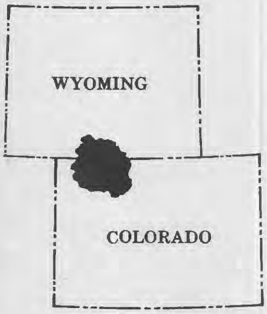

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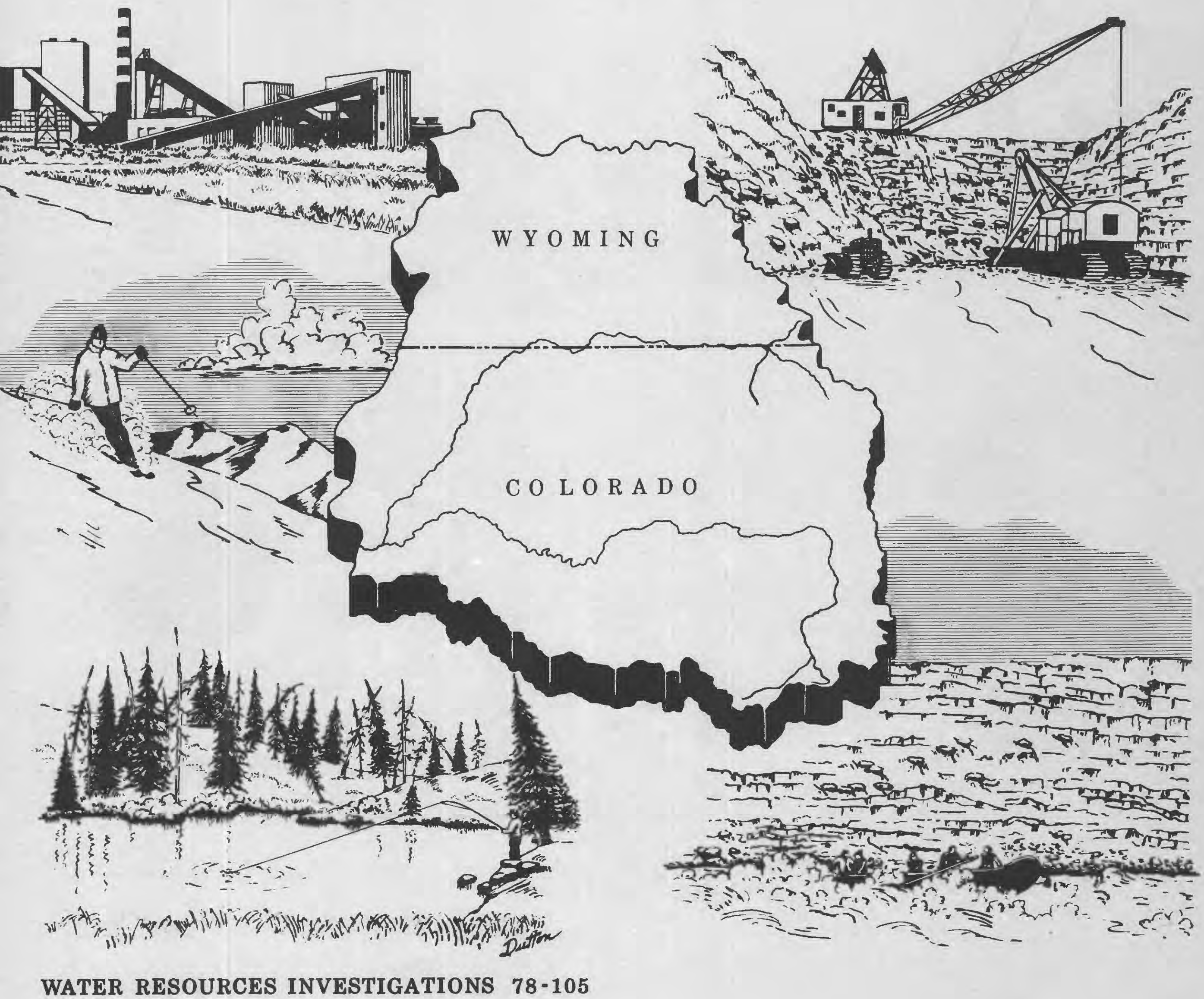
GEOLOGICAL SURVEY

PRESENT AND POTENTIAL SEDIMENT YIELDS IN THE YAMPA RIVER BASIN, COLORADO AND WYOMING



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Projected economic development of the basin, especially surface mining of coal, will impact the physical environment. Depending upon the amount and location of land disturbed, an estimated 10,000 to 30,000 tons per year (9,000 to 27,000 metric tons per year) of additional sediment will be contributed to the main-stem Yampa River.

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METRIC CONVERSIONS

Inch-pound units used in this report may be expressed as metric units by use of the following conversion factors:

Multiply inch-pound unit	*By*	*To obtain metric unit*
inch	25.40	millimeter (mm)
foot per second	0.3048	meter per second
acre	0.4047	hectare (ha)
square mile (mi^2)	2.59	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
ton	0.9074	metric ton (t)
ton per year	0.9074	metric ton per year
ton per acre	2.242	metric ton per hectare (t/ha)
ton per square mile (ton/mi^2)	0.3503	metric ton per square kilometer (t/km^2)
ton per square mile per year [$(ton/mi^2)/yr$]	0.3503	metric ton per square kilometer per year [$(t/km^2)/yr$]

PRESENT AND POTENTIAL SEDIMENT YIELDS IN THE YAMPA RIVER BASIN, COLORADO AND WYOMING

By Edmund D. Andrews

ABSTRACT

Average annual suspended- and total-sediment loads in streamflow were determined by the flow-duration sediment-transport-curve method at 18 sites in the Yampa River basin, Colorado and Wyoming. These computations indicate that about 2.0 million tons (1.8 million metric tons) of sediment are carried by the Yampa River at Deerlodge Park during an average year. Significant areal differences in the sediment yield from various parts of the basin also were determined. The lower Little Snake River subbasin contributes about 60 percent of the total basin sediment yield, although it represents less than 35 percent of the area and supplies less than 3 percent of the streamflow. In contrast, the upland (eastern) one-third of the basin contributes only about 14 percent of the sediment yield but 76 percent of the streamflow.

Projected economic development of the basin, especially surface mining of coal, will impact the physical environment. Depending upon the amount of coal mined, as well as the extent and location of land disturbed, an estimated 10,000 to 30,000 tons per year (9,000 to 27,000 metric tons per year) of additional sediment will be contributed to the main-stem Yampa River. The impact of this additional sediment load will depend upon where within the basin it enters the stream channel. Although the increased sediment load due to surface mining represents approximately 2 percent of the present total-sediment load, it could increase the sediment load of the upper reaches of the Yampa River by as much as 30 percent.

INTRODUCTION

Development of coal resources of the Yampa River basin in northwestern Colorado and south-central Wyoming will have significant effects upon the environment and natural resources of the basin. The Yampa River Basin Assessment (Steele and others, 1976a, 1976b) was designed to describe the availability and quality of the basin's water resources and to evaluate the potential environmental and selected socioeconomic impacts of alternative coal-resource development plans. The study of sediment yields is one of several investigations comprising the overall basin assessment.

Sediment load is a primary factor determining the quality of water and its suitability for various uses. Sediment load also significantly influences the hydraulic stability of a stream channel as well as the aquatic habitat. The supply of sediment to the channel network, and thus the sediment load of the stream, is determined by many factors. Of these, land use is probably the most readily influenced by human activities.

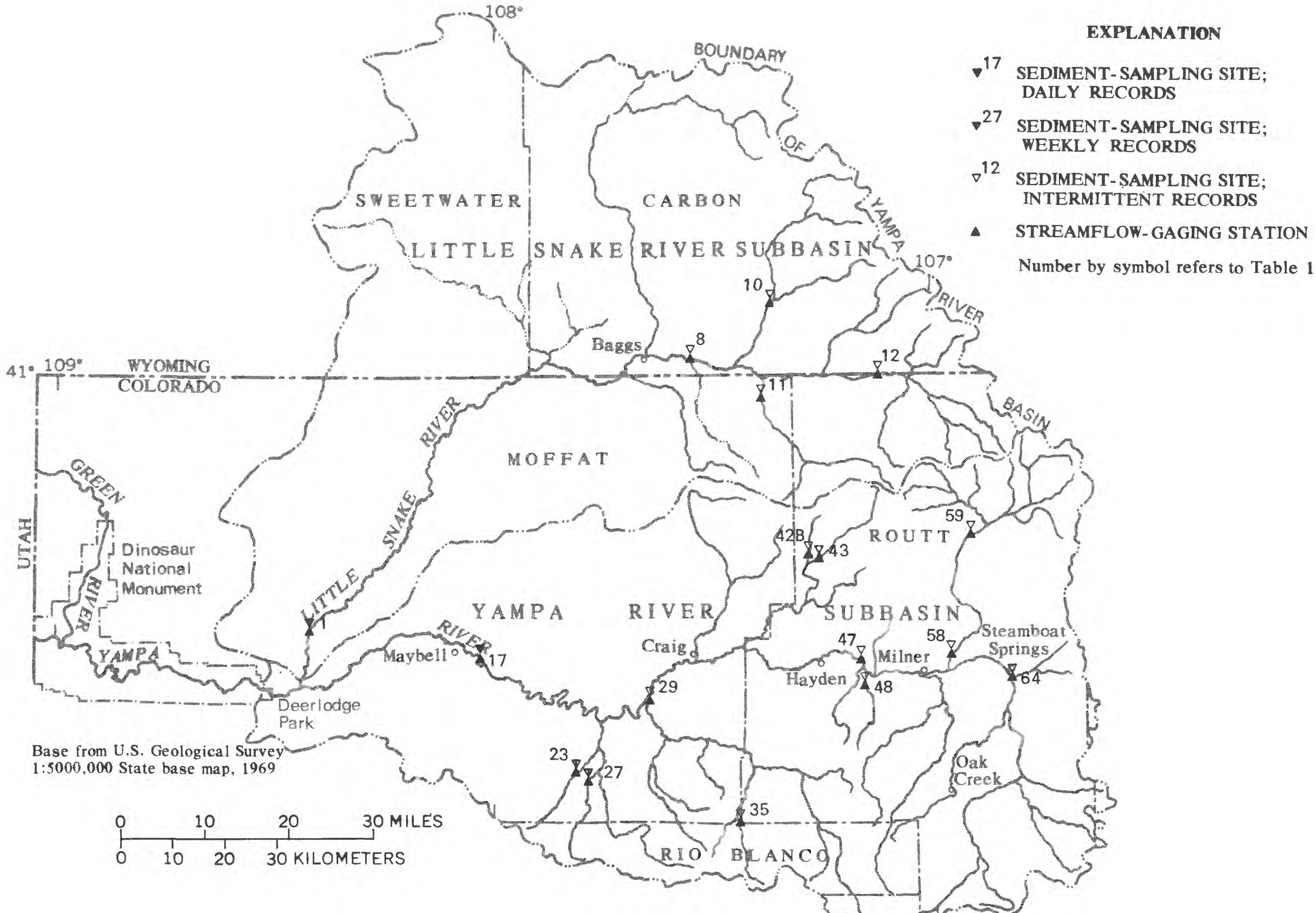
Extensive changes in land use are anticipated in the Yampa River basin during the next 15 years, due primarily to development of energy resources and associated economic development. The amount of coal mined annually in the Yampa River basin is expected to increase from slightly more than 6.0 million tons (5.4 million t) in 1976 to about 20 million tons (18 million t) by 1990. A substantial part of the coal will be mined from the land surface and will be converted within the basin to electric power or possibly to synthetic gases. Other energy resources within the basin include oil and gas, oil shale, uranium, and geothermal springs. Due primarily to the anticipated energy development, the basin population, which in 1975 was nearly 18,000 (Udis and Hess, 1976), is expected to increase 2 to 3 times during the next 15 years (Udis and others, 1977). The changes in land use associated with this development may increase the quantity of sediment supplied to stream channels in the Yampa River basin and thus adversely affect the quality of water in the basin.

