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EFFECTIVE AND BANKFULL DISCHARGES OF STREAMS IN THE YAMPA RIVER BASIN, COLORADO AND WYOMING

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ABSTRACT

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The effective discharge is defined as the increment of discharge that transports the largest fraction of the annual sediment load over a period of years. Increments of the average annual total sediment load transported by various discharges were calculated by the flow-duration, sediment-transport-curve method for 15 gaging stations in the Yampa River basin of Colorado and Wyoming. A total sediment-transport curve was constructed for each gaging station by adding measured instantaneous suspended-sediment discharges to bedload-sediment discharges computed by the Meyer-Peter and Mueller relation. The streamflow durations were compiled from the respective gaging-station records. The quantity of sediment transported by discharges having various frequencies may be computed by combining these two relations.

The 15 gaging stations had diverse hydraulic and sediment characteristics. Contributing drainage area ranged from 51.8 to 9,960 km², and mean-annual discharge ranged from 0.040 to 43.9 m³/s. The median diameter of bed material ranged from 0.4 to 86 mm. Mean-annual sediment load from the drainage basins studied ranged from 500 to 1.3·10⁶ metric tons per year.

The effective discharges at the 15 gaging stations were equaled or exceeded on the average of between 1.5 days per year (0.4% of the time) and 11 days per year (3.0% of the time). The recurrence interval of the effective discharges ranged from 1.18 to 3.26 yr. on the annual flood series. To compare the effective discharge with the bankfull discharge, cross-sections were surveyed in a self-formed reach of the channel in the vicinity of each gaging station. The bankfull discharge was defined as the discharge which filled the channel to the level of the floodplain. At all gaging stations, the effective discharge and the bankfull discharge were nearly equal. Thus, the stream channels appear to be adjusted to their effective discharge.

INTRODUCTION

The concepts of magnitude and frequency of geomorphic forces were developed by Wolman and Miller (1960). Two significant principles of quantitative geomorphology were presented. The first principle is that the effective geomorphic force is a relatively frequent event as shown conceptually in Fig. 1 using the example of river mechanics. The effectiveness of a given discharge
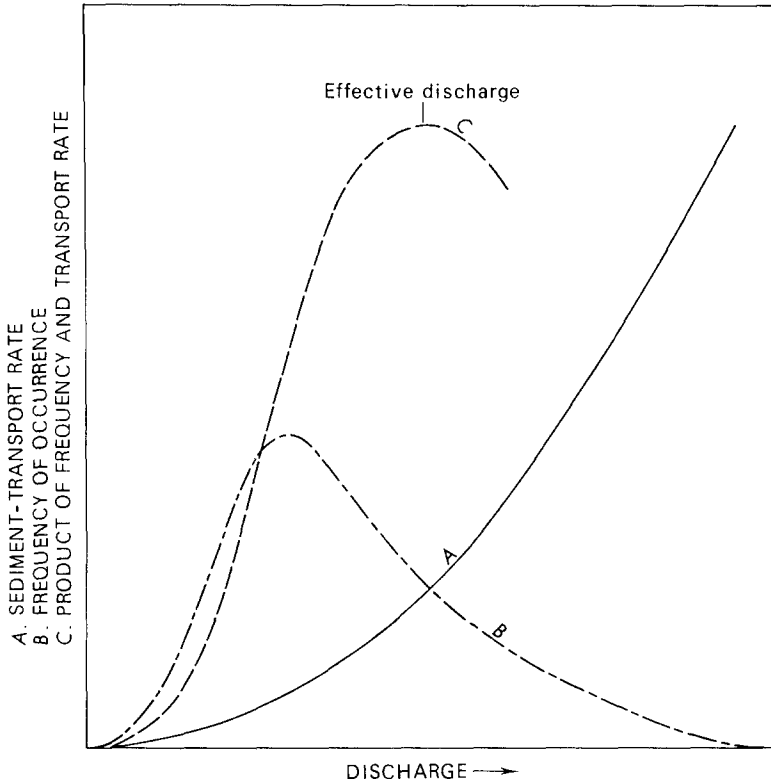
Fig. 1. Relations between discharge and sediment-transport rate, frequency of occurrence and the product of frequency and transport rate (after Wolman and Miller, 1960).

over a period of years is determined by two factors — its magnitude and frequency. The magnitude or relative significance of a given discharge is represented by its sediment-transport rate, curve A. The sediment-transport rate (I_b) commonly varies proportionally with discharge, Q, to a power, n, greater than 1:

$$I_b \propto Q^n \tag{1}$$

Thus, a doubling of the discharge results in more than a two-fold increase in the sediment-transport rate.

The frequency with which a given discharge occurs is represented by curve B, the distribution of streamflows. The most frequent discharges are moderate and transport relatively small amounts of sediment. Conversely, the largest discharges are rare, but transport very large amounts of sediment. The relative effectiveness (curve C) of a given discharge is the product of the sediment-transport rate and the frequency of occurrence. As shown, it is a range of intermediate discharges that transports the largest part of the average annual sediment load. This range of discharge may be represented by the modal sedi-

ment-transporting discharge, which will be called the effective discharge.

The frequency of the effective discharge depends upon the relative significance of large discharges as well as the magnitude of fluid forces required to erode the stream channel. Due to climatic, geologic and physiographic factors, the frequency of the effective discharge will vary from one stream to another, as well as longitudinally along a given stream. The frequency of the effective discharge decreases as the occurrence of large floods increases, i.e. as the tail of curve B (Fig. 1) is extended to greater discharges. The effective discharge, also, will become less frequent as the magnitude of fluid forces needed to erode the stream-channel increase. Baker (1977) has shown that rare, catastrophic floods may be the effective geomorphic events in streams which have a high proportion of very large discharges or channels relatively resistant to erosion.

The second principle concerns the relation between effective geomorphic forces and land forms. Wolman and Miller (1960) noted that in many instances, land features were formed by relatively frequent geomorphic forces and not by rare catastrophic events. In particular, they suggested that meander length and stream-channel size were adjusted to effective discharge.

The concepts of magnitude and frequency of geomorphic forces expressed by Wolman and Miller (1960) have gained wide acceptance. Field investigations, however, have often been inconclusive. In particular, it has been difficult to relate land forms to geomorphic forces of a given magnitude and frequency. This is due principally to the lack of adequate data on the magnitude and frequency of geomorphic forces. Streamflow is probably the most extensively studied geomorphic process; even so, the available data are commonly insufficient to resolve these questions for three reasons: streamflow records are seldom of sufficient length to represent the full range of actual discharges, especially those that rarely occur. Sediment concentrations are measured infrequently and are limited to that part of the sediment load suspended within the flow. Thus, it is rarely possible to compute the effective discharge of a given reach of stream channel accurately. Furthermore, the gaging stations at which sediment data are available are frequently located in reaches of channel stabilized or controlled by natural or man-made features. Thus, even for instances in which the effective discharge may be determined, the geomorphic effect of it may be muted or nonexistent.

