Relations Between Total-Sediment Load and Peak Discharge for Rainstorm Runoff on Five Ephemeral Streams in Wyoming

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Conversion Factors

Multiply	By	To obtain
cubic foot per second	0.02832	cubic meter per second
inch	2.54	centimeter
square mile	2.590	square kilometer
ton	0.9072	megagram
ton per year	0.9072	megagram per year

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Abstract

Total-sediment loads transported by ephemeral flows are a function of rainstorm energy and peak discharge. Rainstorm energy, estimated by rainfall intensity, is the primary mechanism for soil-particle detachment. Vegetation, soil cohesiveness, and land slope also are related to the amount of sediment detached, but these factors remain nearly constant, except for seasonal or human-induced changes in vegetation. Thus, the largest variability in total-sediment loads is the result of variability in rainstorm energy. The magnitude of the peak discharge in a stream from a runoff-producing rainstorm is a function of the intensity and volume of rainfall. The greater the rainfall intensity for the same volume of rainfall, the larger the peak discharge. Therefore, for each drainage area a relation exists between the total-sediment load for a rainstorm and the peak discharge for the rainstorm, because both are a function of rainstorm energy.

Total-sediment loads for runoff-producing rainstorms were computed from sample data collected at five ephemeral streams in semiarid areas of Wyoming. Regression analyses were used to develop equations relating total-sediment load to the peak discharge. Coefficients of determination ranged from 89 to 97 percent. Average standard errors ranged from 35 to 94 percent. The slopes of the lines defined by the equations were not different at the 95-percent level of significance, but the intercepts were significantly different for the five streams.

Introduction

Sediment-load data for semiarid basins drained by ephemeral streams are extremely difficult and expensive to collect. It is almost impossible for a hydrographer to collect depth-integrated samples because of the rapid nature of runoff from intense rainstorms. Automatic-pumping samplers activated by an increase in stage will sample one flow but might not sample the next because the hydrographer has not had a chance to remove the previous set of bottles and reset the sampler. The peak sediment concentration may occur before, at, or after the peak discharge of the rainstorm runoff (Rankl, 1987, p. 11). Frequently, the sediment concentration curve will have a double peak, whereas the runoff hydrograph will have a single peak. Because of the variability of sediment concentration in relation to discharge for ephemeral streams, the missing sediment-load data cannot be estimated accurately from sediment-transport curves (Rankl, 1987, p. 1l); therefore, the annual sediment discharge from rainstorms cannot be computed.

Annual runoff and sediment discharge for ephemeral streams is the sum of a series of discrete runoffs; therefore, an approach for computing annual sediment discharge needs to focus on runoff from individual storms. Woolhiser and Todorovic (1974) suggested that a linear relation exists between the logarithm of sediment load and the logarithm of peak discharge of the runoff from each rainstorm and that relation can be used to estimate annual sediment discharge for a basin. Singh and Chen (1982) developed a linear relation between the logarithms of sediment load and the logarithms of volume of direct runoff. Craig and Rankl (1978) used 105 hydrographs from 35 small basins to define a linear relation between the logarithms of volume of direct runoff and the logarithms of peak discharge. Rankl (1987, fig. 15) identified a linear relation between the logarithms of total-sediment load and the logarithms of peak discharge per rainstorm runoff. Parker and Troutman (1989) used a quadratic model to develop a relation between annual peak discharge and associated suspended-sediment load for large perennial rivers.

Rainstorm intensity is the primary mechanism for soil-particle detachment and has been used to estimate raindrop size (Mutchler and Young, 1975) and rainstorm energy (Wischmeier and Smith, 1958). Vegetation, infiltration rates of soil, soil cohesiveness, and land slope also are related to the amount of sediment detached, but these factors remain nearly constant, except for seasonal or human-induced changes in vegetation. Thus, the largest variability in sediment load is the result of variability in rainstorm energy. Hjelmfelt and others (1986) found that large rainstorm runoff, with an average occurrence of 1 year or less, produced more than 50 percent of the soil loss and sediment yield from cultivated fields.

The magnitude of the peak discharge in a stream from runoff-producing rainstorms is a function of the intensity and volume of rainfall. The greater the rainfall intensity for the same volume of rainfall, the larger the peak discharge. Therefore, a relation should exist between the total-sediment load for a rainstorm and the peak discharge because both are a function of rainstorm energy.

This report documents the relations between total-sediment load and peak discharge for rainstorm runoff for five ephemeral streams in Wyoming. The relations were used to estimate total annual sediment discharge for two of the streams. Sediment and peak-discharge data for rainstorm runoff collected during 1977-87 formed the basis for the analysis. In addition, continuous streamflow data collected during 1971-90 were used. The amount of data available varied among the study sites. The data used in this study were collected in cooperation with the Wyoming State Engineer.

Description of Study Area

Five streams that originate in and drain areas of the Powder, Belle Fourche and Big Horn River basins in Wyoming are used in this study (fig. 1, table 1). The streams are ephemeral, except in places where ground water is intercepted by the channel, thus forming pools. Most of the water evaporates from the pools. Soils generally contain little organic material, are fine grained, and are alkaline. Sagebrush and native grasses predominate.