Purpose and Scope

The purpose of this report is to describe the quantity and areal distribution of sediment loads carried by selected streams within the Yampa River basin, Colorado and Wyoming (fig. 1). Present sediment loads were computed from historical data, supplemented by data collected during 1975-77 as part of the present study. Potential increases in the sediment load carried by streams in the Yampa River basin due to surface mining were computed through analysis of the extent of land disturbance and its increased erodibility. Based upon these computations, probable impacts of surface mining upon sediment yield can be evaluated and the need for more intensive studies can be identified.

Acknowledgments

Timothy D. Steele provided some of the sediment data and numerous helpful suggestions, especially with regard to evaluating the impact of anticipated development. Dana Coffield was a cheerful field assistant and performed most of the computations.



Base from U.S. Geological Survey
1:5000,000 State base map, 1969

Figure 1.--Location of the Yampa River basin, sediment-sampling sites, and streamflow-gaging stations used in this study.

COMPUTATION OF ANNUAL SEDIMENT LOADS AT SELECTED STREAMFLOW-GAGING STATIONS

Available Data

The streamflow and sediment data available at 17 stream-gaging stations within the Yampa River basin are summarized in table 1. The records of daily mean streamflow for the gaging stations used in this study are for periods of different lengths and different times. In general, however, the streamflow records used were sufficient to approximate the long-term average magnitude and frequency of streamflows, assuming that there is no long-term trend in the annual streamflow time series. The gaging station on the Yampa River at Steamboat Springs (fig. 1) has the longest streamflow record in the basin. The annual time series of this record was tested using a technique developed by Conover (1971) and the results indicate there was no long-term trend in streamflow.

The sediment-load records summarized in table 1 include data for only the suspended part of the total-sediment load transported by streamflow at these stations. The sediment load of a river is commonly divided, for computation purposes, into two fractions--the suspended load and the bedload. The suspended load is composed of the relatively finer sediment particles which are transported within the streamflow. The bedload is composed of the relatively coarser sediment particles which move along the bed of the stream. The concentration of suspended sediment in the streamflow is measured by collecting a discharge-weighted sample of the streamflow. The suspended-sediment load for a given period may be computed by multiplying the mean suspended-sediment concentration by the mean discharge and then by 0.0027 times the number of days in the period. All sediment-load data included in the records listed in table 1 were computed in this manner. These data do not include the bedload fraction. Although the bedload-transport rate may be sampled separately, no bedload-transport measurements have been made in the Yampa River basin. Because the bedload fraction may be a substantial part of the total-sediment load in many rivers, it is desirable to obtain an estimate of the bedload fraction. As will be discussed later, the bedload-transport rate at each station was computed from a bedload-transport formula.

Daily suspended-sediment loads have been measured at only two gaging stations in the Yampa River basin for periods longer than a few months. These stations are the Yampa River near Maybell, Colo., from December 1950 through May 1958, and the Little Snake River near Lily, Colo., from May 1958 through September 1964. Annual sediment loads for these gaging stations may be calculated by summing the measured daily sediment loads. A reasonable estimate of the mean-annual sediment load may be calculated by averaging the measured annual sediment loads at each of these two sites. The period of record at both gaging stations, however, is short relative to the observed year-to-year streamflow variation.

The gaging stations on the Yampa River near Maybell and the Little Snake River near Lily are located near the confluence of these rivers. Therefore, the respective records are indicative of the sediment and water yields of the

Table 1.--*Summary of daily streamflow and sediment data for selected stream-gaging stations in the Yampa River basin, Colorado and Wyoming*

Site number on figure 1[1]	U.S. Geological Survey station number	Station name	Period of streamflow records (water years)	Sediment-load records: Period of record (month/year)	Sediment-load records: Frequency	Sediment-load records: Source of data[2]
1	09260000	Little Snake River near Lily, CO.	1922-77	5/58-9/64	Daily--	A
				10/75-9/76	Weekly-	B
8	09257000	Little Snake River near Dixon, WY.	1911-23, 1939-71	10/72-9/76	Intermittent	D
10	09256000	Savery Creek near Savery, WY.	1942-46, 1948-71	4/53-8/53	--do---	C
				10/75-7/77		B
11	09255000	Slater Fork near Slater, CO.	1932-77	4/52-8/53	--do---	C
				10/75-9/77		B
12	09253000	Little Snake River near Slater, CO.	1943-47, 1951-77	4/52-5/52	--do---	C
				10/75-9/77		B
17	09251000	Yampa River near Maybell, CO.	1917-77	12/50-5/58	Daily--	A
				10/75-9/76	--do---	B
23	09250600	Wilson Creek near Axial, CO.	1975-77	10/75-	Weekly-	B
27	09250400	Good Springs Creek near Axial, CO.	1975-77	10/75-	--do---	B
29	09249750 [3](09249500)	Williams Fork at mouth, near Hamilton, CO.	1905-6, 1910-27	12/75-9/77	Intermittent	B
35	09249200	South Fork of Williams Fork near Pagoda, CO.	1966-77	12/75-9/77	--do---	B
42B	09245500	North Fork of Elkhead Creek near Elkhead, CO.	1959-73	10/75-9/77	--do---	B

Table 1.--*Summary of daily streamflow and sediment data for selected stream-gaging stations in the Yampa River basin, Colorado and Wyoming*--Continued

Site number on figure 1[1]	U.S. Geological Survey station number	Station name	Period of streamflow records (water years)	Sediment-load records: Period of record (month/year)	Sediment-load records: Frequency	Sediment-load records: Source of data[2]
43	09245000	Elkhead Creek near Elkhead, CO.	1954-77	10/75-9/77	Intermittent	B
47	09244410 [4](09244400)	Yampa River below diversion, near Hayden, CO.	1966-77	10/75-9/77	--do---	B
48	09244300	Grassy Creek near Mount Harris, CO.	1959-66	10/75-9/77	--do---	B
58	09242500	Elk River near Trull, CO.	1905-6, 1910-27	10/75-9/77	--do---	B
59	09241000	Elk River at Clark, CO.	1911-22, 1931-77	10/75-9/77	--do---	B
64	09239500	Yampa River at Steamboat Springs, CO.	1905-6, 1910-77	7/58-8/58	--do---	C
				10/25-9/77		B

[1]Site-designation codes used by Steele, Bauer, Wentz, and Warner (1978).

[2]Sources: A, U.S. Geological Survey (1950-63); B, U.S. Geological Survey (1976-77); C, Iorns, Hembree, Phoenix, and Oakland (1964); and D, U.S. Geological Survey (1972-76).

[3]Streamflow records were collected at 09249500, and sediment concentrations were collected at 09249750.

[4]Published record 1966-71 water years for 09244400 and 1970 to the present for 09244410.

two subbasins (fig. 1). In addition to these two gaging stations with relatively long periods of measured daily sediment loads, daily sediment measurements for periods as long as several weeks, as well as intermittent instantaneous measurements, have been made at several other gaging stations throughout the Yampa River basin (fig. 1). The frequency and period of record of these measurements are noted in table 1. Several gaging stations have different periods of streamflow record. Suspended-sediment samples were collected intermittently at most of the active gaging stations during the 1976 and 1977 water years as part of the Yampa River Basin Assessment. In addition, suspended-sediment samples were collected intermittently at several gaging stations prior to 1960 by the U.S. Bureau of Reclamation (Iorns and others, 1965). Other suspended-sediment measurements were made periodically for the Yampa River near Maybell and Little Snake River near Lily as part of the National Stream Quality Assessment Network (NASQAN) program (Ficke and Hawkinson, 1975). The frequency of data collection at these stations was changed during the 1976 water year to a daily frequency for the Yampa River near Maybell and to a weekly frequency for the Little Snake River near Lily. Also, daily or monthly sediment measurements are made at several gaging stations in the Yampa River subbasin as part of ongoing cooperative programs (U.S. Geological Survey, 1976).

Method of Computation

Estimates of mean-annual sediment loads for the 17 selected gaging stations in the Yampa River basin (fig. 1) were computed using the flow-duration, sediment-transport-curve method described by Miller (1951). This method is useful when the gaging-station record of streamflows is sufficient to define the frequency of occurrence of various discharges, and when sediment data are limited. A sediment-transport curve relating the daily suspended-sediment load and daily water discharge was developed for each of the 17 stations based upon the available measurements. Similarly, a relation between the computed bedload-transport rates and discharges was developed as described subsequently. A total-sediment-transport curve was determined by summing the suspended-load and bedload relations. Then, the total-sediment-load relation was combined with the average-annual frequency of occurrence of various discharges recorded at each gaging station to obtain the mean-annual total-sediment load at that location.

Total-Sediment-Load versus Discharge Relations

An example of how the total-sediment-discharge versus water-discharge relations were constructed for each of the gaging stations is illustrated in figure 2. As noted previously, the total-sediment discharge was composed of two parts, the suspended load which was measured and the bedload which was computed. Initially, sediment-transport curves relating the measured suspended load and the computed bedload to the water discharge were developed separately. The suspended-sediment-discharge versus water-discharge relation was determined by plotting daily mean suspended loads against the daily mean discharges. A mean relation, shown by a dashed line in figure 2, was calculated by a least-squares linear-regression function of the log-transformed data.