This paper describes a study of effective discharges and their geomorphic significance in the Yampa River basin. Streamflow and sediment data were collected from gaging stations located in self-formed alluvial reaches of stream channel to make this analysis.

YAMPA RIVER BASIN

The Yampa River basin is located in northwest Colorado and southwest Wyoming (Fig. 2). It is divided into two subbasins of about equal area; the
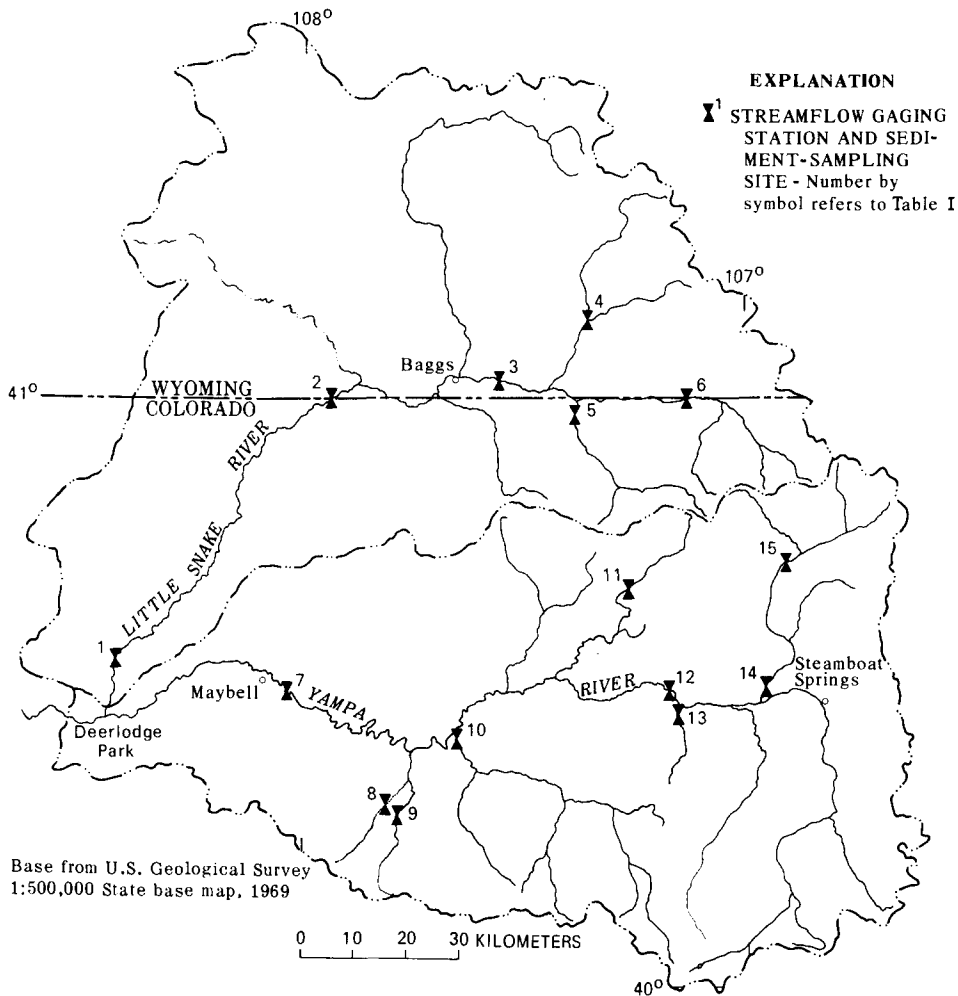
EXPLANATION

X^1 STREAMFLOW GAGING STATION AND SEDIMENT-SAMPLING SITE - Number by symbol refers to Table I

Fig. 2. Location of streamflow-gaging stations and sediment-sampling sites used in the study.

Little Snake River subbasin has an area of 9,700 km² and the Yampa River subbasin has an area of 10,100 km². The eastern part of the basin is mountainous with a maximum elevation of 3,780 m. Mean-annual precipitation ranges from 600 to 1,250 mm/yr., and the vegetation is a pine—spruce forest. Westward across the basin, the elevation decreases to 1,530 m at Deerlodge Park. Mean-annual precipitation in the central and western parts of the Yampa River basin ranges from 200 to 360 mm/yr. Here the vegetation is sparse grass and sagebrush.

Fifteen gaging stations were selected for study. The criteria for selection were a minimum of 5 years of streamflow record and 25 measured suspended-sediment concentrations covering the range of discharges. Furthermore, it is

required that the gaging stations be located in a self-formed reach of alluvial stream channel, with a well-developed floodplain so that the channel could be considered to be in quasi-equilibrium. The mean-annual discharges for these stations range from 0.04 to 43.9 m^3/s, while the drainage areas range from 51.8 to 9,660 km^2.

Method of computing total sediment loads

Total sediment loads were computed for the 15 gaging stations in the Yampa River basin using the streamflow-duration, sediment-transport-curve method described by Miller (1951). This method is useful when the gaging-station records of streamflow are sufficient to determine the average duration of various discharges, and the necessary data are available to construct a relation between total sediment-transport rate and discharge. The sediment discharge of a river is composed of two parts — the suspended load, which can be measured readily, and the bedload, which must be computed in most instances. Therefore, separate relations describing the variation of the suspended load and the bedload with water discharge were developed. The relation between suspended load and discharge was determined by converting the measured instantaneous concentrations to daily suspended-sediment loads, and then plotting the loads against the corresponding daily mean discharge. A mean relation was calculated by a least-squares linear regression of the log-transformed data.