The land is semiarid to arid. The mean annual precipitation ranges from a low of 9 inches for Fifteenmile Creek near Worland to 13 inches for Dead Horse Creek near Buffalo (Lowham, 1988). Most of the precipitation from October through March occurs as snow that sublimates. During April through September, precipitation occurs as rain showers and occasional intense thunderstorms.

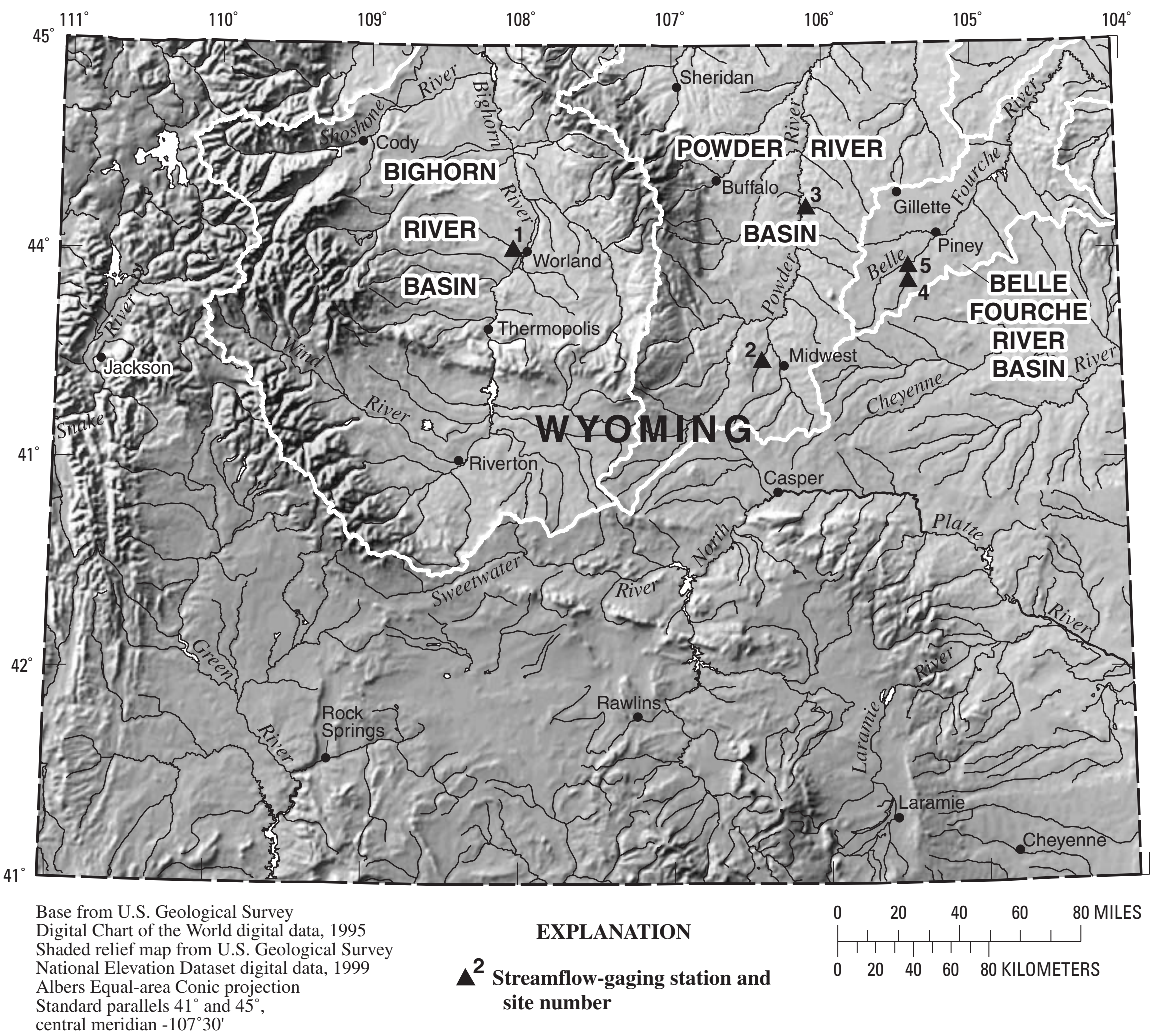

Figure 1. Location of data-collection sites on ephemeral streams used in the study.

Table 1. Streamflow-gaging stations used in the analysis

Site no. (fig. 1)	Streamfow-gaging station number	Station name	Drainage area (square miles)
1	06268500	Fifteenmile Creek near Worland, Wyo.	518
2	06313180	Dugout Creek tributary near Midwest, Wyo.	.81
3	06313700	Dead Horse Creek near Buffalo, Wyo.	151
4	06425750	Coal Creek near Piney, Wyo.	71.8
5	06425780	Belle Fourche River above Dry Creek near Piney, Wyo.	594

Runoff primarily occurs in response to rainstorms, but drainage basins within the Powder, Belle Fourche, and Big Horn River basins have some snowmelt runoff. Continuous streamflow records collected at Dugout Creek tributary near Midwest (site 2) during 1975-83 and Dead Horse Creek near Buffalo (site 3) during 1971-90) were analyzed to estimate the percentage of runoff attributed to rainstorms. Records for October through March were used to estimate snowmelt runoff, and records for April through September were used to estimate rainstorm runoff. Occasionally, runoff in October was from rainstorms, and some runoff in April was from snowmelt; however, records from the two 6-month periods generally are representative of the two types of runoff. About 74 percent of the annual runoff from Dugout Creek tributary (site 2) and about 81 percent of the annual runoff from Dead Horse Creek (site 3) were from rainstorms. The duration of runoff from rainstorms is measured in hours, whereas the duration of runoff from snowmelt, is measured in days and weeks.

