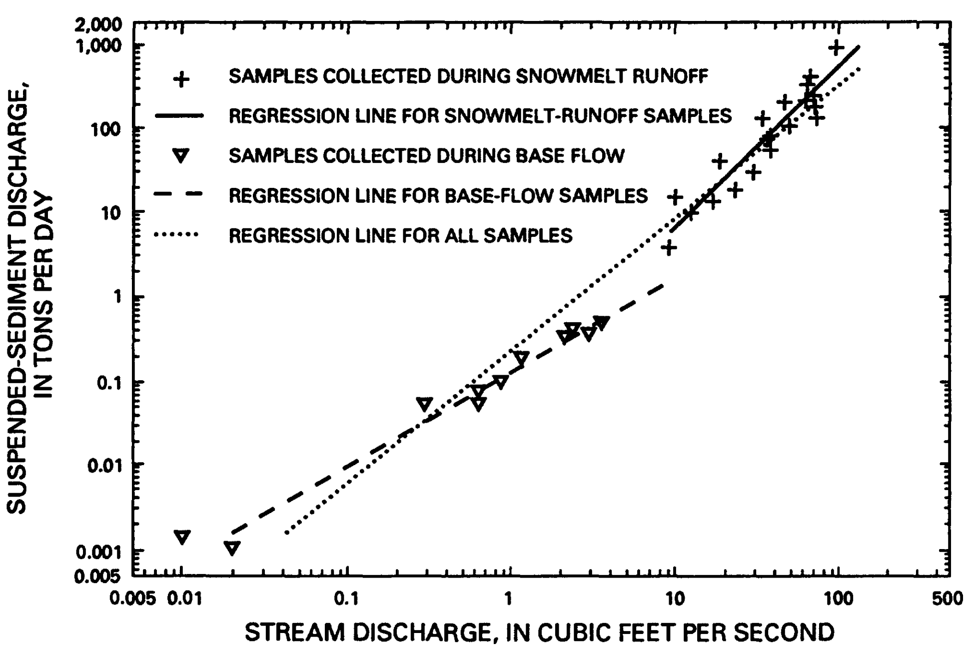

Figure 7.--Relations of computed suspended-sediment discharge to stream discharge at gaging station 09246920, Fortification Creek near Fortification.

Table 4.--*Regression relations of sediment discharge to stream discharge at gaging station 09246920, Fortification Creek near Fortification*

[n, number of data pairs; r^2, coefficient of determination; se, standard error of estimate, in percent; ln, base e logarithm; *Qs*, computed suspended-sediment discharge, in tons per day; *Q*, daily mean stream discharge, in cubic feet per second; *Qb*, computed bedload discharge, in tons per day]

Dependent variable	Statistical values for regression of dependent variables as function of stream discharge			
	n	r^2	se	Regression equation
Suspended-sediment discharge, all samples	31	0.96	86	$\ln(Qs) = -1.58 + 1.55[\ln(Q)]$
Suspended-sediment discharge, snowmelt-runoff samples	20	.88	52	$\ln(Qs) = -2.55 + 1.87[\ln(Q)]$
Suspended-sediment discharge, base-flow samples	11	.97	45	$\ln(Qs) = -2.17 + 1.09[\ln(Q)]$
Bedload discharge	16	.70	172	$\ln(Qb) = -8.84 + 2.15[\ln(Q)]$

Suspended-sediment discharge relations for the snowmelt-runoff period have been based on the date of the peak stream discharge by other sediment studies of proposed reservoir sites in western Colorado (Butler, 1986; Ruddy, 1987). The hydrographs in figures 4 and 5 indicate that such relations for Fortification Creek would be impossible to determine from the limited data because of the large variability of daily stream discharge during the snowmelt-runoff periods. Changes in suspended-sediment concentrations and discharge may be related to rising and falling limbs of each peak on the hydrograph rather than to the peak stream discharge of the year.

The data in figure 6 indicate that there might be seasonal relations of suspended-sediment concentration to stream discharge. The data were divided into two groups--snowmelt-runoff samples and base-flow samples. The samples collected from February through May in 1986 and from March through June in 1987 were considered snowmelt-runoff samples, and all other samples were con-idered base-flow samples. The regression relations of computed suspended-sediment discharge to stream discharge determined for these two groups are shown in figure 7 and listed in table 4. These relations were considered more representative of suspended-sediment discharge in Fortification Creek than was the single regression relation for all data collected in 1986 and 1987. The effect of the samples collected at small stream discharges is removed from the relation for determining suspended-sediment discharges for large stream discharges.