The relation between bedload-transport rate and discharge was computed with the Meyer-Peter and Mueller (1948) equation, using a form derived by H.H. Stevens (pers. commun., 1978). The whole channel bedload-transport rate (I_b) is given by:

$$I_b = (2.52 D_{90}{}^{1/4} \bar{u}^{3/2} S^{1/4} - 0.86 D_m)^{3/2} W \tag{2}$$

where

W	= channel width	(m)
D_{90}	= grain diameter at the 90th percentile fraction	(mm)
$\bar{u}$	= mean velocity	(m/s)
S	= water-surface slope	
D_m	= effective grain diameter	(mm)

The velocity, depth and width of flow for a given discharge were selected from discharge measurements made at the gaging station. The water-surface slope was measured over a reach of channel at least 20 channel widths in length, including the gaging-station cross-section. The size parameters of bed material were computed from sieve analyses of composited bed-material samples collected at 6—10 sites across the stream channel at the gaging station. Several of the streams studied have a large range in size distribution of bed

material and significant quantities of material larger than 100 mm in diameter. For these streams, a bedload-transport rate was computed for each size class, which then was multiplied by the fraction of the bed in the size class. The bedload-transport rate for a given discharge at the gaging station was determined by summing the bedload-transport rates of the several size classes. Computed bedload-transport rates were typically less than 20% of the total sediment load. Thus, although the uncertainty of the bedload-transport rate may be large ($\pm 50\%$) (White et al., 1975), the uncertainty in the total sediment load introduced by computing rather than measuring the bedload-transport rate is small.

The bedload-transport rate vs. discharge relation was determined by fitting a curve to several computed bedload-transport rates for the range of discharges. The total sediment-load vs. discharge relation (daily values) was determined
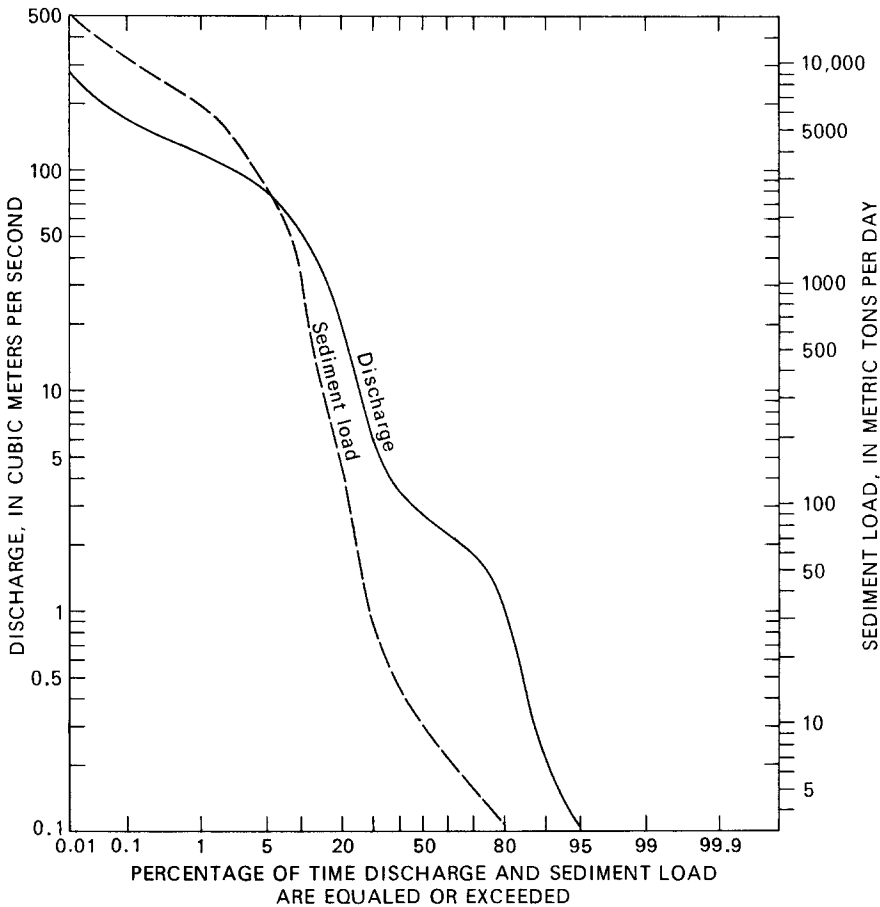

Fig. 3. Streamflow and total sediment-load-duration curves for the Little Snake River near Dixon, Wyoming.

by adding the measured suspended-load and the computed bedload relations. The mean-annual total-sediment load transported by increments of discharge may be computed by combining this relation with the average frequency of discharge recorded at the gaging station.

The cumulative frequency of daily mean discharges at a gaging station for the period of record may be represented by a streamflow-duration curve. The flow-duration curve shows the percentage of time a given discharge is equaled or exceeded. When several years of record are used to construct a flow-duration curve, the resulting relation describes the average or probable frequency of various discharges during a year. The streamflow-duration curve for the Little Snake River near Dixon, Wyoming, gaging station is shown in Fig. 3.
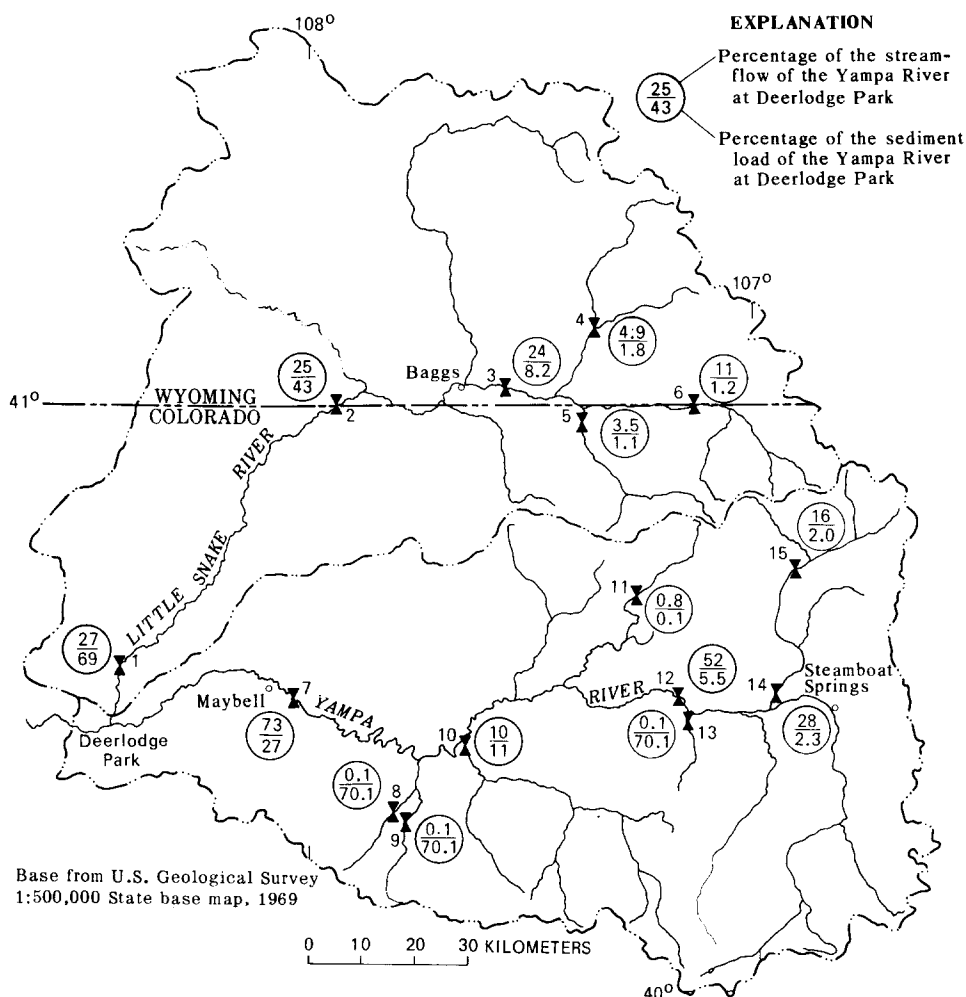