The bedload-transport-rate versus water-discharge relations were computed by the Meyer-Peter and Mueller (1948) equation. The total channel bedload-transport rate (I_b), is given by:

$$I_b = \left(2.52 D_{90}^{\frac{1}{4}}\, \bar{u}^{\frac{3}{2}}\, S^{\frac{1}{4}} - 0.86 D_m\right)^{\frac{3}{2}} W,$$

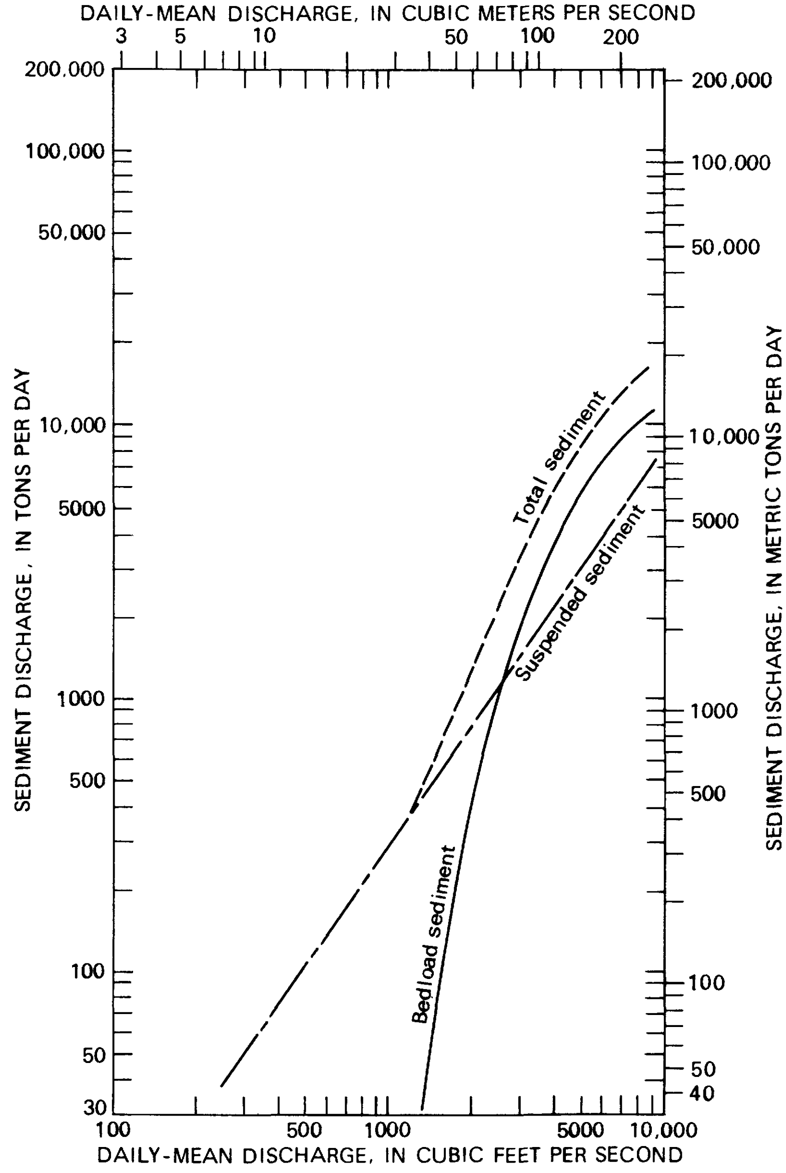


Figure 2.--Suspended-, bedload-, and total-sediment discharge transport curves for the Little Snake River near Dixon, Wyo.

where

W=channel width, in feet;

D_{90}=grain size of bed material at the 90th percentile fraction, in millimeters;

$\bar{u}$=mean velocity, in feet per second;

S=slope of the water surface; and

D_m=effective grain size, in millimeters.

The velocity, depth, and width of flow for a given discharge were selected from discharge measurements made at the gaging stations. The bed-material size parameters were computed from sieve analysis of a composite bed-material sample collected at each gaging station. The water-surface slope was measured over a reach of channel, at least 20 channel widths in length and including the gaging-station cross section. The mean bedload-transport-rate versus water-discharge relation was determined by visual fit of the approximately 10 computed points.

The total-sediment-discharge versus water-discharge relation, shown by a dashed line in figure 2, was determined by summing the suspended- and bedload-sediment relations. With the mean relation between daily total-sediment load and daily water discharge established, the average-annual sediment load at the gaging stations may be calculated from the average-annual frequency of daily mean water discharges (Miller, 1951).

Discharge-Duration Relations

The cumulative frequency of daily mean discharges observed at a gaging station may be represented by a flow-duration curve (fig. 3). The flow-duration curve shows the percentage of time a specific discharge was equaled or exceeded in the period of record used. When several years of record are used, the flow-duration curve describes the average or probable frequency of various ranges of water discharges during a year.

The gaging stations in the Yampa River basin have been operated at different times and durations since October 1904 (table 1). Therefore, the daily water-discharge records are not concurrent and cannot be compared directly. In order to obtain an estimate of the possible variations in the flow-duration curves due to variable times and periods of record, flow-duration curves for the Yampa River at Steamboat Springs were computed for different periods of record. A comparison of the flow-duration curves based on several subrecords with the flow-duration curves based on the entire record indicates variations of less than 5 percent. Because this value is less than the errors in the total-sediment-load versus discharge relation, no attempt was made to synthesize daily water discharges for a standard period of record at all gaging stations.

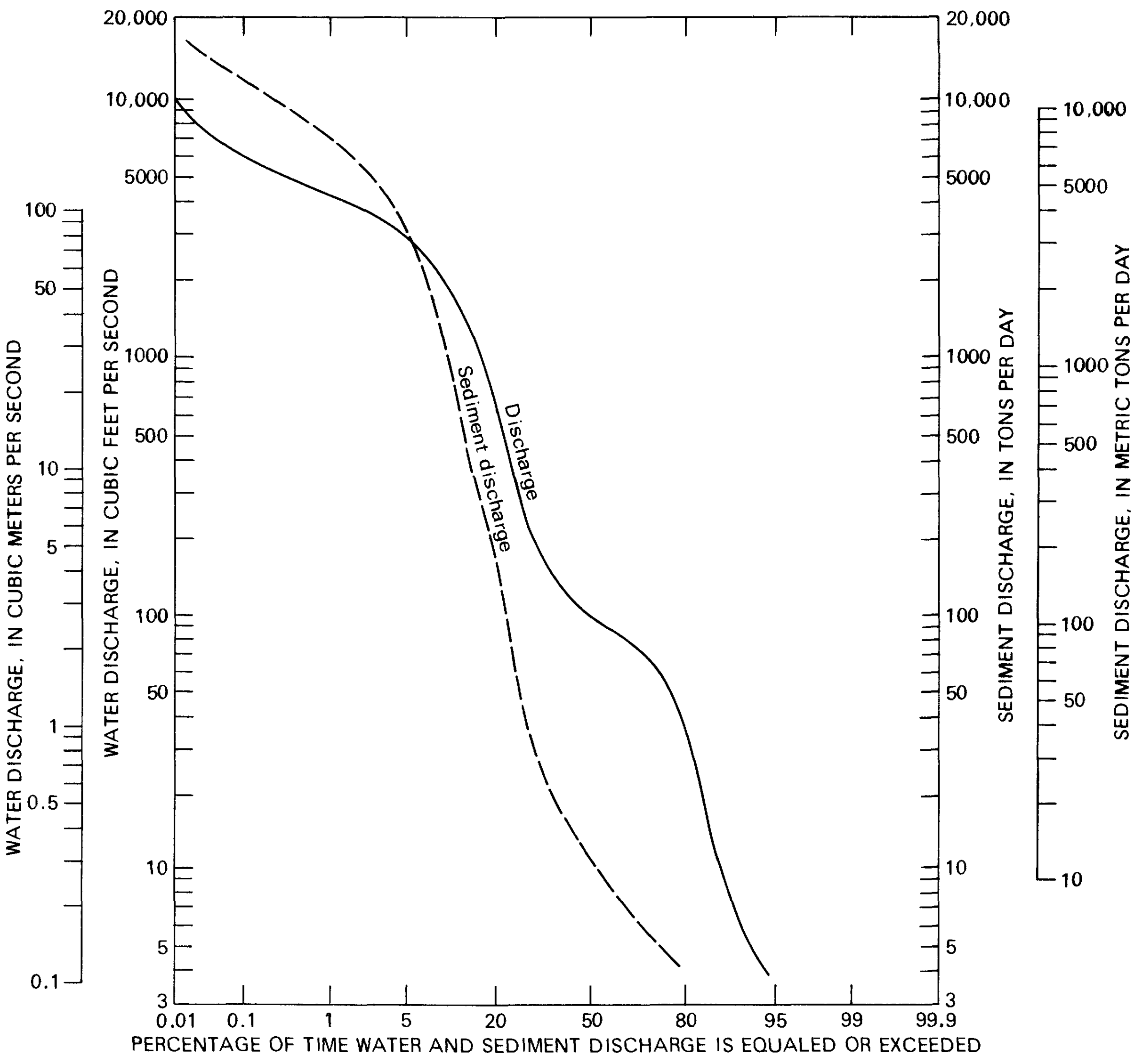


Figure 3.--Water- and sediment-discharge duration curves for the Little Snake River near Dixon, Wyo.

Mean-Annual Total-Sediment Loads

The mean-annual total-sediment load for each of the selected gaging stations in the Yampa River basin was computed by combining the daily total-sediment load versus daily mean-discharge relations with the respective flow-duration curves to give sediment-load-duration curves. The latter curves were integrated and the sums were multiplied by 365 days per year. The average-annual total-sediment loads and water discharges for the 17 gaging stations are summarized in table 2. Sediment loads and water discharges for an additional station, the Yampa River at Deerlodge Park (fig. 1), were computed by summing the sediment and water discharges for the Little Snake River near Lily and the Yampa River near Maybell, and adjusting for the intervening ungaged drainage area. The estimated mean-annual total-sediment load and water discharge of the Yampa River at Deerlodge Park are 2.0 million tons (1.8 million t) and 2,125 ft^3/s (60.2 m^3/s), respectively.

Accuracy of Computational Method

Annual sediment loads computed by the flow-duration, sediment-transport-curve method are less accurate than the values which would be obtained from continuous or daily measurements. Commonly, there is a considerable scatter of observations about the mean relation between sediment load and water discharge. Furthermore, there are occasionally seasonal shifts in the sediment-load, water-discharge relation. Consequently, it is unlikely that a single sediment-transport curve will accurately represent the actual sediment-load curves during an extended period of time.

A comparison by Miller (1951) indicated an error of only 4 percent during a 19-year period between the measured average annual sediment loads and the sediment loads computated by the flow-duration, sediment-transport-curve method. Larger errors of 10 to 20 percent were computed by Colby (1956) and Bennett and Sabol (1973). Measurements and computations by Walling (1977) indicate that the flow-duration, sediment-transport-curve method may underestimate the annual sediment load by as much as 30 percent in small drainage basins where sediment loads consist predominantly of silt and clay.