Eight years (1979-86) of continuous streamflow and sediment records collected at Fifteenmile Creek near Worland (site 1) were analyzed to estimate the percentages of sediment discharge attributed to rainstorm runoff and to snowmelt runoff. The same time periods used for Dugout Creek tributary (site 2) and Dead Horse Creek (site 3), October through March and April through September, were used for Fifteenmile Creek. The analysis indicated that 88 percent of the runoff was from rainfall, and 12 percent of the runoff was from snowmelt. About 95 percent of the annual sediment discharge occurred during the rainstorm-runoff period and 5 percent during the snowmelt-runoff period.

Sediment-Load Computations

Total-sediment loads for rainstorm runoff were computed from sediment-sample data collected at each of the five sites (table 1). Sediment samples were collected using automatic pumping samplers. Sediment concentrations in the pumped samples were verified by comparing them to concentrations in depth-integrated samples (Rankl, 1987, p. 8). Discharge and total sediment concentration data were collected at Dead Horse Creek near Buffalo (fig. 2) and Dugout Creek tributary near Midwest to define the total-sediment load for a rainstorm runoff. For the remaining three sites, total sediment loads for each rainfall-runoff storm were computed from sediment records used to compute the annual suspended-sediment discharge. Sediment loads for rainstorm runoff data were computed from sediment-concentration samples, not from sediment-concentration curves. Data were not included in this study unless sediment-sample data were available for more than 75 percent of the water volume of the rainstorm runoff.

Total-sediment loads, consisting of suspended sediment and bedload material, were accounted for at each of the streamflow-gaging stations used in the analysis. At Fifteenmile Creek near Worland, the unmeasured bedload was computed using a method developed by Colby (1957). At Dugout Creek tributary near Midwest and at Belle Fourche River above Dry Creek near Piney, samples were collected in the turbulent section of the control structure where all sediment particle sizes were in suspension. The channels at Dead Horse Creek near Buffalo and Coal Creek near Piney consist of clay and silt; therefore, the samples of suspended sediment are assumed to represent the entire sediment load (Guy and Norman, 1970, p. 54). The peak discharge and total-sediment load for each rainstorm runoff at each station used in this study are listed in table 2.

Relation Between Total-Sediment Load and Peak Discharge

Equation 1 is used to define the relation between total-sediment load and peak discharge for a rainstorm runoff:

$$\log L_s = \log a + b\,(\log Q_p), \qquad (1)$$

where L_s is the total-sediment load of the rainstorm runoff, in tons;
Q_p is the peak discharge of the rainstorm runoff, in cubic feet per second;
a is the regression constant; and
b is the slope of the relation.