Fig. 4. Variation in streamflow and sediment loads in the Yampa River basin.

TABLE I

Summary of streamflows and sediment loads for gaging stations in the Yampa River basin

Site number in Fig.1	U.S. Geological Survey Station No.	Station name	Drainage area (km²)	Mean annual discharge (m³/s)	Mean annual sediment load (tons)
1	09260000	Little Snake River near Lily	9,660	16.3	1,300,000
2	09259700	Little Snake River near Baggs	7,820	14.8	330,000
3	09257000	Little Snake River near Dixon	2,560	14.6	150,000
4	09256000	Savery Creek near Savery	855	2.95	33,000
5	09255000	Slater Fork near Slater	417	2.10	20,000
6	09253000	Little Snake River near Slater	738	6.43	20,000
7	09251000	Yampa River near Maybell	8,820	43.9	490,000
8	09250600	Wilson Creek near Axial	51.8	0.051	790
9	09250400	Goodsprings Creek near Axial	90.5	0.057	500
10	09249750	Williams Fork at mouth near Hamilton	1,200	6.10	190,000
11	09245000	Elkhead Creek near Elkhead	54.5	0.480	1,600
12	09244410	Yampa River below diversion near Hayden	3,700	31.2	98,000
13	09244300	Grassy Creek near Mt. Harris	67.4	0.040	2,500
14	09242500	Elk River near Trull	1,080	16.8	39,000
15	09241000	Elk River at Clark	535	9.50	36,000

The total sediment-load vs. discharge relation may be combined with the streamflow-duration relation to give a sediment-load—duration relation for the gaging station (Fig. 3). The relation represents the percentages of time a given daily sediment load is equaled or exceeded.

Areal variation of sediment load and discharge

The mean-annual discharges and sediment loads at the 15 gaging stations are listed in columns 5 and 6 of Table I. A comparison of these values for the station shows that annual sediment load and streamflow are not contributed to the channel network evenly throughout the basin. In Fig. 4 the mean-annual discharge and sediment load at each gaging station are expressed as percentages of the estimated streamflow and sediment load for the Yampa River at Deerlodge Park. The relative proportion of sediment and water flowing past individual gaging stations is significantly 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 *7*). Although the drainage areas contributing to these two gaging stations are about equal — 9,660 km² for site *1* vs. 8,820 km² for site *7* — the respective sediment loads and streamflows are markedly different.

Effective discharge (m³/s)	Duration of effective discharge (percentage of time)	Bankfull discharge (m³/s)
127	1.1	133
119	1.1	167
113	1.4	114
31.4	0.7	28.9
14.2	2.8	16.1
53.8	1.2	72.2
258	2.5	255
0.481	0.65	0.538
0.312	0.4	0.312
46.2	2.8	46.7
17.3	1.3	15.6
172	3.0	167
1.42	0.7	1.40
96.3	2.1	101
58.1	2.1	60.9

The Little Snake River subbasin supplies 27% of the annual runoff to the Yampa River at Deerlodge Park but 69% of the sediment load. Conversely, the Yampa River subbasin contributes 73% of the runoff and 27% of the sediment load (Fig. 4).

Comparisons for other gaging stations are equally striking. The relatively large sediment load of the Little Snake River subbasin enters the Little Snake River between Dixon (site 3) and Lily (site 1) (Fig. 4). Approximately 60% of the entire sediment load of the Yampa River at Deerlodge Park is contributed from the drainage area between these two gaging stations. The drainage area between the gaging stations is less than 35% of the entire basin area and supplies less than 3% of the runoff. Approximately 76% of the total streamflow is supplied by the eastern part of the basin upstream from site 3 on the Little Snake River and site 12 on the Yampa River.

These comparisons show that the 15 stream reaches studied in the Yampa River basin were varied and diverse. The streams represent a considerable range of discharges, sediment loads and bed-material-size distributions that result from climatic, geologic and physiographic differences within the basin (Andrews, 1978).