Mean-annual total-sediment loads computed by the flow-duration, sediment-transport-curve method compare very well with those computed from measured daily sediment loads for the Yampa River near Maybell and the Little Snake River near Lily. For the Yampa River near Maybell, the flow-duration, sediment-transport curve estimate was 11 percent greater than the 7-year average load based on measured daily sediment loads. The flow-duration, sediment-transport-curve estimate of the average annual sediment load of the Little Snake River near Lily was only 4 percent greater than the average annual loads based on nearly 6 years of measured daily sediment loads. These comparisons indicate a somewhat greater accuracy for the flow-duration, sediment-transport-curve method than previous studies. In general, however, the uncertainties in the computed annual sediment loads for streams in the Yampa River basin are probably larger; perhaps 10 to 20 percent, as found by Colby (1956) and Bennett and Sabol (1973).

Table 2.--*Summary of mean-annual streamflow and computed sediment load at selected stream-gaging stations in the Yampa River basin, Colorado and Wyoming*

Site number on figure 1[1]	U.S. Geological Survey station number	Station name	Drainage area (square miles)	Mean-annual discharge (cubic feet per second)	Mean-annual sediment load, in tons[2]		
					Suspended-sediment load	Bedload	Total-sediment load
1	09260000	Little Snake River near Lily, CO.	3,730	575	1,300,000	70,000	1,400,000
8	09257000	Little Snake River near Dixon, WY.	988	514	78,000	85,000	160,000
10	09256000	Savery Creek near Savery, WY	330	104	25,000	11,000	36,000
11	09255000	Slater Fork near Slater, CO-	161	74	12,000	10,000	22,000
12	09253000	Little Snake River near Slater, CO.	285	227	19,000	3,600	23,000
17	09251000	Yampa River near Maybell, CO	3,410	1,550	420,000	120,000	540,000
23	09250600	Wilson Creek near Axial, CO-	20	1.8	450	420	870
27	09250400	Good Springs Creek near Axial, CO.	35	2.0	540	12	550
29	09249750	Williams Fork at mouth, near Hamilton, CO.	463	217	160,000	49,000	210,000
35	09249200	South Fork of Williams Fork near Pagoda, CO.	47	43.8	22,000	700	23,000

Table 2.--*Summary of mean-annual streamflow and computed sediment load at selected stream-gaging stations in the Yampa River basin, Colorado and Wyoming*--Continued

Site number on figure 1[1]	U.S. Geological Survey station number	Station name	Drainage area (square miles)	Mean-annual discharge (cubic feet per second)	Mean-annual sediment load, in tons[2]		
					Suspended-sediment load	Bedload	Total-sediment load
42B	09245500	North Fork of Elkhead Creek near Elkhead, CO.	21	17	1,300	490	1,800
43	09245000	Elkhead Creek near Elkhead, CO.	64	53	11,000	5,900	17,000
47	09244410	Yampa River below diversion, near Hayden, CO.	1,430	1,100	70,000	38,000	110,000
48	09244300	Grassy Creek near Mount Harris, CO.	26	1.4	2,380	320	2,700
58	09242500	Elk River near Trull, CO---	415	593	7,600	18,000	26,000
59	09241000	Elk River at Clark, CO-----	206	336	5,200	11,000	16,000
64	09239500	Yampa River at Steamboat Springs, CO.	604	468	11,000	3,700	15,000

[1]Site designations used by Steele, Bauer, Wentz, and Warner (1978).
[2]Sediment loads have been rounded to two significant figures.

SEDIMENT YIELDS IN THE YAMPA RIVER BASIN

Source Areas of Sediment and Water

Frequently, the sediment load of the stream is not supplied equally from all areas of the drainage basin. Some areas of a drainage basin contribute a relatively large part of the annual sediment load; whereas, other areas of the drainage basin contribute relatively minor quantities of sediment. Similarly, runoff seldom is supplied evenly from throughout the drainage basin. Thus, sediment- and runoff-source areas often can be identified for a drainage basin provided the sediment loads and runoff are measured or estimated at several points within the drainage basin. The term "source area" is used in a relative sense to describe those parts of the drainage basin which supply a large percentage of the sediment load or runoff compared to their areal extent.

The mean-annual sediment load and runoff at the gaging stations in the Yampa River basin are shown on figure 4 as a percentage of the total sediment and runoff of the Yampa River at Deerlodge Park (fig. 1). A comparison of the values of the individual stations shows that sediment and runoff are not contributed to the streams equally throughout the basin. Furthermore, the principal source areas of sediment and runoff are different. One of the most striking differences exists between values at sites on main-stem rivers draining the two major subbasins--the Little Snake River near Lily (site 1) and the Yampa River near Maybell (site 17). Although the drainage areas contributing to these two gaging stations are about equal, 3,730 mi^2 (9,660 km^2) for the Little Snake River subbasin at site 1 versus 3,410 mi^2 (8,830 km^2) for the Yampa River subbasin at site 17, the respective sediment loads and runoff are markedly different. The Little Snake River subbasin supplies 27 percent of the annual runoff to the Yampa River at Deerlodge Park but nearly 69 percent of the sediment load. Conversely, the Yampa River subbasin contributes 73 percent of the runoff and only 27 percent of the estimated total-sediment load for the entire Yampa River basin (fig. 4).

Comparisons for other areas are equally striking. Most of the large sediment load of the Little Snake River subbasin enters the main-stem Little Snake River between Dixon (site 8) and Lily (site 1) (fig. 4). About 60 percent of the entire sediment load of the Yampa River at Deerlodge Park is contributed from the drainage area between the Little Snake River near Dixon and the Little Snake River near Lily gaging stations. Thus, the lower part of the Little Snake River subbasin is the major sediment source area within the Yampa River basin. This area is less than 35 percent of the entire basin area and supplies less than 3 percent of the runoff.

In contrast, the eastern part of the basin upstream from site 8 on the Little Snake River and site 47 on the Yampa River supplied approximately 76 percent of the total basinwide runoff and only 14 percent of the sediment load.

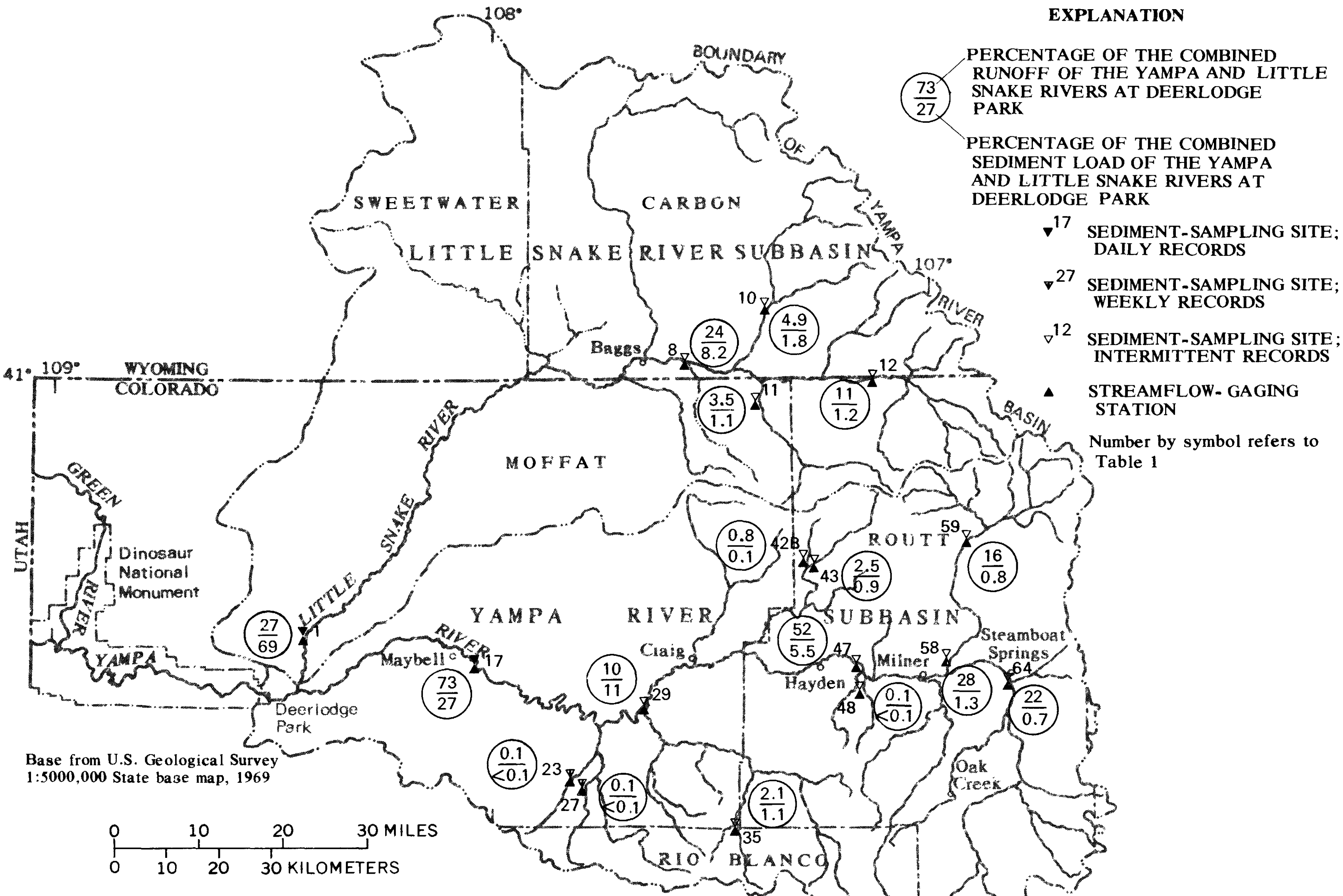


Figure 4.-- Mean-annual runoff and total-sediment load at selected gaging stations expressed as percentages of the combined runoff and combined total-sediment loads of the Yampa and Little Snake Rivers, estimated for the Yampa River at Deerlodge Park, Colo.

Sediment Yields

A sediment-yield map of the Yampa River basin (fig. 5) was prepared from the data summarized in table 2. The sediment-yield areas were drawn from the average unit-area sediment yields computed for each gaging station. Local areal irregularities then were smoothed, based on mean-annual precipitation, for reasons which will be discussed in detail later. Two areas of relatively large sediment yield, 300-500 (tons/mi^2)/yr or 105-175 (t/km^2)/yr, were identified (fig. 5). The largest area lies in the northwestern one-third of the basin and is drained by the Little Snake River. This area, as previously noted, contributes about 60 percent of the total-sediment load of the Yampa River at Deerlodge Park. A second smaller area lies near the southern boundary of the basin and is drained primarily by Milk Creek and the Williams Fork River (fig. 5), both tributaries to the Yampa River. This area contributes approximately 20 percent of the annual total-sediment load of the Yampa River at Deerlodge Park.