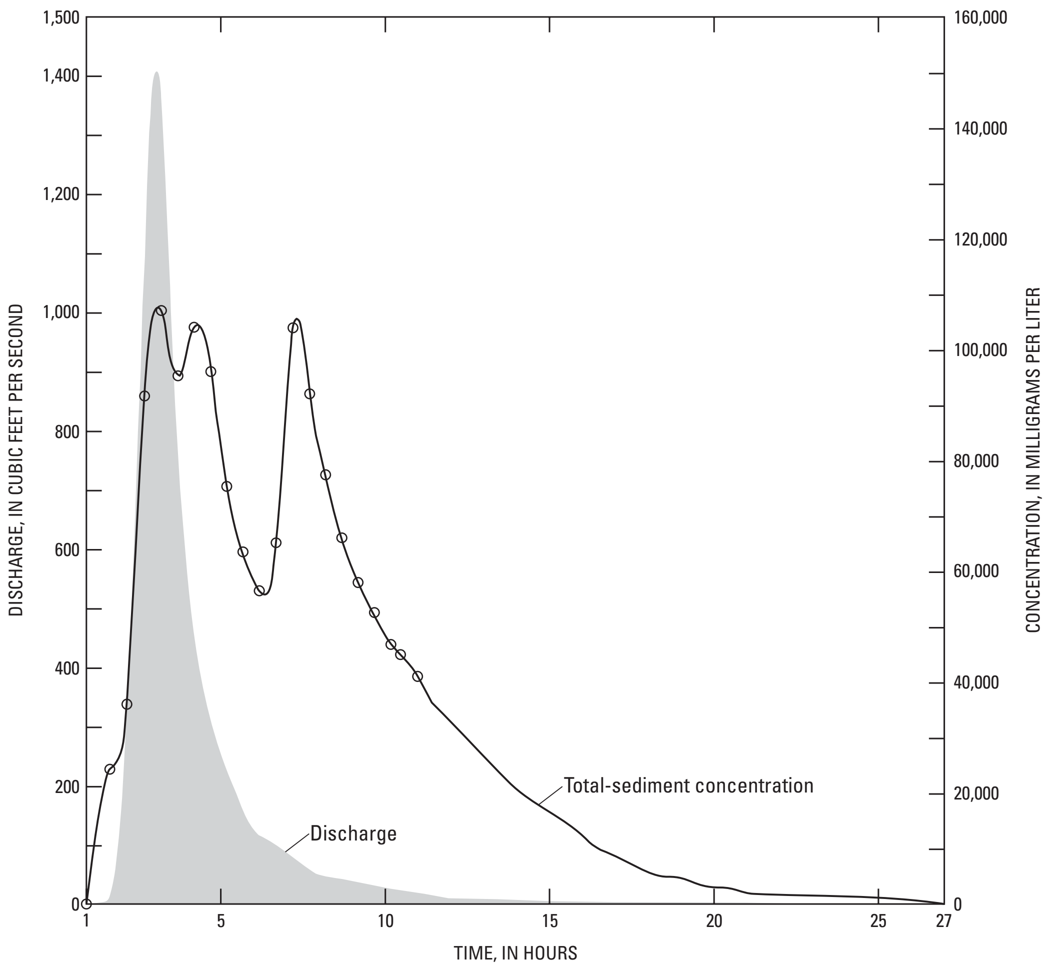

Figure 2. Discharge and total-sediment concentration for Dead Horse Creek near Buffalo, Wyo., storm of June 5, 1986.

The annual total-sediment discharge from rainstorm runoff for a year can be computed using:

$$Q_{sa} = \sum_{i=1}^{n} aQ_{p_i}^{b}, \tag{2}$$

where Q_{sa} is the annual rainstorm sediment discharge, in tons per year; and
n is the number of rainstorm runoff peaks per year.

When regressions relating the logarithms of concentration and the logarithms of discharge are retransformed to the nonlinear form of the equation, a statistical bias occurs in computing the sediment load for each storm. Several investigators have explored the magnitude of statistical bias in computing sediment loads and have developed procedures to correct for the bias (DeLong, 1982; Ferguson, 1986; DeLong and Wells, 1987; and Cohn and others, 1989). The magnitude of the bias is a function of the number of samples and the value of the variance of the random error, σ_ε^2.

Cohn and others (1989) stated that the Quasi Maximum Likelihood Estimator, called the bias correction factor by Ferguson (1986), performs well for a large number of samples and for a σ_ε^2 less than 1.0. Although the number of samples for this study is small, the variance of the random error is considerably less than 1.0. The retransformed total-sediment discharges (equation 2) were corrected by the bias-correction factor developed by Ferguson (1986):

$$Q_{sa} = \sum_{i=1}^{n} aQ_{p_i}^{b} \exp(2.65 s^2), \tag{3}$$

where s^2 is an estimate of the variance of the random error of the population.

The log-Pearson type III probability distribution is useful to describe floodflow characteristics. Because the total-sediment load for a rainstorm runoff is a floodflow type of occurrence, the log-Pearson type III distribution was used to describe the distribution of the annual series of total-sediment discharge from rainstorm runoff. The median (0.50 probability) sediment discharge of the series also was computed.

Table 2. Peak discharge and total-sediment load for rainstorm runoff

Date of rainstorm runoff	Peak discharge (cubic feet per second)	Total-sediment load (tons)
Site 1. Fifteenmile Creek near Worland[1]		
5/17/81	443	42,900
5/22/81	1,110	208,000
5/27/81	718	46,400
6/01/81	175	7,320
8/10/82	995	94,400
8/11/83	1,840	99,600
6/11/84	272	27,000
6/16/84	410	33,600
6/17/84	389	21,400
[2] 7/24/84	93	932
8/01/84	365	15,170
5/27/85	77	5,250
7/14/85	66	4,120
7/31/85	395	30,800
6/30/86	287	16,600
9/09/86	222	17,800
Site 2. Dugout Creek tributary near Midwest[3]		
5/19/82	16	91
5/27/82	88	679
6/08/82	2.6	6.5
6/16/82	70	275
7/24/82	11	40
8/09/82	15	43
8/20/82	5.9	12
6/03/83	22	130
7/23/83	129	1,340
8/04/83	194	1,160
Site 3. Dead Horse Creek near Buffalo[3]		
6/5/86	1,400	26,500
6/30/86	82	1,970
Site 3. Dead Horse Creek near Buffalo–continued[3]		
9/02/86	43	1,220
9/10/86	61	684
7/17/87	401	17,550
8/25/87	288	6,910
Site 4. Coal Creek near Piney[1]		
5/27/81	1,170	2,760
7/04/81	10	20
7/14/81	52	142
7/19/81	45	163
7/25/81	544	1,630
8/16/81	10	20
5/20/82	44	202
5/27/82	17	27
6/01/82	42	156
8/09/82	46	140
8/17/82	8.2	11
8/21/82	34	147
9/14/82	173	468
9/27/82	20	60
Site 5. Belle Fourche River above Dry Creek near Piney[1]		
6/14/77	1,630	761
7/09/77	77	256
6/30/79	126	301
5/27/81	838	1,780
8/16/81	8.5	4.6
5/21/82	70	102
5/28/82	30	12
7/26/82	7.5	5.8
8/21/82	574	1,780
9/14/82	184	394

[1]Total sediment load for a rainstorm runoff computed from sediment record used to compute annual suspended-sediment discharge.

[2]This rainstorm not used in regression analysis.