Bedload Discharge

Bedload samples were collected at the Fortification Creek gage by using a 3-in. Helley-Smith bedload sampler and sampling techniques described by Emmett (1980). Bedload discharge was computed (William Emmett, U.S. Geological Survey, written commun., 1989, modified from Edwards and Glysson, 1987, p. 103) from field data by the equation:

$$Q_b = 1.1428 \frac{(wt)\ (W)}{(nti)} \qquad (3)$$

where Q_b = bedload discharge, in tons per day;
1.1418 = conversion factor;
wt = weight of the bedload sample, in grams;
W = stream width, in feet;
n = number of sampling verticals;
t = duration of sampling time at each vertical, in seconds; and
i = width of bedload sampler intake, in inches.

Computed values of bedload discharge are listed in table 1 and shown in figure 8. The particle-size distribution of the bedload samples is listed in table 5.

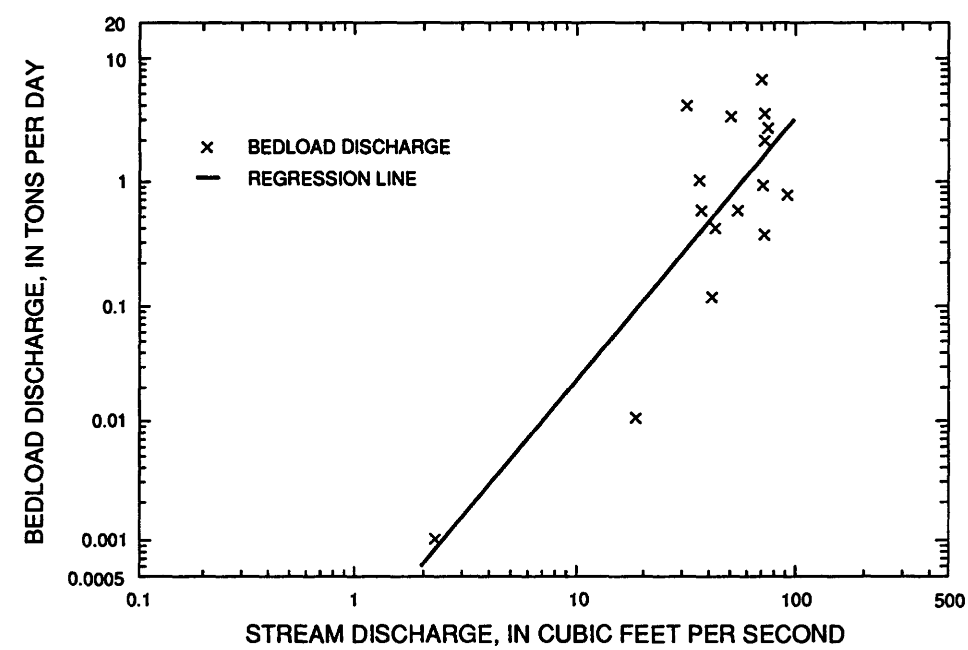

Figure 8.--Relation of computed bedload discharge to stream discharge at gaging station 09246920, Fortification Creek near Fortification.

Table 5.--*Particle-size distribution of bedload sediment in samples collected at gaging station 09246920, Fortification Creek near Fortification, water years 1986 and 1987*

Date of sample	Percent finer than indicated size (millimeters)								
	16.0	8.0	4.0	2.0	1.0	0.500	0.250	0.125	0.062
02-18-86	100	100	100	99	98	96	73	29	11
02-21-86	100	100	100	100	97	33	5	3	0
02-26-86	100	100	100	98	86	70	22	8	4
03-04-86	100	100	99	94	92	68	14	7	4
[1]03-11-86	100	99	98	97	92	75	48	45	43
04-07-86	100	100	99	99	91	72	32	13	6
04-30-86	100	100	99	97	89	72	21	9	3
05-06-86	100	100	100	98	91	79	32	12	5
05-20-86	100	100	100	99	98	95	54	17	6
05-27-86	100	100	100	100	98	89	40	10	3
[2]07-22-86	100	100	100	71	35	12	0	0	0
03-05-87	100	100	100	100	98	77	7	3	2
04-08-87	100	100	100	99	98	95	22	5	2
04-24-87	100	100	100	100	99	90	25	6	2
04-27-87	100	100	100	100	98	80	17	5	2
05-18-87	100	100	100	100	99	93	31	5	2

[1]Concreted clays in sample may have caused unusually large percentage of fine material.