About 48 percent of the Yampa River basin has sediment yields from 100 to 300 (tons/mi^2)/yr or 35 to 105 (t/km^2)/yr (fig. 5). The smallest sediment yields, less than 100 (tons/mi^2)/yr or 35 (t/km^2)/yr, occur along the eastern fringe of the drainage basin. This area is about 1,300 mi^2 (3,370 km^2) or 17 percent of the basin.

Factors Affecting Sediment Yields

The quantity of sediment eroded from a watershed is influenced by several factors. Bedrock geology, soil type, vegetation, climate (particularly precipitation and air temperature), topography, and land use are the most important factors determining sediment yield. Many of these factors are interrelated. Soil type is primarily a function of bedrock and climate; whereas, vegetation is determined largely by soil type and climate.

As described above, sediment yields vary considerably throughout the Yampa River basin. A majority of the total-sediment load of the Yampa River at Deerlodge Park is contributed by only 35 percent of the basin. Conversely, more than 30 percent of the basin, primarily in the eastern upland areas, contributes less than 14 percent of the total-sediment load. It is useful to consider which of the above-named factors are primarily responsible for the basinwide variability in distribution of sediment yields.

Geology

A generalized bedrock geologic map of the Yampa River basin (fig. 6, adapted from Steele and others, 1978) combines formations of similar lithology and age so that the units shown indicate their relative erodibility. For the most part, the bedrock of the Yampa River basin is composed of interbedded sandstones, mudstones, and shales of Tertiary and Cretaceous age. The induration of the fine-grained sediments generally increases with age, so

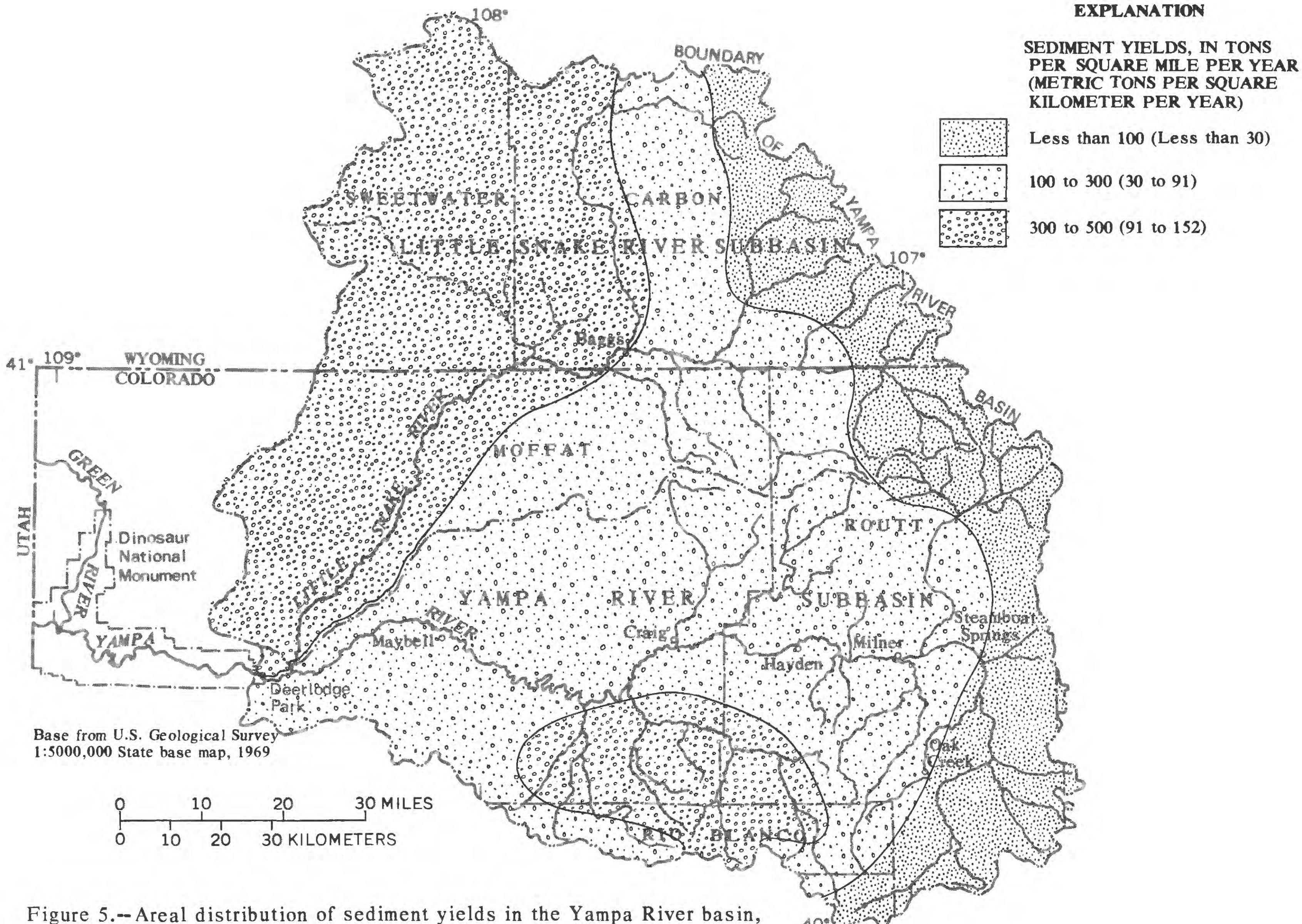


Figure 5.--Areal distribution of sediment yields in the Yampa River basin, extrapolated from station records.

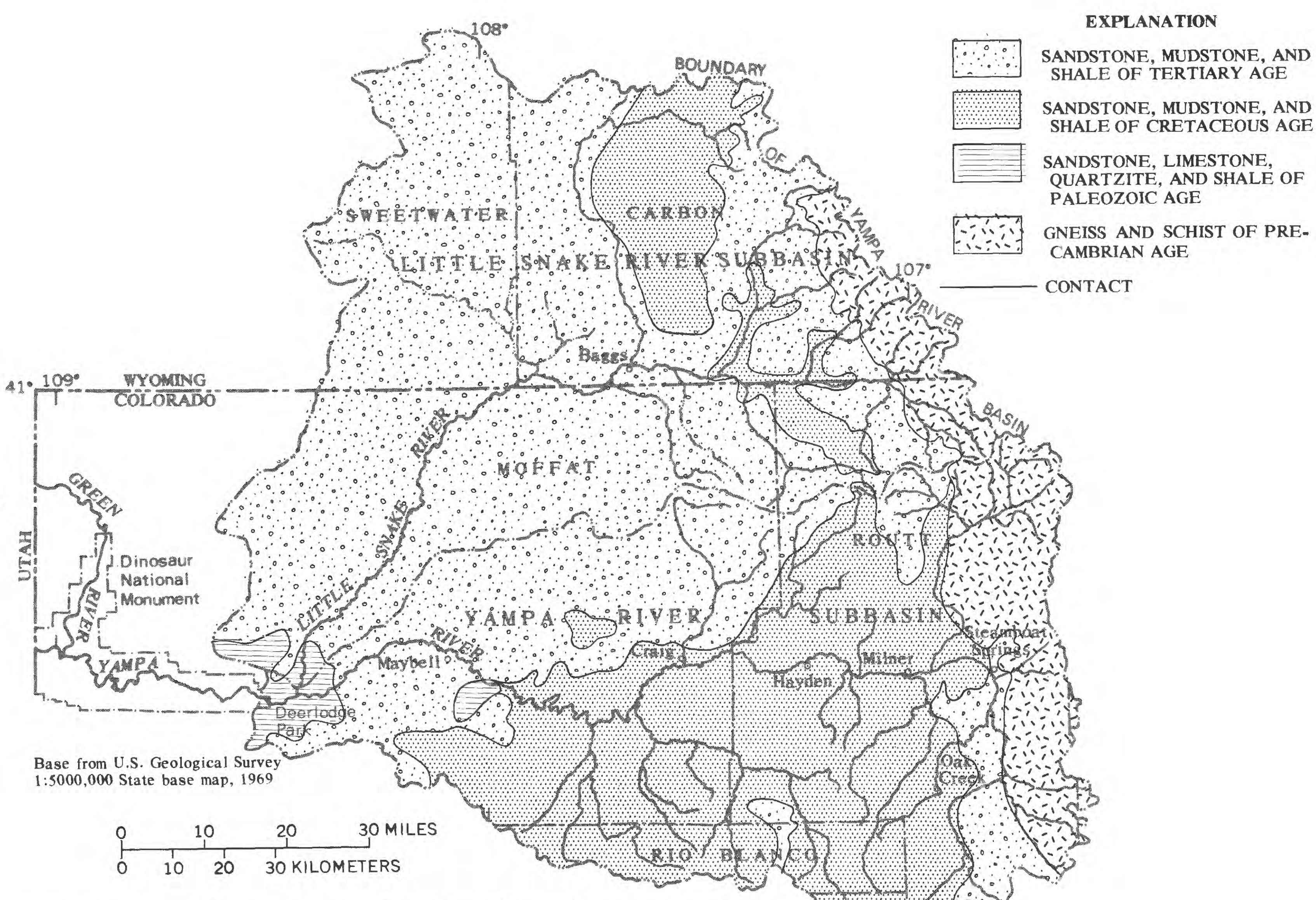


Figure 6.--Generalized bedrock geology of the Yampa River basin (adapted from Steele and others, 1978). Formations of similar lithology and age have been grouped to form units with similar erodibility.

that shales are more common in the Cretaceous units and mudstones are more common in the Tertiary units. The Tertiary and Cretaceous sedimentary rocks lie in a broad synclinal basin, the axis of which strikes northwest.

In the extreme western part of the basin, Paleozoic sedimentary rocks, primarily limestone, sandstone, and siltstone, are exposed on the land surface. These rocks are well indurated and are relatively resistant to erosion compared to the younger sediments. Precambrian gneiss and schist outcrop along the eastern fringe of the Yampa River basin (fig. 6). These rocks also are relatively resistant to erosion compared to the Tertiary and Cretaceous sedimentary rocks.

The interbedded sandstones, mudstones, and shales shown in figure 6 and described above are relatively erodible. They crop out widely throughout the basin, in areas of both relatively large and small sediment yield. Therefore, the observed distribution of sediment yields cannot be entirely due to similarities or differences in the bedrock geology.