[3]Total sediment load for a rainstorm runoff computed from sediment samples.

Discharge and sediment data compiled in table 2 for the five streamflow-gaging stations were analyzed to determine the regression constant and slope for the log-linear relation between total-sediment load and peak discharge for a rainstorm runoff. The distribution of the data for each of the stations is shown in figures 3 through 7. The data for Fifteenmile Creek near Worland included runoff from a localized rainstorm on July 24, 1984, that was not representative of runoff and total-sediment load from the basin. This rainstorm runoff with a total-sediment load of 932 tons was not included in the regression analysis. Total-sediment load and peak discharge were available for only six rainstorms at Dead Horse Creek near Buffalo, but the analysis was included in the study because of the availability of the peak discharges for all rainstorm runoff for 14 years. The number of total-sediment load and peak-discharge rainstorms available for analysis, N, the computed parameters, the coefficient of determination, R^2, the sample standard deviation, *s*, and the standard error of estimate in percent are shown in table 3.

Residuals computed in the regression analysis were analyzed to determine if the data are approximately normally distributed. Skewness and kurtosis were computed for the residuals of each of the five data sets. For an approximately normal distribution, skewness is close to 0 and kurtosis should be close to 3. Skewness values for the five data sets ranged from positive 0.31 for Fifteenmile Creek to negative 0.67 for the Belle Fourche River. Kurtosis values ranged from 1.99 for Dugout Creek tributary to 3.75 for Dead Horse Creek. All of these values suggest that the data are approximately normally distributed.

The regression lines from figures 3 through 7 are plotted together on figure 8. The regression lines seem to indicate the relation is consistent for all five sites. To determine if that was the case, an analysis of covariance was made for slopes and intercepts summarized in table 3. Dummy variables were applied to a multiple-regression model (Kleinbaum and others, 1988) to determine if there was a significant difference in the slopes or intercepts at the 95-percent confidence level. The analysis indicated that the slopes are not significantly different and that the intercepts are significantly different. The parallel regression lines indicate that the relation is consistent for the five basins. However, field inspections of the basins indicated that the sediment availability and erodibility are different in each of the five basins, which may account for the significant difference in the intercepts of the five regression lines.

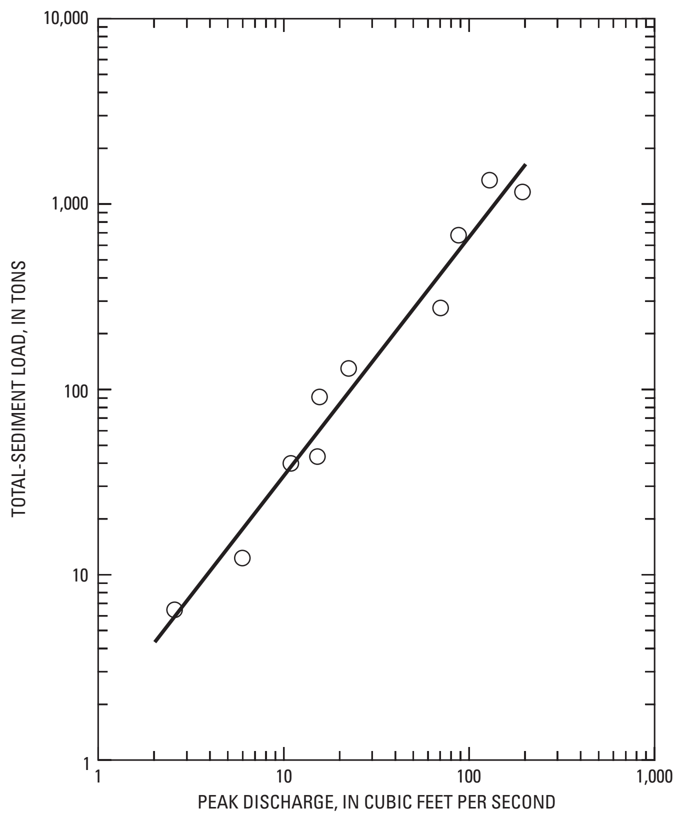

Figure 3. Relation between total-sediment load and peak discharge for rainstorm runoff, Dugout Creek tributary near Midwest, Wyo. (from Rankl, 1987, fig. 15).