[2]Sample weight was only 1.7 grams.

Based on the 16 samples collected in 1986 and 1987, computed bedload discharge was not a large part of the computed total-sediment discharge in Fortification Creek. In only two of the samples (May 27, 1986, and May 18, 1987) did bedload discharge account for more than 2 percent of the computed total-sediment discharge. Bedload discharge was less than 1 percent of the computed total-sediment discharge in most of the samples collected in 1986. Almost all of the bedload sediment that was sampled was composed of sand less than 1.0 mm in diameter (table 5). A weak regression relation between bedload discharge and stream discharge is listed in table 4. The error estimate for this relation is large (172 percent), and the sample collected on July 22, 1986 (bedload discharge 0.001 ton/day, listed as <0.01 ton/day in table 1), had a large effect on the regression. When that sample is removed from the data set, there essentially is no relation between bedload discharge and stream discharge (coefficient of determination 0.37). However, the bedload results, both in terms of the small fraction of the computed total-sediment discharge accounted for by bedload and the rather poor regression relation, do provide useful and important information regarding bedload transport in streams in western Colorado. In the case of Fortification Creek, bedload does not seem to be an important factor (at least for reservoir sedimentation), and many samples would need to be collected to define bedload transport.

Total-Sediment Discharge

The computed total-sediment discharges listed in table 1 are the sum of the computed suspended-sediment and bedload discharges, which can overestimate the total-sediment discharge. The suspended-sediment sampler does not sample the bottom 0.3 ft of the stream (the unsampled zone). Because the suspended-sediment discharge was computed (eq. 1) by using the entire stream discharge and the sediment concentration of the sampled zone, the suspended-sediment concentration in the unsampled zone was assumed to be equal to the suspended-sediment concentration of the sampled zone. Almost all of the sampled suspended sediment was finer than 0.25 mm (table 2), and the Helley-Smith bedload sampler collected sediment that is finer than 0.25 mm in the bottom 0.3 ft. Therefore, some of the suspended sediment was included in both the suspended-sediment discharge and the bedload discharge. The quantity of sediment collected by the bedload sampler usually was less than 2 percent of the total-sediment discharge; therefore, relative to the total-sediment discharge, the quantity of suspended sediment that was collected by the bedload sampler was considered minimal and would have no measurable effect on estimating the sedimentation rate of the proposed reservoir.

Annual Sediment Discharge

Daily suspended-sediment discharge was estimated in Fortification Creek by using the daily mean stream discharge and the seasonal regression relations for suspended-sediment discharge. Sums of the daily suspended-sediment discharges result in the annual suspended-sediment discharge for each year of stream discharge data (1985-87). Bedload discharge was not computed using the regression equation. Instead, the bedload discharge was estimated conservatively (overestimate) to account for 2 percent of the annual total-sediment discharge in Fortification Creek. The annual total-sediment discharge was approximated by multiplying the annual suspended-sediment discharge by 1.02.

Sediment discharge estimated by log-log regression relations will be underestimated by a factor that is dependent on the variance of the regression relation (Ferguson, 1986). For regression relations that are expressed in base e logarithms, the correction factor is equal to $\exp[(se^2)/2]$, where exp is the base e antilog and se is the standard error of estimate in logarithm units. For the two seasonal regression relations, the correction factor was 1.13 for the snowmelt-runoff relation and 1.10 for the base-flow relation. These correction factors were incorporated into the computer program that was used for computing annual sediment discharges, and all suspended-sediment discharges were adjusted using the correction factors.