DURATION OF EFFECTIVE DISCHARGE

The quantity of sediment transported by various discharges at a gaging station during a period of years was computed directly from the total sediment-load-duration curve. The range of discharges was divided into approximately 20 equal increments. Then the sediment-load-duration curve was integrated between the limits of each increment, and multiplied by 365 days. The quantity of sediment transported by equal increments of discharge for the Little Snake River near Dixon is shown in Fig. 5. The computed values are shown plotted against the mean discharge of the increment. A smooth curve was then fitted to the computed points. The modal discharge, or the discharge that transported the most sediment during the period of record was 113 m³/s. This discharge will be termed the effective discharge because it transported
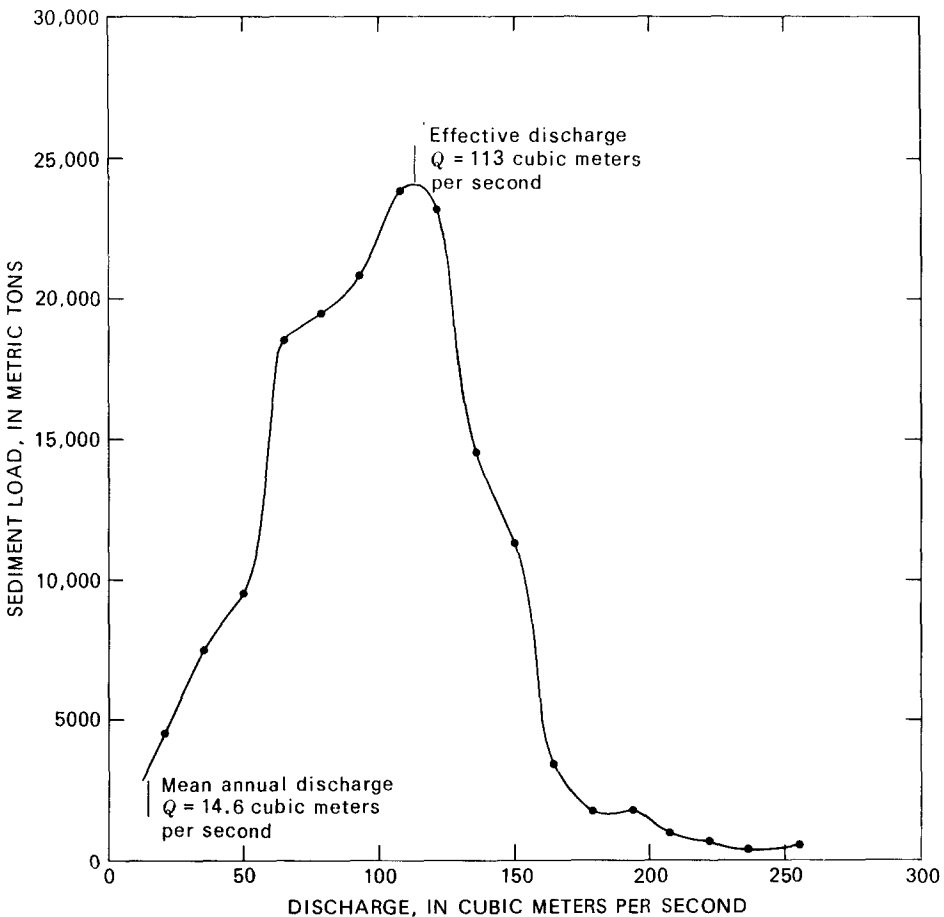
Fig. 5. Mean-annual sediment load transported by increments of discharge for the Snake River near Dixon, Wyoming.

the largest increment of the annual total sediment load through the channel.

The effective discharge at the Little Snake River near Dixon gage has been equaled or exceeded on the average of 5.1 days per year, or 1.4% of the time, during the period of streamflow record, 1939—1976. A number of other significant characteristics of the sediment discharge are shown in Fig. 5. Approximately 73% of the total sediment load at this station was transported by discharges between 57 and 156 m^3/s. These discharges are equaled or exceeded on the average between 8.8 and 0.2% of the time, or between 32 and 0.70 day per year. Thus, neither the rare large floods nor the common streamflows have been significant sediment-transporting discharges at this station during the period of record. In particular, the mean-annual discharge has not been an important sediment-transporting discharge, as it has transported only a small fraction of the annual sediment load. More than 90% of the mean-annual sediment load has been transported by discharges larger than the mean-annual discharge.

The effective discharge at all gaging stations was computed by the method described above. The effective discharges and their durations are summarized in Table I, columns 7 and 8, and compared in Fig. 6. The streamflow duration of the effective discharge varies between gaging stations. The observations range from 0.4 to 3.0% of the time or from 1.5 to 11 days per year. On the average, the effective discharge was equaled or exceeded 1.6% of the time or 5.8 days per year. These observations agree with the conclusion of Wolman and Miller (1960) that the effective discharge is a relatively frequent flow that occurs on an average of several days per year.
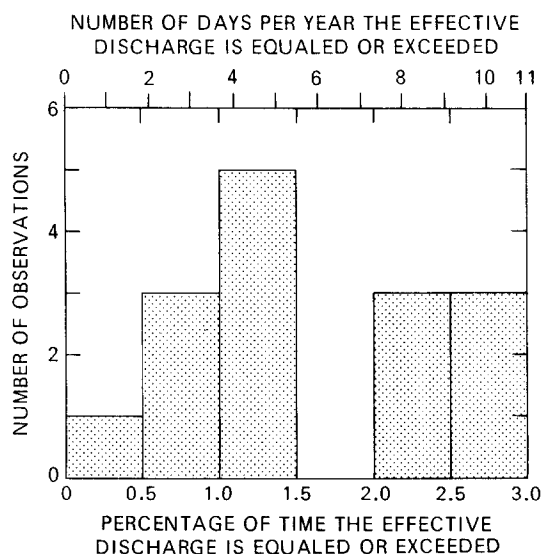

Fig. 6. Streamflow duration of effective discharges at 15 gaging stations in the Yampa River basin.

Factors influencing the duration of the effective discharge

The conceptual model of geomorphic forces presented by Wolman and Miller (1960) (Fig. 1) indicates that the duration of the effective discharge should depend upon the distribution of streamflows and the threshold of sediment movement. As described previously, the duration of the effective discharge will become shorter as the relative proportion of large flows increases, or as the threshold of sediment movement increases, or both. Conversely, the duration of the effective discharge will become longer as the relative proportion of large flows decreases, or as the threshold of sediment movement decreases, or both.

The relative significance of large streamflow at a gaging station may be represented by the skew of the distribution of the streamflows. The skew (SK)
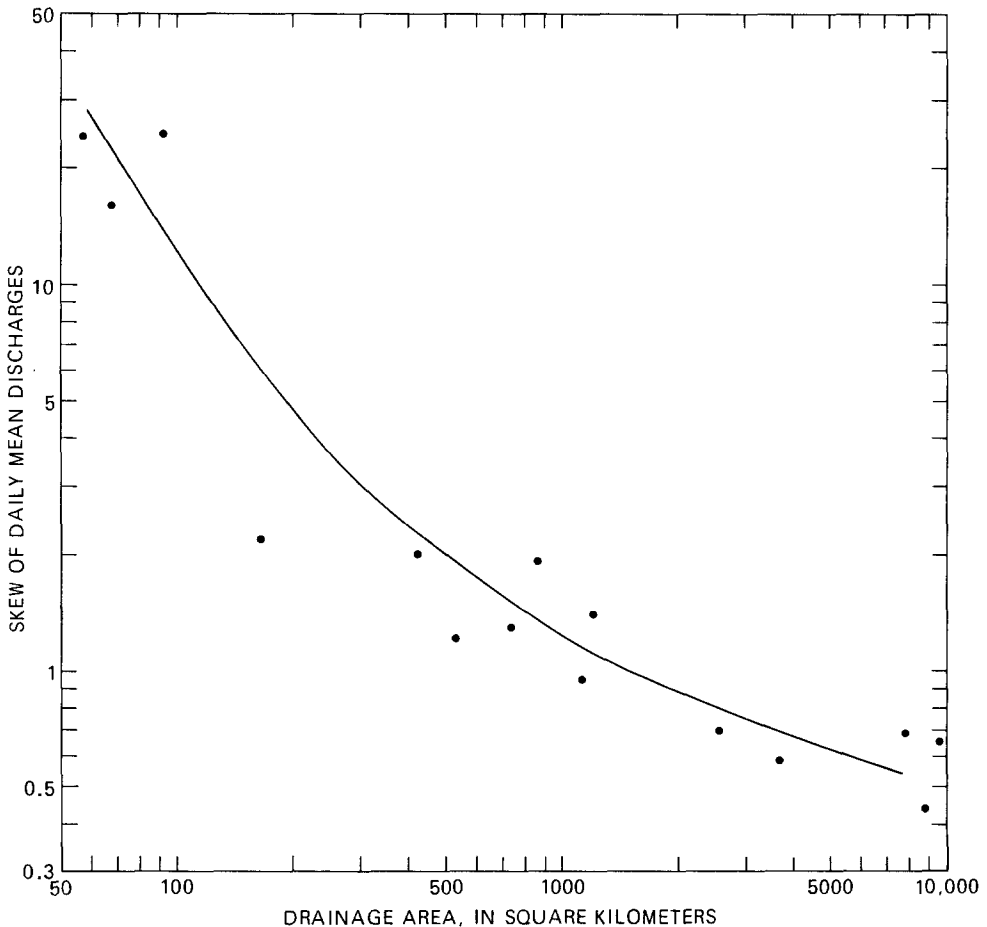
Fig. 7. Relation between drainage area and the skew of daily mean discharge.