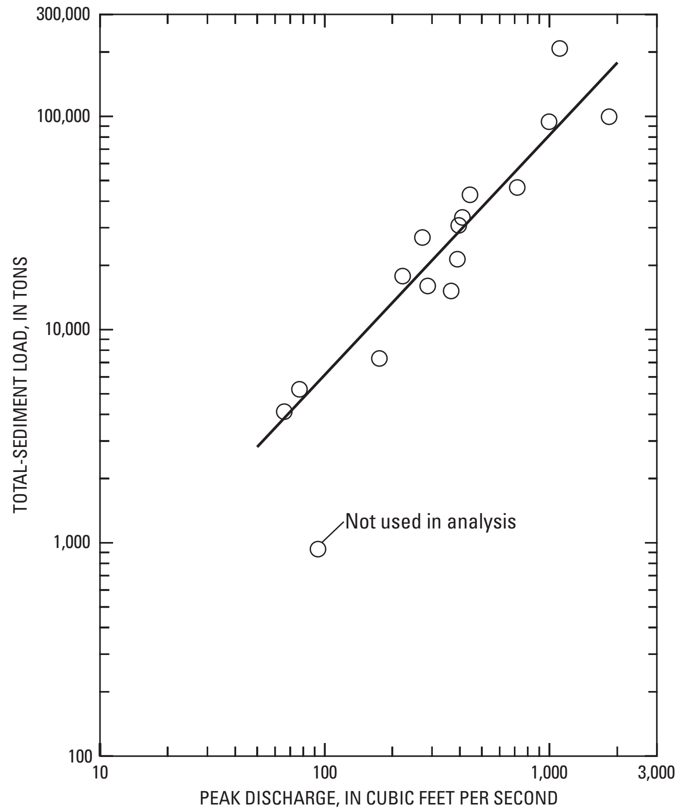

Figure 4. Relation between total-sediment load and peak discharge for rainstorm runoff, Fifteenmile Creek near Worland, Wyo.

The limitations of the study are the upper limits of the total-sediment load and discharge relation defined by the data listed in table 2. Total-sediment load for runoff greater than bankfull stage was measured at two of the stations without an apparent deterioration in the relations. Extension of the relations beyond the data could result in errors. However, if the relations are to be useful for predicting annual total-sediment discharge resulting from rainstorm runoff, then the magnitude of these errors needs to be evaluated.

To explore the potential magnitude of error due to extension of the total-sediment load and peak-discharge relation beyond the limits of the data used in the regression models, a linear error was assumed, ranging from zero at the upper limit of the defined relation to a plus or minus 50 percent at the maximum peak discharge of record. The peak discharge of record was about 8 times the upper limit of the defined relation at Dugout Creek tributary near Midwest, and the peak discharge of record was about 2.5 times the upper limit of the defined relation at Dead Horse Creek near Buffalo. The magnitude of two errors was explored—the error in the arithmetic mean and the error in the geometric mean of the annual sediment load. For Dugout Creek tributary near Midwest, the error in the arithmetic mean was a plus or minus 15 percent, and the error in the geometric mean ranged from a positive 1.0 percent to a negative 1.1 percent. For Dead Horse Creek near Buffalo, the error in the arithmetic mean was a plus or minus 14 percent, and the geometric mean ranged from a positive 0.4 percent to a negative 0.6 percent. The small errors in the geometric mean indicate that the log- Pearson type III distribution could minimize the effects of the potential errors in median sediment discharge (0.50 probability) from the basins when records are extended beyond the defined regression equations.

To define the distribution of the annual total-sediment discharge from rainstorm runoff for Dugout Creek tributary near Midwest and Dead Horse Creek near Buffalo, values for the mean, standard deviation, and the coefficient of skewness were computed for the log-Pearson type III distribution. Equation 3 was used to compute the estimated annual total-sediment discharge from the peak discharge for all rainstorm runoff compiled for the two stations. The fit of the log-Pearson type III distribution to the annual total-sediment discharge for the two sites is shown in figure 9. The median annual total-sediment discharge for Dead Horse Creek near Buffalo is about 10 times the median annual total-sediment discharge at Dugout Creek tributary near Midwest.

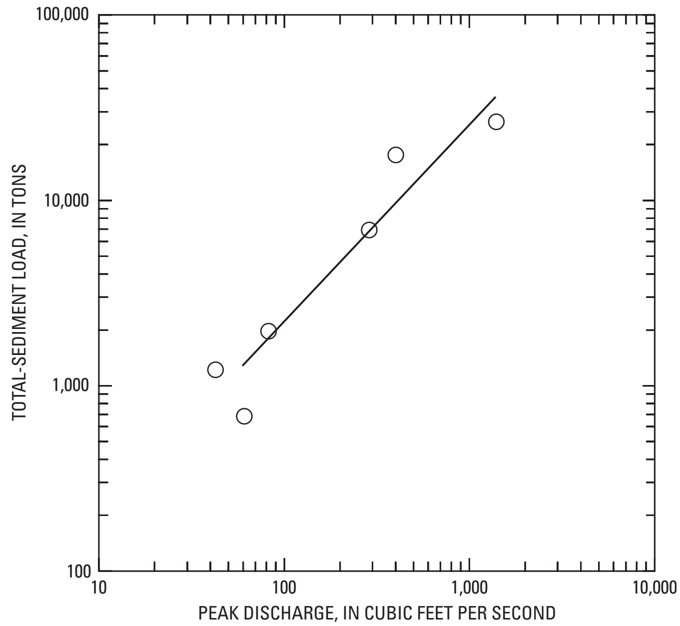

Figure 5. Relation between total-sediment load and peak discharge for rainstorm runoff, Dead Horse Creek near Buffalo, Wyo.