Mean-Annual Precipitation

In many areas, sediment yields are closely correlated with mean-annual precipitation. Although mean-annual precipitation alone is but one of the important factors controlling sediment yields, many of the other factors, such as vegetation, soil-type and climate, are related to precipitation. Langbein and Schumm (1958) developed a general relation between sediment yield and mean-annual precipitation (fig. 7). The most significant feature of this relation for the present discussion is that maximum sediment yields may be expected from watersheds with a mean-annual precipitation of about 12 inches (305 mm) per year. The peak in the sediment-yield curve at an intermediate level of precipitation is partly explained by the generalized vegetation profile shown at the top of the graph (fig. 7). With increases in mean-annual precipitation, the vegetative cover becomes progressively thicker and more diverse. As a result, the potential erodibility decreases because the soil is protected from intense rainfall, the soil particles are bound together more firmly, and the soil profile is generally more permeable. Thus, the decrease in sediment yield for a watershed which receives greater than 12 inches (305 mm) of mean-annual precipitation is primarily due to increased vegetative cover and development of a soil profile.

If mean-annual precipitation is less than 12 inches (305 mm), sediment yields are limited by the available runoff. Thus, although potential erodibility probably increases continually as precipitation decreases, the runoff is insufficient to transport the available supply of sediment.

The areal distribution of mean-annual precipitation in the Yampa River basin is shown on figure 8. The 12-inch (305-mm) per year line is of particular interest, because the greatest sediment yields might be expected from areas near this line. About 40 percent of the Yampa River basin receives

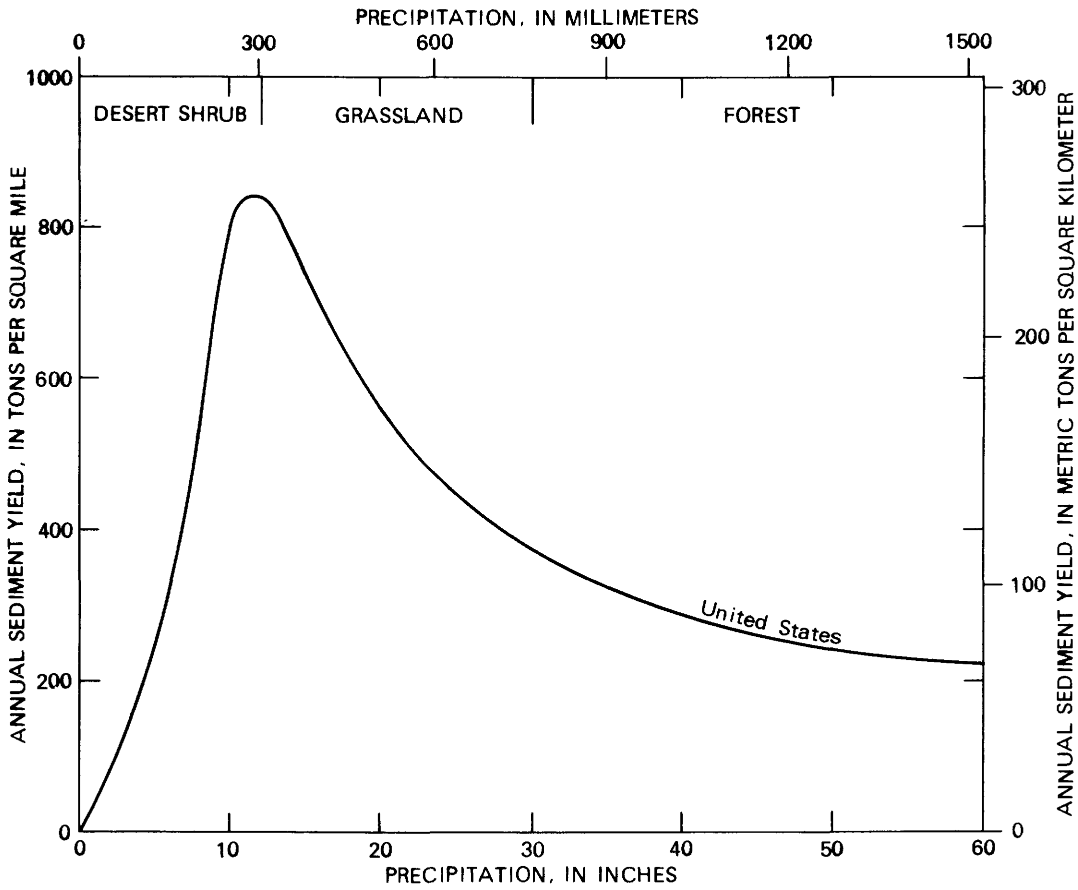
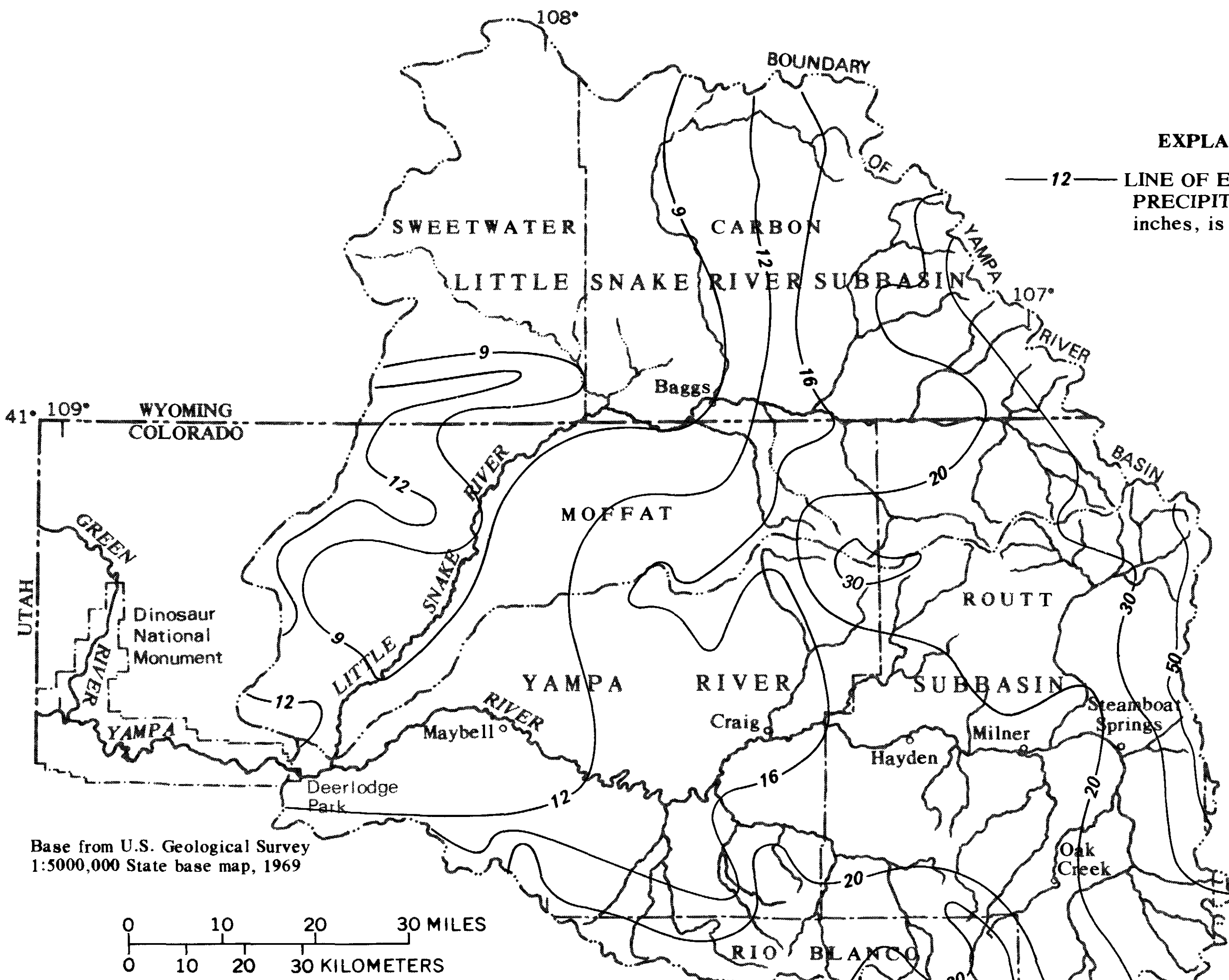


Figure 7.--General relation between sediment yield and mean-annual precipitation for the United States (from Langbein and Schumm, 1958).



EXPLANATION

——12—— LINE OF EQUAL MEAN-ANNUAL PRECIPITATION– Interval, in inches, is variable

Figure 8.--Areal distribution of mean-annual precipitation in the Yampa River basin (adapted from Steele and others, 1978).

from 10 to 14 inches (250 to 360 mm) of precipitation annually. A comparison of figures 5 and 8 shows that the areas of large sediment yield are also those areas which receive from 10 to 14 inches (250 to 360 mm) of precipitation annually. Sediment yields decrease eastward as precipitation increases, and the smallest sediment yields are from those areas that receive the most precipitation.

Comparison with Estimates by Other Investigations

A sediment-yield map of Colorado was prepared by the Colorado Land Use Commission (1973) using the Pacific Southwest Inter-Agency Committee (1968) or PSIAC method. This method develops a numerical rating of the potential erodibility of a watershed in nine categories, as shown in table 3. The erosion rate is estimated by comparing the numerical score with the measured erosion rate of drainage basins with a similar score.

Sediment yields were computed at the 17 gaging stations in the Yampa River basin from the Colorado State map. The percentage of a subbasin in each level of erosion was determined and then the average erosion rate for the drainage. In order to obtain an accurate estimate at each station, the average erosion rates must be adjusted to the drainage area. Brune (1948) showed that, other factors being constant, sediment yields (Y_s) vary inversely with drainage area (A) to the 0.15 power:

$$\frac{Y_{s_1}}{Y_{s_2}} \propto \left(\frac{A_2}{A_1}\right)^{0.15}$$

The erosion rate determined by the PSIAC method applies to a drainage area of 1 mi^2 (2.59 km^2). Hence, the average erosion rate (Y_1) for a given drainage area must be multiplied by

$$\left(\frac{1}{A}\right)^{0.15}$$

to give the estimated sediment yield (Y_A) at the gaging station.

A comparison of the sediment yields computed in the investigation (abscissa) with the sediment yields determined by the PSIAC method (ordinate) is shown in figure 9. There is considerable scatter around the line of agreement, and no consistent relation between the two methods is apparent. Thus, although sediment yields estimated by the PSIAC method may agree with the average of several measured sediment yields, the PSIAC method probably will not provide a good estimate of the actual sediment yield for a specific location.