of the distribution of daily mean streamflows was computed as:

$$SK = \int (Q - \bar{Q})^3 p(Q) \, dQ \, / \, [\int (Q - \bar{Q})^2 \, p(Q) \, dQ]^{3/2} \tag{3}$$

where Q = discharge, in m^3/s; and $p(Q)$ = cumulative-density duration of discharge.

Both Wolman and Miller (1960) and Baker (1977) have noted that the skew of the distribution of streamflows increases with decreasing drainage area. The skews of streamflow at the 15 Yampa River basin gaging stations are plotted against the contributing drainage areas in Fig. 7. As expected, the skews are inversely related to drainage areas. The agreement is quite good and differences in climate between the several watersheds do not appear to be significant.

The relative thresholds of sediment movement at the gaging stations were approximated by the ratio of the median diameter of bed material to the stream power per unit width at the effective discharge. The possible significance of streamflow variability and the threshold of sediment movement upon the frequency of the effective discharge was tested by a multiple regression correlation between the duration of effective discharge and the skew of streamflow and $D_{50}/\gamma \, q_{eff} \, S$ was computed. The effective-discharge duration and skews were related; however, no improvement in the correlation was obtained by addition of the $D_{50}/\gamma \, q_{eff} \, S$ ratio. The relation between effective-discharge duration and streamflow skew is shown in Fig. 8. Variation in streamflow
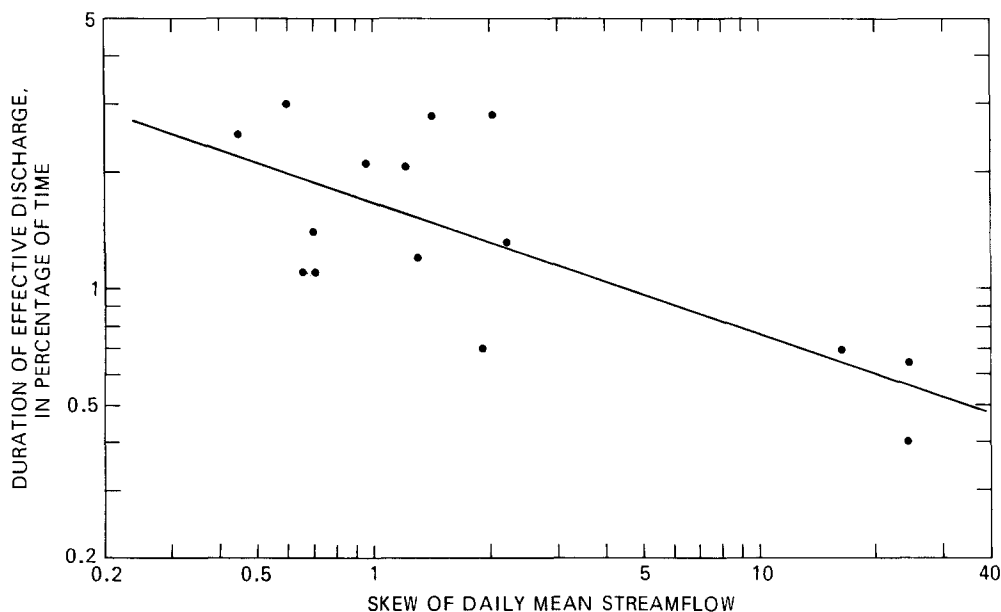

Fig. 8. Relation between the skew of daily mean discharges and the duration of the effective discharge.

skew accounts for slightly more than one-half (r^2 = 0.52) of the variation in effective-discharge duration. Although the scatter of data is appreciable a T-test indicates that the relation is significant at the 99% level.

The apparent insignificance of median bed-material size and unit stream power upon the effective-discharge duration probably is due to several factors. Although the median size of bed material varied greatly between sites — ranging from 0.35 to 86 mm — a majority of the sediment load at all sites was suspended load and thus relatively fine-grained. Consequently, the thresholds of sediment movement were relatively small and did not vary much between sites. The difference in bed-material size primarily influenced the fraction of bed material in transport at a given discharge.