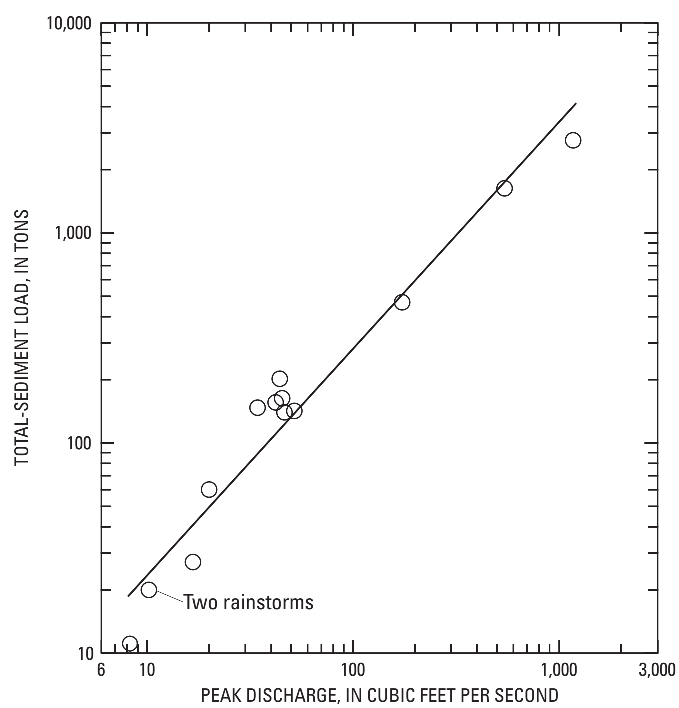

Figure 6. Relation between total-sediment load and peak discharge for rainstorm runoff, Coal Creek near Piney, Wyo.

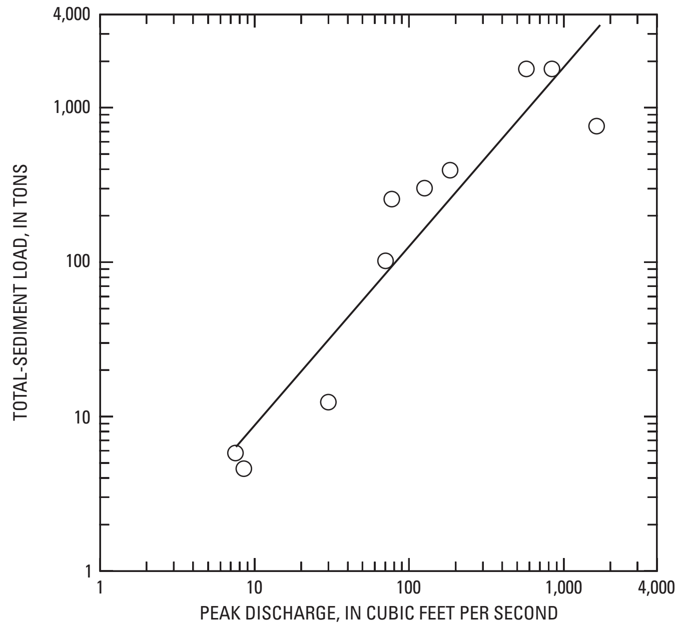

Figure 7. Relation between total-sediment load and peak discharge for rainstorm runoff, Belle Fourche River above Dry Creek near Piney, Wyo.

Table 3. Results of regression analysis for relation between total-sediment load and peak discharge for rainstorm runoff

[N, number of runoff rainstorms; R^2, coefficient of determination; *s*, sample standard deviation]

Site No.	Station name	N	Regression constant	Slope	R^2	*s*	Standard error of estimate (percent)
1	Fifteenmile Creek near Worland	15	33.88	1.13	0.89	0.164	39
2	Dugout Creek tributary near Midwest	10	1.78	1.29	.97	.146	35
3	Dead Horse Creek near Buffalo	6	16.59	1.07	.91	.219	54
4	Coal Creek near Piney	14	1.98	1.08	.96	.154	37
5	Belle Fourche River above Dry Creek near Piney	10	.62	1.16	.89	.348	94