The seasonal regression relations were applied to the daily mean stream discharges that were measured at the Fortification Creek gage to compute an estimated mean annual suspended-sediment discharge of 19,300 tons for water years 1985-87. The snowmelt-runoff season was March through June for 1985 and 1987 and February through June for 1986. The estimated mean annual total-sediment discharge was about 19,700 tons for the same period. These estimates were based on only 3 years of stream-discharge data. An estimate of total-sediment discharge for a longer time period may be more realistic of long-term conditions for determining the sedimentation rate of the proposed reservoir if extension could be made of the stream-discharge record for Fortification Creek. As described previously in the "Stream Discharge" section of this report, the Elkhead Creek gage was used to extend the stream-discharge record for the Fortification Creek gage to include water years 1954-84. When the simulated stream discharges for water years 1954-84 are combined with the measured stream discharges for water years 1985-87, the estimated mean annual suspended-sediment discharge was 17,800 tons for water years 1954-87. The estimated mean annual total-sediment discharge was about 18,200 tons at the Fortification Creek gage.

An error estimate was made for the mean annual suspended-sediment discharge by computing the 95-percent confidence interval for the regression relations. The 95-percent confidence interval was computed for the daily suspended-sediment discharges, and these values were summed to obtain the 95-percent confidence interval for each year. The 95-percent confidence interval for an estimated mean annual suspended-sediment discharge of 17,800 tons (water years 1954-87) was 9,630 to 34,600 tons. Converting those values to an estimated mean annual total-sediment discharge results in a 95-percent confidence interval of 9,820 to 35,300 tons at the Fortification Creek gage.

SEDIMENTATION RATE OF THE PROPOSED RAMPART RESERVOIR

Several factors can affect the sedimentation rate of a reservoir: (1) Trap efficiency of the reservoir, (2) specific weight of the deposited sediments, (3) particle size of the sediment, (4) sediment-inflow discharge, and (5) reservoir size and operation. The decrease in water-storage capacity of a reservoir caused by sediment deposition can be estimated if sediment-inflow discharge, stream discharge, particle-size distribution data, and the operation plans and dimensions of the proposed reservoir are known.

The trap efficiency of a reservoir is the percentage of incoming sediment that remains in the reservoir and is a function of stream discharge, reservoir size, and reservoir operations. The trap efficiency of the proposed Rampart Reservoir was computed to be almost 100 percent by using either the Brune method or the Churchill method (Vanoni, 1975). The trap efficiency of the reservoir was estimated to be at least 95 percent even after 100 years of sediment deposition.

The specific weight of sediment is used to convert sediment discharge to the volume that the deposits would occupy in the proposed reservoir. A method using particle-size distribution of the incoming sediment and reservoir operations (Strand and Pemberton, 1982) was used to determine initial specific weight of the sediment deposits. The particle-size distribution of the suspended-sediment samples was used to compute specific weight because suspended sediment accounted for at least 98 percent of the total-sediment discharge in Fortification Creek. An initial specific weight of 53.7 lb/ft^3 was calculated by using a particle-size distribution of 15 percent sand, 26 percent silt, and 59 percent clay. That particle-size distribution was estimated using the particle-size data for the suspended-sediment samples collected for this study.

The specific weight of deposits in a reservoir will increase with time because of compaction. A function reported in Strand and Pemberton (1982) was used to estimate the specific weight of the deposits after various time periods. For example, the specific weight would increase to 59.2 lb/ft^3 after 25 years and to 62.3 lb/ft^3 after 100 years.

The weight of the sediment deposits (in tons) is determined by multiplying the mean annual total-sediment discharge by the number of years of interest and by the trap efficiency. After converting that weight to pounds and dividing by the specific weight of the deposits, the volume (in cubic feet) that the sediment deposits would occupy in the reservoir has been calculated. That value can be converted to acre-feet, and the reservoir capacity after a certain number of years of sediment deposition can be determined.

The estimated mean annual total-sediment discharge of 18,200 tons (water years 1954-87) was computed for the Fortification Creek gage. The proposed damsite is about 1 mi upstream from the gaging station, and there is 9.0 mi^2 of drainage area between the damsite and the gage. There are four ephemeral washes between the damsite and the gage that may contribute sediment to Fortification Creek early in the runoff period when snow is melting in low-elevation areas. Therefore, the sediment discharge at the Fortification Creek gage probably is larger than the actual sediment discharge at the damsite. The drainage area upstream from the damsite is 78 percent of the drainage area upstream from the gage. The sediment discharge at the damsite was estimated to be equal to 90 percent of the estimated mean annual total-sediment discharge at the Fortification Creek gage. Therefore, the estimated mean annual total-sediment discharge for the reservoir site was about 16,400 tons and has a 95-percent confidence interval of about 8,800 to 32,000 tons.