The Little Snake River near Dixon is typical of the streams with relatively coarse bed material. The relation between bed-material size and the discharge necessary to initiate motion is shown in Fig. 9. This relation was determined by modifying the Shields criterion for critical-shear stress. Shields (1936) used
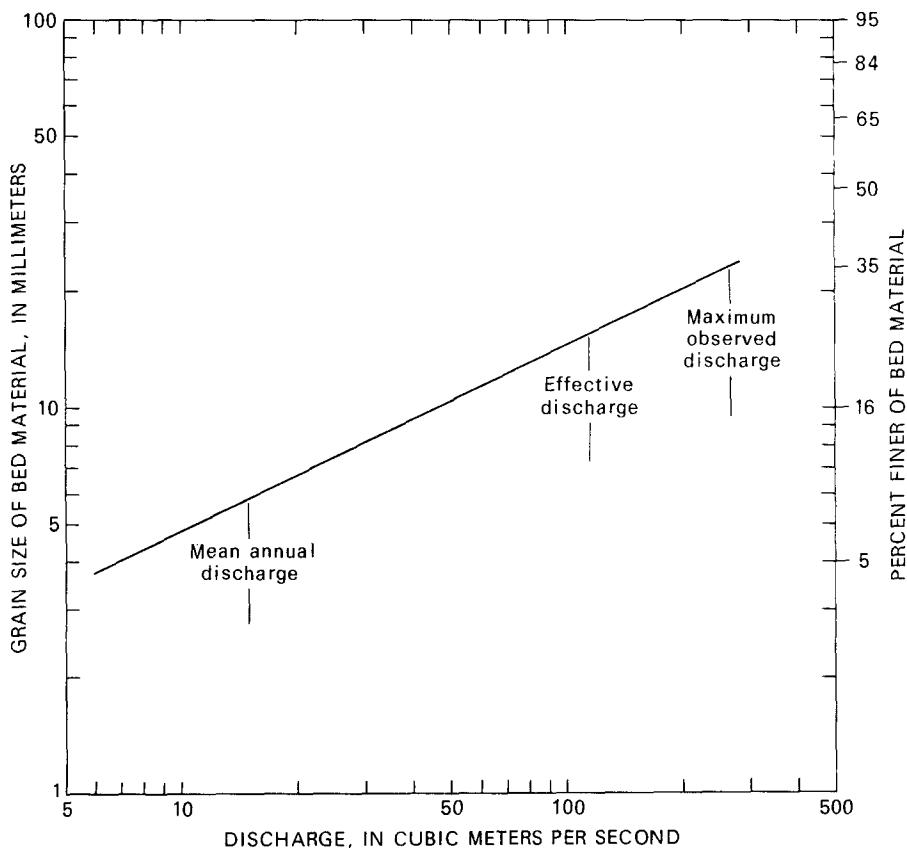

Fig. 9. Relation between discharge and the grain size of bed material at the threshold of transport at the Little Snake River near Dixon, Wyoming.

only uniform size of bed material to develop his relation. For bed material with a range of grain sizes, the smaller grains tend to be "hidden" behind the larger grains. Thus, for a given flow, the shear stress on the smaller particles of a poorly sorted mixture is less than it would be on a bed of uniform size grains. Consequently, a larger shear stress is necessary to initiate motion of the smaller grains in a mixture of bed-material than would be required in a bed of uniform grain size. Einstein (1950) developed a technique for estimating the reduction in forces on a particle that is part of a mixture of grain sizes. It was found that the reduction of force on a particle that is part of a mixture of grain sizes was approximately proportional to $(D/D_{65})^2$ for D less than D_{65}. For grain sizes larger than D_{65}, there is no apparent reduction of force due to the mixture. The relation between discharge and grain size of particles at the threshold of motion shown in Fig. 9 was constructed by modifying the Shields critical-shear—stress relation in accordance with the reduction of force.

No more than 35% of the bed material of the Little Snake River near Dixon is transported by even the largest recorded flood (Fig. 9). The maximum observed discharge at this site is 270 m³/s in 43 years of record, and has a recurrence interval of approximately 75 years. At the effective discharge, 113 m³/s, only the smallest 25% of the bed material is transported. The most significant feature, however, is that a small fraction of the bed material is transported by even moderate discharges. Thus, although the median-size bed material is very coarse, the threshold of bed-material transport is small, because some relatively fine bed material is available. To varying degrees, this circumstance is true for the eight stream channels studied which had predominantly coarse bed material. The threshold of bed-material transport occurs at relatively moderate discharges, even though the median diameter of bed material is very coarse and, in some instances, not even transported by extreme flood flows. As a result, the threshold of transport for some fraction of the bed material (the intercept of the sediment-transport curves, or curve A in Fig. 1) does not vary greatly between gaging stations even though there is considerable variation in the median bed-material size. This condition may explain the lack of correlation between the frequency of the effective discharge and the median bed-material size.

COMPARISON OF THE EFFECTIVE AND BANKFULL DISCHARGES

The probable significance of the effective discharge in forming channel features was recognized by Wolman and Leopold (1957), and Wolman and Miller (1960). They suggested that channel size and meander pattern were closely correlated to, and, hence, were the result of the effective discharge. In particular, they noted that the effective discharge might approximate the bankfull discharge — that is, the discharge that filled the channel to the level of the floodplain. Although this hypothesis has been considered by several studies, the results have generally been inconclusive, Harvey (1969) and Pickup and Warner (1976). Frequently, these investigations have been limited by the avail-

ability of data on sediment loads, lack of consistent and clearly defined channel features, or uncertainty whether the stream are in quasi-equilibrium.

In order to evaluate the geomorphic significance of the effective discharge, 3—5 cross-sections were surveyed in the vicinity of each gaging station. The cross-sections were located in a self-formed reach of channels with a well-developed floodplain, so that the bankfull discharge could be identified. The elevation of the floodplain was taken to be the level of the bankfull stage. Secondary geomorphic and botanic features were also noted to verify that the surface was, in fact, the floodplain rather than a terrace. These features include the top of point bars and the lower limit of vegetation. The floodplain elevations were plotted to give a longitudinal profile of the bankfull stage through the reach of channel including the gaging station. The bankfull discharge was then determined from the stage—discharge relation of the gaging station.

A typical cross-section of the Little Snake River near Dixon, Wyo., is shown in Fig. 10. The effective discharge and the bankfull discharge are nearly identical. The mean-annual discharge is about 12% of the bankfull and effective discharges. The close agreement between the effective and bankfull discharges indicates that the stream channel is adjusted to the range of discharges that transport the largest part of the annual sediment load.