The measured sediment yields in the Yampa River basin also may be compared with the Langbein-Schumm (1958) relation shown on figure 6. The mean-annual precipitation for each of the 17 subbasins was determined from

Table 3.--*Factors and rating ranges used in the Pacific Southwest Inter-Agency Committee method for estimating sediment yields using terrain characteristics*

[From Shown, 1970]

Factor	Rating range	Main characteristics considered
Surface geology------	0-10	Rock type. Weathering. Hardness. Fracturing.
Soils----------------	0-10	Texture. Salinity. Aggregation. Caliche. Shrink-swell. Organic Matter. Rockiness.
Climate--------------	0-10	Storm frequency, intensity, and duration. Snow. Freeze-thaw.
Runoff---------------	0-10	Volume per unit area. Peak flow per unit area.
Topography-----------	0-20	Steepness of upland slopes. Relief. Fan and flood-plain development.
Ground cover---------	-10-10	Vegetation. Litter. Rocks. Understory development beneath trees.
Land use-------------	-10-10	Percentage cultivated. Grazing intensity. Logging. Roads.
Upland erosion-------	0-25	Rills and gullies. Landslides. Wind deposits in channels.
Channel erosion and sediment transport.	0-25	Bank and bed erosion. Flow depths. Active headcuts. Channel vegetation.

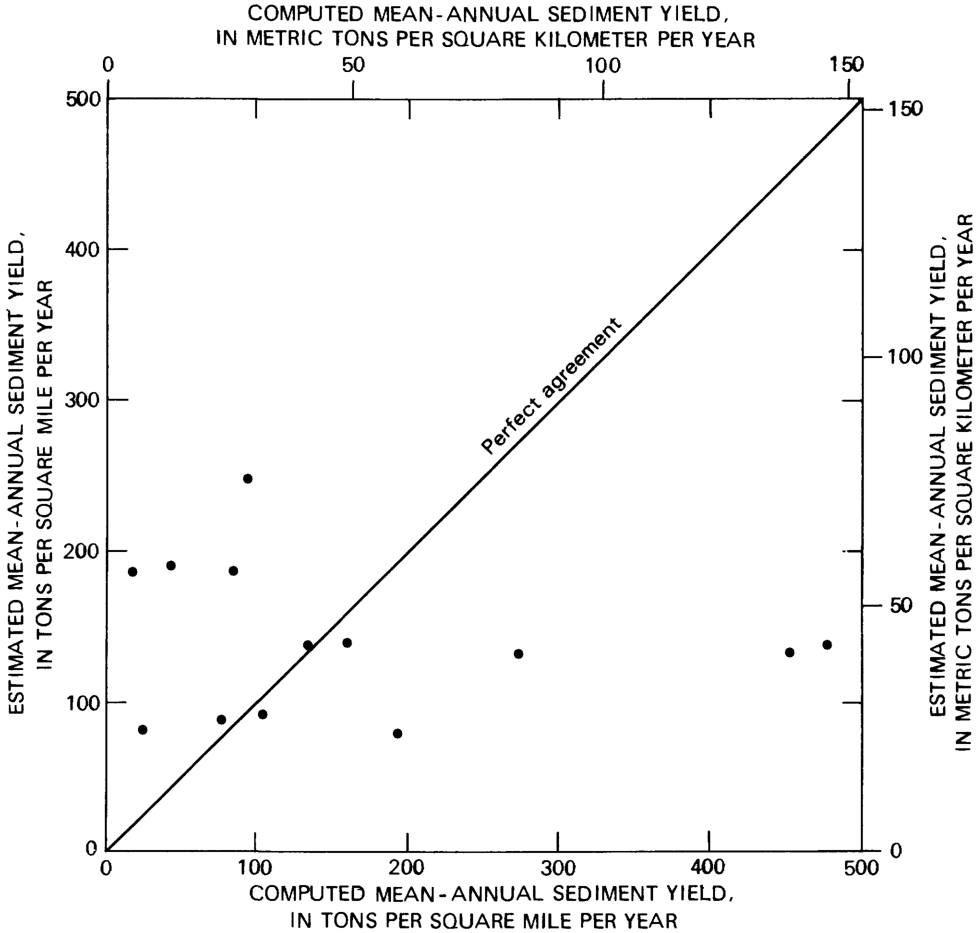


Figure 9.--Comparison of computed sediment yields in the Yampa River basin with estimated sediment yields using the Pacific Southwest Inter-Agency Committee method.

figure 8, and the respective values were plotted against the corresponding computed sediment yields. For this comparison, shown in figure 10, all sediment yields were adjusted to 1,500 mi^2 (3,900 km^2), in order to be compatible with the Langbein-Schumm (1958) relation.

The sediment yields determined at 13 of the 17 gaging stations are considerably less than the estimates that would have been made using the Langbein-Schumm (1958) relation, as shown in figure 10. This discrepancy may be explained, in part, by recent regional trends towards channel aggradation. Studies by Leopold, Emmett, and Myrick (1966) and Emmett (1974) have shown that small perennial and ephemeral stream channels throughout the Rocky Mountain region have been aggrading since about 1950; that is, sediment is being stored in the channel network. L. M. Brush (oral commun., 1977) noted extensive and rapid aggradation of some stream channels tributary to the Little Snake River during the late 1950's and early 1960's. In contrast, channel degradation was widespread throughout the region from 1880 to 1950 (Bailey, 1935; Bryan, 1941; Hack, 1942; Thornwaite and others, 1942; Leopold and Miller, 1954; Miller and Wendorf, 1958). The factors that have caused this regional change are not well understood. Unfortunately, no sediment records at gaging stations in the Yampa River basin cover the pre- and post-1950 period sufficiently well to confirm that sediment loads have actually decreased. Only four daily sediment stations were operated in the Colorado River basin prior to 1948, and all of these have been affected by the construction of large reservoirs in the past 30 years.

The data used by Langbein and Schumm (1958) in their nationwide study were collected prior to 1957 and therefore represent primarily a period prior to observed channel aggradation. Conversely, most of the data used in this investigation for the Yampa River basin have been collected since 1975, and no data were collected prior to 1950. Thus, the data for the Yampa River basin represent the period of observed channel aggradation. Therefore, it is probable that generally smaller sediment yields have occurred for a given amount of mean-annual precipitation, as indicated in figure 10. This decrease in sediment yield probably is due to the storage of sediment in the channels of small streams throughout the Yampa River basin.

ESTIMATED INCREASE IN SEDIMENT YIELDS DUE TO SURFACE MINING IN THE YAMPA RIVER BASIN

Large increases in the volume of coal mined from the Yampa River basin are anticipated during the next 15 years. Most of the additional production during the next 15 years will be by surface mining (U.S. Department of the Interior, 1976; Udis and others, 1977). As a result, there will be an increase in land disturbance and probably an increase in the quantity of sediment supplied to the stream channels draining the surface-mined areas. The Surface Mining Control and Reclamation Act of 1977 (Public Law 95-87) requires that surface-mined areas must be reclaimed and revegetated according to specified standards. During and immediately following mining, however, the hillslopes will be unvegetated, will have no soil, and,in many instances,

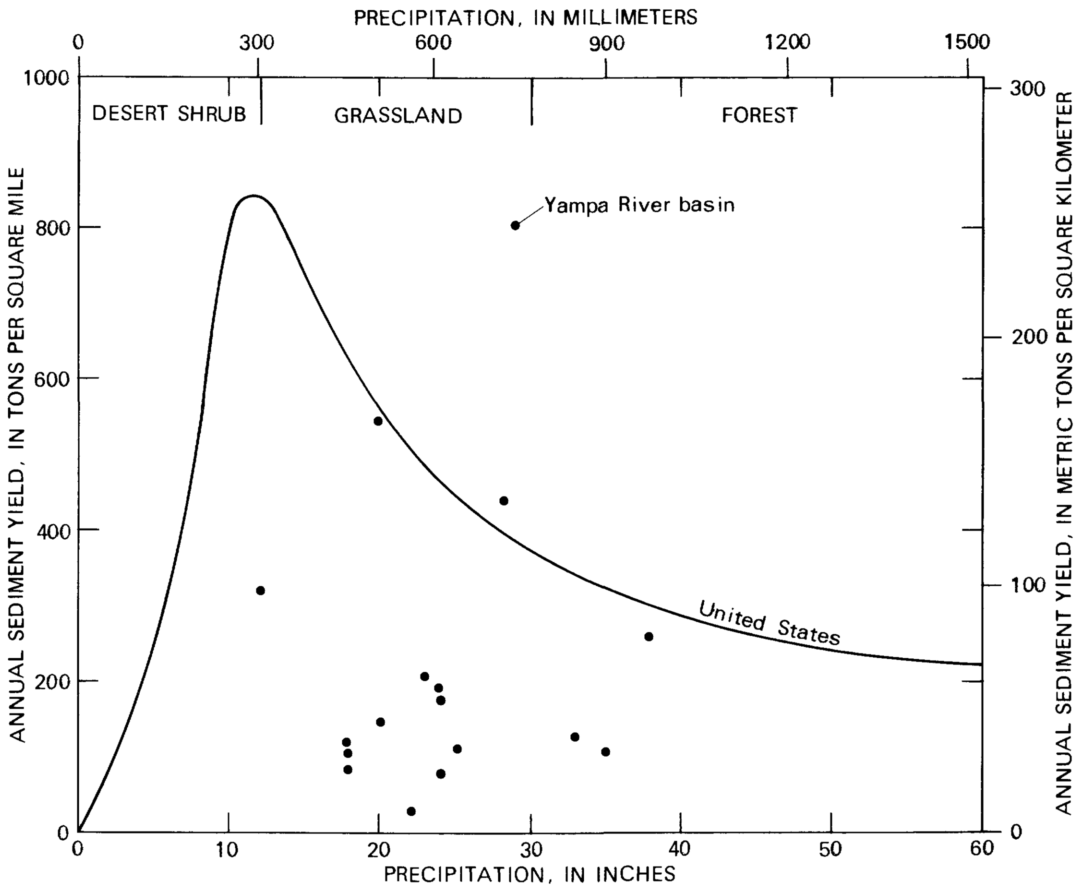


Figure 10.--Comparison of average sediment yields versus mean-annual precipitation for 17 gaging stations in the Yampa River basin with the general relation between sediment yield and mean-annual precipitation for the United States (from Langbein and Schumm, 1958).

will be steeper. These hillslopes probably will have greater runoff and erosion rates than the original undisturbed hillslopes. As reclamation proceeds and vegetation becomes reestablished, the erosion rate should gradually decrease to amounts comparable to adjacent undisturbed hillslopes.

An estimate of the change in sediment yield due to surface mining may be computed by the PSIAC method. As described previously, this method rates the character of a watershed in nine categories (table 3). An estimated sediment yield is determined by comparing the numerical score of the watershed being evaluated with the numerical score of watersheds with measured sediment yields. The PSIAC method is appropriate for estimating the increased sediment yield due the surface mining, because some of the categories listed in table 3, such as soil and vegetation cover, will change. Other categories, such as surface geology and climate, will not change.