The estimated storage capacity of the proposed reservoir for 100 years is shown in figure 9. A trap efficiency of 100 percent was assumed for the 100-year period. At a total-sediment discharge of 16,400 tons/yr for 100 years, the storage capacity of the reservoir would decrease from 12,133 acre-ft to about 11,000 acre-ft, or a loss of about 9 percent of storage capacity after 100 years. The change in storage capacity also was determined for the 95-percent confidence interval of the mean annual total-sediment discharge. The error estimate of storage capacity in the reservoir is depicted by the upper and lower lines shown in figure 9. At 8,800 tons/yr of sediment inflow, the reservoir storage capacity would be about 11,500 acre-ft, or a loss of about 5 percent of storage capacity after 100 years. At 32,000 tons/yr of sediment inflow, the reservoir storage capacity would be about 9,900 acre-ft, or a loss of about 18 percent of storage capacity after 100 years.

The sedimentation rate estimated for this study was dependent on several assumptions. It was assumed that sediment samples were collected at a range of stream discharges to sufficiently define regression relations of sediment discharge to stream discharge. Sediment discharge from summer thunderstorms was not considered in the determination of the sedimentation rate because no data were collected to define sediment runoff produced by thunderstorms.

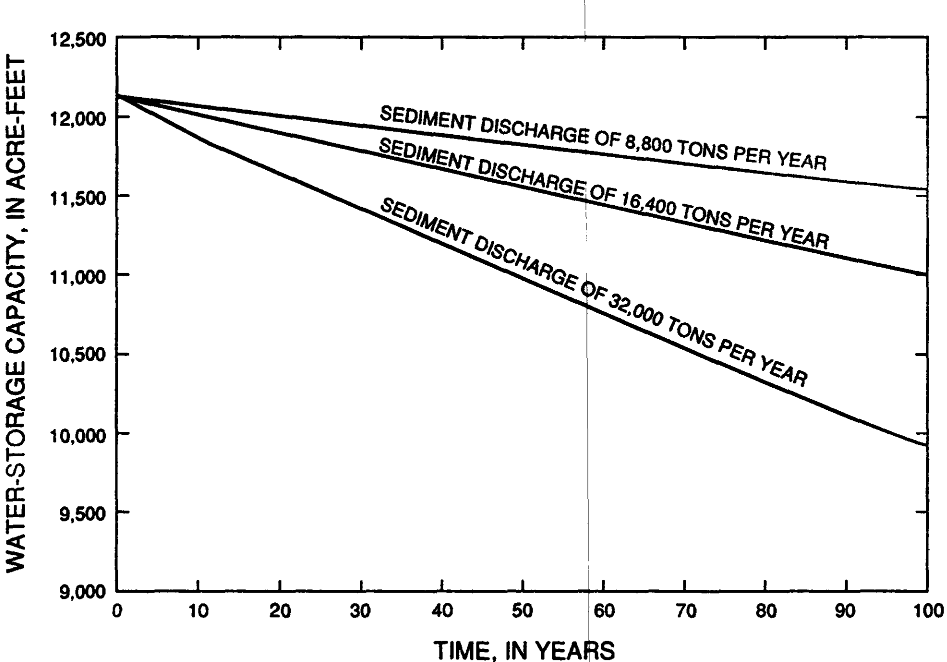

Figure 9.--Water-storage capacity of the proposed Rampart Reservoir based on the 95-percent confidence interval of the estimated sediment discharge in Fortification Creek.

Thunderstorm runoff in the Fortification Creek basin is relatively rare. The estimates for the long-term sediment discharge in Fortification Creek were based on the assumption that the regression relations developed from the sediment data collected in 1986 and 1987 were applicable to the period used to estimate the mean annual total-sediment discharge (water years 1954-87). The simulated stream discharges for water years 1954-84 were assumed to be reasonably representative of stream discharge in Fortification Creek with respect to magnitude of daily mean stream discharge and the distribution of the runoff. Also, 90 percent of the sediment discharge at the Fortification Creek gage was assumed to represent the sediment discharge at the reservoir site. Changes in land use or sediment yield in the drainage basin upstream from the reservoir site could cause changes in relations of suspended-sediment discharge to stream discharge.