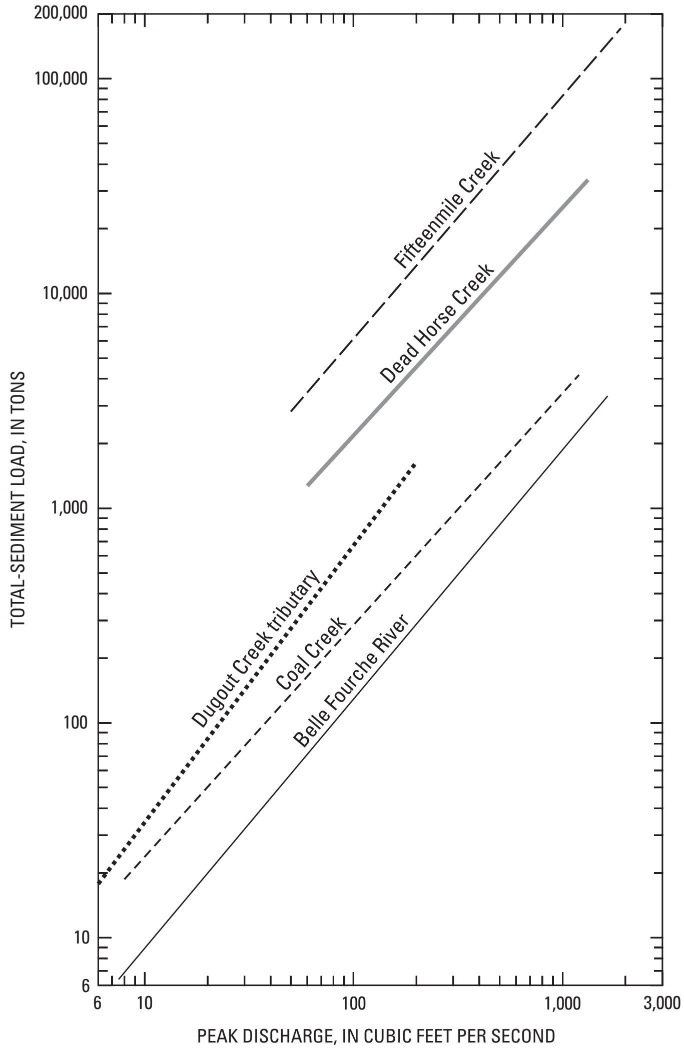

Figure 8. Relation between total-sediment load and peak discharge for rainstorm runoff at the five sites on ephemeral streams used in the study.

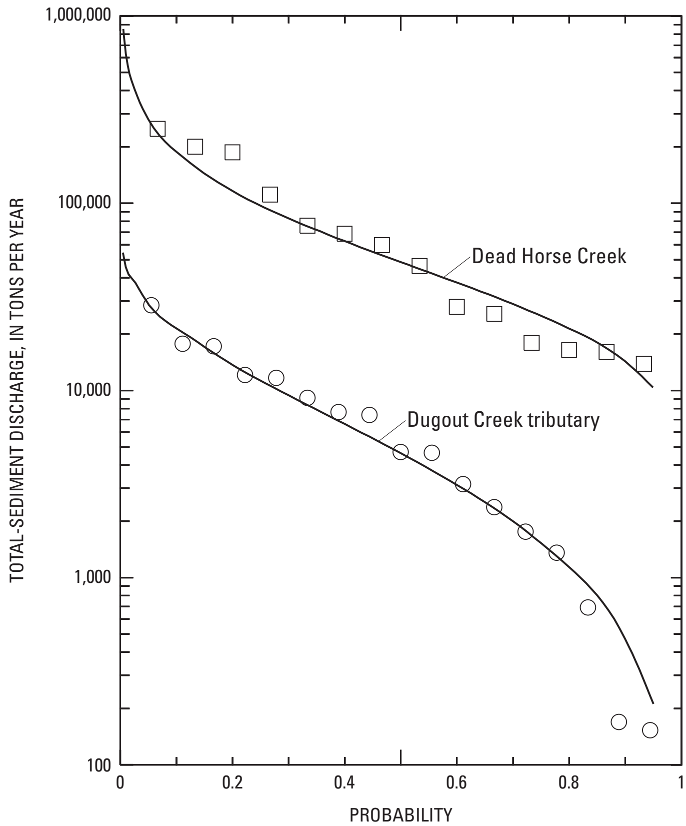

Figure 9. Log Pearson type III probability distribution of annual total-sediment discharges for Dugout Creek tributary near Midwest, Wyo. and Dead Horse Creek near Buffalo, Wyo.

Summary and Conclusions

Total-sediment load is related to peak discharge for rainstorm runoff in ephemeral streams. Regression equations were developed from data for five ephemeral streams in Wyoming. Coefficients of determination ranged from 89 to 97 percent. Standard errors ranged from 35 to 94 percent. The slopes of the equations for the five streams are not statistically different at the 95-percent confidence limit, which may indicate that slopes are a function of rainstorm intensity for detaching the sediment particles. The intercepts are statistically different for the five basins, which may indicate that this difference is a function of sediment availability; that is, vegetation, soil erodibility, and land slope.

The annual sediment discharge primarily is a function of sediment availability, the number of rainstorms, and the magnitude of the rainstorms. The relative sediment availability is defined by the position of each of the relations for total-sediment load and peak discharge (fig. 8). Onsite reconnaissance of the five basins indicated that the relative positions (increasing sediment availability with increasing sediment loads for a given peak discharge) of the relations for total-sediment load and peak discharge are correct.

Peak discharges for all rainstorm runoff were compiled for Dugout Creek tributary near Midwest and for Dead Horse Creek near Buffalo. The peak discharges for each basin were applied to the total-sediment load and peak-discharge equation for that basin to determine the sediment load for each rainstorm runoff. The sediment loads for rainstorm runoff were summed to obtain the annual sediment discharge for rainstorms. The statistics for a log-Pearson type III distribution were computed from the annual total-sediment discharges to determine the median annual total-sediment discharge.

Total-sediment discharge from rainstorms at Dugout Creek tributary and Dead Horse Creek was estimated to be between 90 and 95 percent of the annual total-sediment discharge. This estimate takes into consideration that runoff from rainstorms accounts for 74 percent of the annual runoff at Dugout Creek tributary and 81 percent of the annual runoff at Dead Horse Creek. This estimate also takes into consideration the smaller suspended concentrations in snowmelt than in rainstorm runoff (Rankl, 1987, p. 15) and the relation between sediment discharge for snowmelt and rainfall runoff at Fifteenmile Creek near Worland.

The relation between total-sediment load and peak discharge of rainstorm runoff has an application not explored in this study that could prove useful. A shift in the relations could be used to define changes in sediment loads as a result of an environmental change—either anthropogenic or natural. Because the slopes of the relations for the streams studied are not significantly different and the intercepts are significantly different, sediment availability possibly might be regionalized.

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