Approximately 6.0 million tons (5.4 million t) of coal were mined in the Yampa River basin during 1976. The amount of coal mined has increased significantly since 1962, and there is some uncertainty as to how rapidly coal mining and utilization will expand in the basin in the near future. Three alternative levels of coal production through 1990 have been assumed (Udis and others, 1977; Steele and others, 1978). The three estimates assume that, in 1990, 80 percent of the coal production will come from surface mines and 20 percent from underground mines. It is projected that surface-mined coal will increase to 8.0 million tons (7.3 million t) per year as a slow-growth estimate, 16 million tons (14.5 million t) per year as a moderate-growth estimate, and 24 million tons (21.8 million t) per year as a rapid-growth estimate. By using a coal-yield ratio of 20,000 tons per acre (44,840 t/ha) of land mined, these projected levels of coal production can be expressed in terms of land area disturbed per year. It is further assumed that the disturbed land will be partly reclaimed within 5 years and completely reclaimed in 10 years. On the basis of these projections and assumptions, the area of land affected each year by mining as well as partly reclaimed can be calculated for each of the three levels of production for 1990. For purposes of this analysis, it will be assumed that all increased surface mining will occur in the Yampa River subbasin (U.S. Department of the Interior, 1976).

Estimates of sediment yield from recently mined and partly reclaimed land were computed using the PSIAC method. First, a numerical rating was computed for the unmined area, and the calculated sediment yield compared with the measured sediment yield. The numerical rating then was revised so that the calculated sediment yield agreed with the measured sediment yield.

Not all of the factors rated by the PSIAC method will change due to surface mining. Bedrock geology and climate, of course, will remain unchanged by surface mining. Other factors, such as runoff and topography, will most likely change slightly; whereas, soil type, ground cover, and land use will be radically changed. The numerical rating of these factors must be adjusted accordingly. The PSIAC method indicates annual sediment yields of 4,000 tons/mi^2 (1,400 t/km^2) from unreclaimed surface-mined land and 2,000 tons/mi^2 (700 t/km^2) for partly reclaimed land.

The relative significance of these estimates is shown in a comparison with the existing sediment yields (fig. 5). Presently (1978), the sediment yield from the Yampa River subbasin upstream from Steamboat Springs is less than 100 $(tons/mi^2)/yr$ or 35 $(t/km^2)/yr$. Therefore, an almost fortyfold increase in sediment yield is indicated for unreclaimed surface-mined areas. This relatively large increase is due to the fact that the soil profile and ground cover in this part of the basin will be changed appreciably. In the western part of the basin, the soil profile and ground cover are less developed; consequently, surface mining will not affect the erodibility as much. The western area has relatively large sediment yields even though it is presently largely undisturbed. Thus, surface mining will not increase sediment yields as much on a relative basis. Depending on the area, sediment yields probably will increase by fivefold to twentyfold due to surface mining.

Based upon the surface-mining projections and impact estimates described above, table 4 was prepared to summarize the estimated sediment yields from surface-mined areas through 1990. As noted previously, not all of the sediment eroded from hillslopes and small tributaries is supplied directly to the main-stem stream. Because most of the surface mines will be located on secondary tributaries, the estimated sediment yields were adjusted to reflect a drainage area of 40 mi^2 (104 km^2). This area was chosen in order to approximate the effect increased sediment yield from surface mines would have on the main-stem Yampa River. Between 10,000 and 30,000 tons (9,000 and 27,000 t) of additional sediment are estimated to be supplied to the main-stem Yampa River annually due to surface mining within the basin for projected conditions in 1990 (table 4).

The impact of this additional sediment load in the Yampa River and its tributaries depends primarily on the location of the surface mining within the basin. Sediment yields in the eastern part of the basin generally are less than 100 $(tons/mi^2)/yr$ or 35 $(t/km^2)/yr$. Surface mining in this part of the basin may increase substantially the quantity of sediment supplied to the stream channels. For example, if all new surface mining in the basin were in areas upstream from the gaging station on the Yampa River below diversion near Hayden (site 47, fig. 1), the estimated increase in sediment load measured at this location would be 10 to 30 percent. This increase would be the probable result of mining only about 1 to 3 percent of the contributing drainage area.

It is doubtful, however, that all additional mining will be located upstream from the gaging station near Hayden (U.S. Department of the Interior, 1976). A more realistic estimate is that only about 50 percent of the new surface mining will be upstream of Hayden. If so, the likely increase in the sediment load carried by the Yampa River near Hayden due to surface mining through 1990 is estimated to be 5 to 15 percent, depending upon the volume of coal mined.

Farther west in the basin, the relative impact of increased sediment yields due to the surface mining will be less for two reasons. Existing

Table 4.--*Potential sediment yields from surface-mined areas in the Yampa River basin for three estimated levels of coal production by 1990*

	Slow-growth projection[1]		Moderate-growth projection[1]		Rapid-growth projection[1]	
	Square miles[2]	Tons per year[3]	Square miles[2]	Tons per year[3]	Square miles[2]	Tons per year[3]
1975-80:						
Area mined	2.0		2.9		3.4	
Area partly reclaimed	0		0		0	
Sediment yield from surface-mined and partly reclaimed areas		4,500		6,700		7,800
1980-85:						
Area mined	2.6		4.9		7.3	
Area partly reclaimed	2.0		2.9		3.4	
Sediment yield from surface-mined and partly reclaimed areas		8,100		15,000		21,000
1985-90:						
Area mined	3.1		6.0		9.4	
Area partly reclaimed	2.6		4.9		7.3	
Sediment yield from surface-mined and partly reclaimed areas		10,000		19,000		30,000

[1]Projected coal production from Steele, Bauer, Wentz, and Warner (1978, table 4).
[2]Assuming 50 acres of land are mined to produce 1 million tons of coal.
[3]Sediment yields have been adjusted to reflect a basin of 40 square miles.

sediment yields are already relatively large due to a lack of soil development and sparse ground cover. Thus, because surface mining will not greatly alter these factors, the relative increase in sediment yield will be small. Furthermore, areas of surface mining in the western part of the basin actually being disturbed are expected to be relatively small. Thus, the additional sediment load carried by the Yampa River at the Maybell gaging station due to surface mining will be only an estimated 2 to 7 percent of the present mean-annual sediment load passing that site, depending upon the volume of coal production. Thus, even at the greatest projected volume of coal production in the basin by 1990, the additional quantity of sediment contributed to the streams will be small relative to the total quantity of sediment being transported out of the Yampa River subbasin or the basin in its entirety.

SUMMARY

The mean-annual sediment loads at 17 gaging stations in the Yampa River basin of Colorado and Wyoming were computed by the flow-duration, sediment-transport-curve method (Miller, 1951). Sediment-transport curves for each gaging station were constructed by combining separate curves for suspended- and bedload-sediment discharges. The suspended-sediment curves were determined by fitting a mean relation between measured suspended-sediment discharge and water discharge. The bedload-transport curves were derived from bedload-transport rates computed for various discharges by the Meyer-Peter and Mueller (1948) relation. The annual sediment loads were computed by combining the total sediment-transport curve with the observed cumulative frequency of water discharges and summing the products.

Average sediment yields for the contributing drainage areas upstream from the 17 gaging stations show that sediment is not contributed equally throughout the basin. The most significant sediment-source area lies in the downstream part of the Little Snake River subbasin. This area supplies about 60 percent of the entire sediment load passing in the Yampa River at Deerlodge Park, although it is less than 35 percent of the total basin drainage area, and contributes less than 3 percent of the total runoff. In contrast, the eastern part of the basin contributes only 14 percent of the sediment load and 76 percent of the annual runoff.

The distribution of sediment yields in the Yampa River basin closely reflects the variations in annual precipitation. The largest sediment yields are found in those parts of the basin which receive from 10 to 14 inches (250 to 360 mm) of precipitation annually. This observation is in agreement with the conclusion of Langbein and Schumm (1958) that the greatest sediment yields in the United States occur from drainage areas having about 12 inches (305 mm) of annual precipitation. As the mean-annual precipitation increases above 12 inches, the sediment yield decreases. Thus, as precipitation increases from west to east across the Yampa River basin, sediment yields decrease.

Although several other factors besides precipitation commonly influence sediment yield, these either are associated with precipitation or are broadly uniform throughout the Yampa River basin. The bedrock geology of the Yampa River basin is principally interbedded sandstone, mudstone, and shales. Likewise, hillslope relief is generally similar throughout the basin so that neither of these factors can be primarily responsible for the observed variations in sediment yields. Conversely, soil type and ground cover vary in the basin, but these factors are closely related to the distribution of precipitation. Increasing ground cover and soil development as precipitation increases are primarily responsible for these decreases in sediment yield. Thus, although the potential erosion by rainfall increases eastward in the basin, increased soil development and ground cover more than compensate, so that sediment yield decreases with increasing precipitation.

Large increases (from 60 to 500 percent) in coal mining in the Yampa River basin are projected for the next 15 years. Most of this additional coal production will be from surface mines. Even with the regulatory controls of the Surface Mining Control and Reclamation Act of 1977 (Public Law 95-87), substantial quantities of additional sediment are estimated to be eroded from the surface-mined areas and may be transported into the main-stem Yampa River.

The potential impact of surface mining would be the greatest in the eastern part of the basin. Existing sediment yields are less than 100 $(tons/mi^2)/yr$ or 35 $(t/km^2)/yr$ in this area, because of the extensive ground cover and soil development. Rainfall intensities are, however, greater in the eastern part of the basin than in the western part. Consequently, one can anticipate significantly greater sediment yields in the eastern part of the basin from lands which have been disturbed by surface mining.

Estimated sediment yields from surface-mined lands were computed by the PSIAC method. During mining and before complete reclamation, sediment yields are likely to be 4,000 $(tons/mi^2)/yr$ or 1,400 $(t/km^2)/yr$. Based on these estimates and the projected ranges of volumes of mined coal, the total amount of additional sediment supplied to the Yampa River in 1990 due to surface mining may be between 10,000 and 30,000 tons (9,000 and 27,000 t) annually.

The significance of this additional sediment load within the basin depends largely upon where the majority of the sediment enters the main-stem Yampa River. Streams in the eastern part of the basin carry relatively small sediment loads under present conditions, and, hence, the additional sediment yield from surface-mined land could have a considerable impact. For example, if all of the surface mining were located in areas of the Yampa River subbasin upstream from Hayden, the additional sediment could increase the annual load by as much as 30 percent, even though the amount of land disturbed would be less than 3 percent. As the amount of surface mining shifts to areas west of Hayden, the potential impact to the Yampa River decreases in relative terms. Even at the greatest projected volume of coal production, the additional sediment yields due to surface mining probably may not increase the present sediment load carried by the Yampa River near Maybell by more than an estimated 7 percent.

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