SUMMARY

The sediment discharge into the proposed Rampart Reservoir (initial storage capacity 12,133 acre-ft) on Fortification Creek was determined, and the change in storage capacity of the reservoir was estimated for 100 years. Stream discharge was recorded for water years 1985-87 at gaging station 09246920, Fortification Creek near Fortification; the mean annual stream discharge was 17.6 ft^3/s. A record extension technique, using gaging station 09245000, Elkhead Creek near Elkhead, as the base station was used to simulate the stream discharge for the Fortification Creek gage for water years 1954-84. The estimated mean annual stream discharge for water years 1954-87 was 15.5 ft^3/s at the Fortification Creek gage.

Suspended- and bedload-sediment data that were collected on 31 days during water years 1986 and 1987 at the Fortification Creek gage were used to estimate sediment discharge from stream discharge in Fortification Creek. It was assumed that it was appropriate to use instantaneous values of stream discharge and suspended-sediment concentrations to compute the daily suspended-sediment discharge. Although the errors inherent with this assumption are unknown, the assumption needs to be used if the sediment discharge for Fortification Creek and the sedimentation rate of the proposed Rampart Reservoir are to be estimated. Regression relations between suspended-sediment discharge and stream discharge were determined for snowmelt-runoff and base-flow periods. Suspended sediment accounted for more than 98 percent of the total-sediment discharge at the Fortification Creek gage based on the data collected during this study. Bedload discharge did not have a statistically significant relation to stream discharge.

The regression relations for suspended-sediment discharge were used with the daily mean stream discharges that were recorded at the Fortification Creek gage to estimate a mean annual suspended-sediment discharge for water years 1985-87 of 19,300 tons. The regression relation for bedload discharge was not used to estimate the mean annual bedload discharge from stream discharge; instead, bedload discharge was assumed to account for 2 percent of the total-sediment discharge based on the data collected for the study. The mean annual total-sediment discharge of about 19,700 tons was determined by multiplying the mean annual suspended-sediment discharge by 1.02. A longer term estimate of total-sediment discharge was obtained by incorporating the simulated stream discharge for water years 1954-84 with the stream discharge record for water years 1985-87. The estimated mean annual suspended-sediment discharge for Fortification Creek was 17,800 tons, or about 18,200 tons of total-sediment discharge, for water years 1954-87. The 95-percent confidence interval for the estimated mean annual total-sediment discharge was 9,820 to 35,300 tons.

The total-sediment discharge used to estimate the sedimentation rate in the proposed Rampart Reservoir was adjusted from the total-sediment discharge estimated at the Fortification Creek gage because the damsite for the reservoir is about 1 mi upstream from the gage. The total-sediment discharge into the reservoir site was assumed to be 90 percent of the mean annual total-sediment discharge (18,200 tons/yr) in Fortification Creek at the gaging station. Therefore, total-sediment discharge at the reservoir site was estimated to be 16,400 tons/yr with a 95-percent confidence interval of about 8,800 to 32,000 tons/yr. At 100-percent trap efficiency, the reservoir storage capacity would decrease from 12,133 acre-ft to 11,000 acre-ft, or a loss of about 9 percent of storage capacity after 100 years of sediment discharge of 16,400 tons/yr. Using the 95-percent confidence interval of the total sediment discharge, the reservoir storage capacity would range from 9,900 to 11,500 acre-ft, or about an 18- to 5-percent decrease in storage capacity after 100 years.

Determination of the sedimentation rate for the Rampart Reservoir was dependent on several assumptions. It was assumed that it was appropriate to apply regression relations derived from instantaneous measurements of stream discharge and sediment discharge to daily mean stream discharges to estimate daily sediment discharge. It also was assumed that the regression relations are valid for the range of stream discharges for the long-term record. It also was assumed that the simulated stream-discharge record was representative of stream discharge in Fortification Creek with respect to magnitude of the daily mean values and the seasonal distribution of stream discharge. Sediment discharge produced by thunderstorms was not determined and was assumed to have a negligible effect on the sedimentation rate. Another assumption was that present-day land use and sediment-yield characteristics in the basin upstream from the reservoir site will remain unchanged for the life of the project (100 years).

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