Baker (1977) suggested that relatively rare floods may be the significant
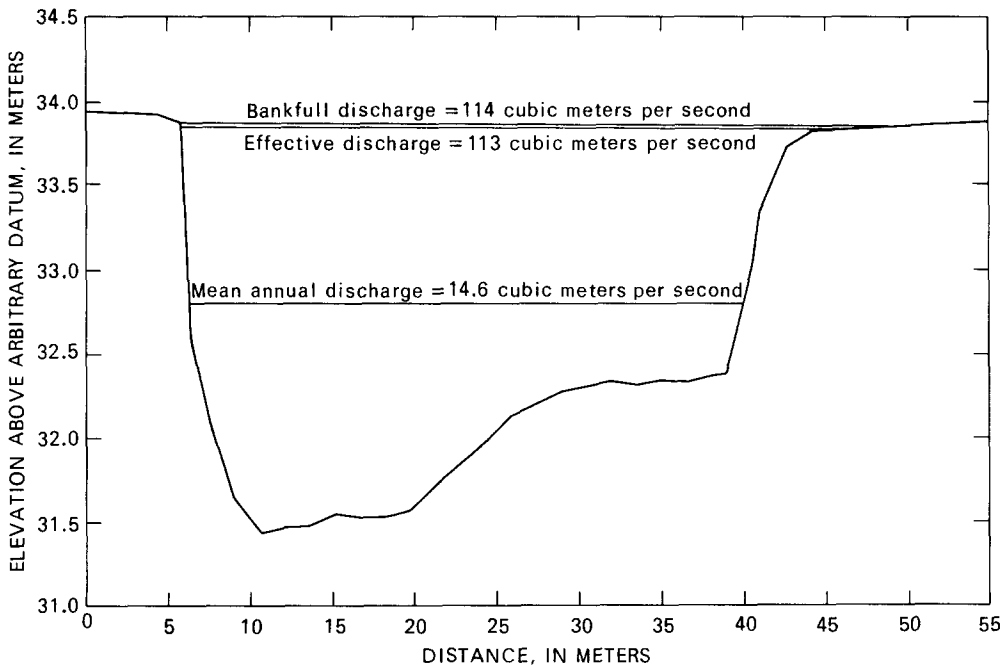

Fig. 10. Cross-sectional profile of the Little Snake River near Dixon, Wyoming, showing the elevation of the mean-annual, effective and bankfull discharges.

geomorphic events for streams in which the more frequent floods are insufficient to transport the available bed material. Although bed material in the Little Snake River near Dixon is very coarse, the less frequent floods do not appear to be geomorphically important. As noted above, the largest recorded flood in the Little Snake near Dixon occurred in 1920 and had a recurrence interval of approximately 75 years. It is unknown what immediate effects this flood had upon the stream channel. In any case, neither this flood nor previously unrecorded floods appear to have affected the bankfull stream channel as it was in 1977.

The effective and bankfull discharges of the 15 Yampa River basin gaging stations are listed in Table I, columns 7 and 9, and compared in Fig. 11. The
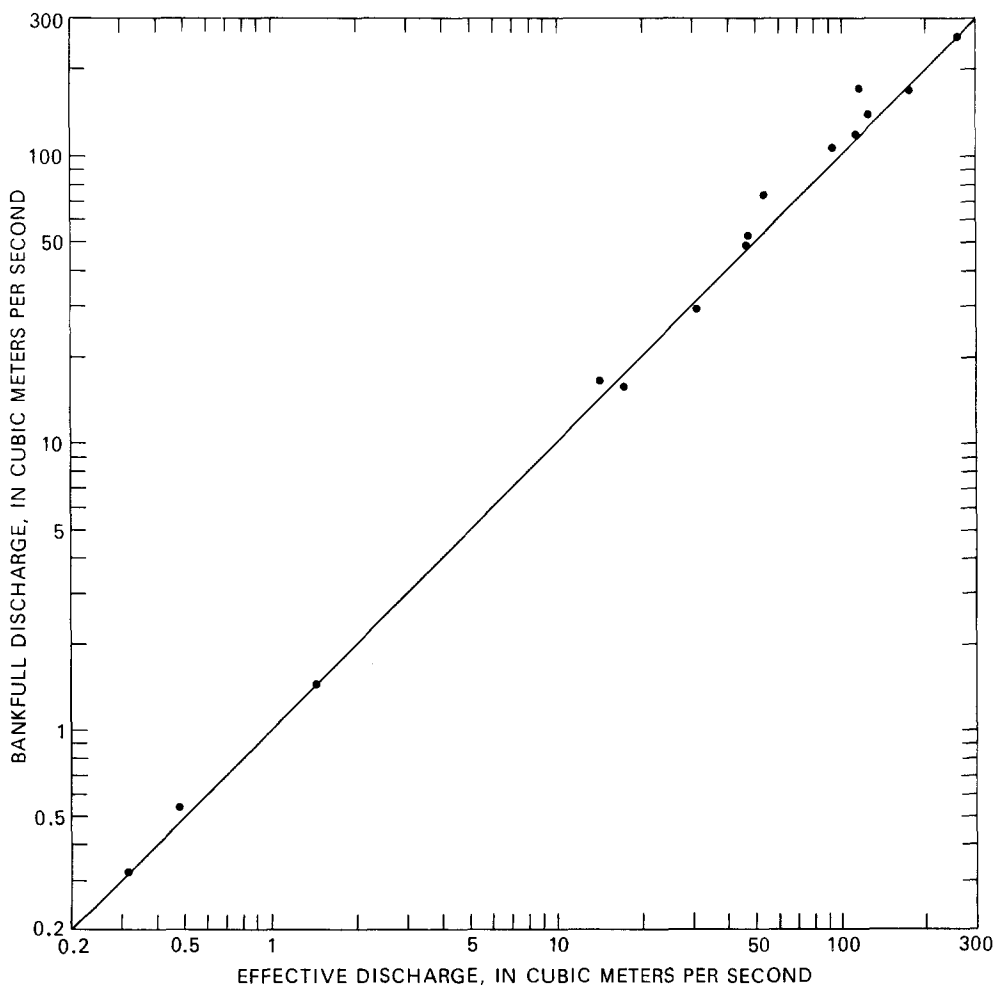

Fig. 11. Comparison of computed effective discharges with the observed bankfull discharges at 15 gaging stations.

agreement between the effective discharges and the bankfull discharges is excellent. The standard error is 14%. The effective and the bankfull discharges are nearly equal for all the streams studied in this investigation.

The close agreement shown in Fig, 11 appears to indicate that the stream channels studied are adjusted to their effective discharges, or more precisely, to the range of discharges that transport the vast majority of the sediment load of the stream over a period of years. The stream channels appear to be in quasi-equilibrium because floodplains have been constructed over a number of years. Consequently, there has been a balance between channel erosion and deposition. That is, the stream channels were formed and maintained as much by deposition as by erosion. Because a vast majority of the annual sediment load is transported by the range of discharges represented by the effective discharge, the stream channels studied may be said to be formed by and adjusted to the effective discharge.

Recurrence interval of the bankfull discharge

The recurrence interval of the bankfull discharge is of considerable practical significance. Not only is it the flow of incipient flooding but also, as shown above, the bankfull discharge corresponds to the effective or channel-forming discharge. Therefore, it is useful to determine the bankfull discharge in order to consider many hydrologic (Emmett, 1975) and geomorphic (Dury, 1973) questions. Determining the magnitude of the bankfull discharge, however, is not always possible and is, in fact, impossible when considering paleohydrology. These difficulties would be lessened if the bankfull discharge could be represented by a discharge with a constant-recurrence interval. Leopold et al. (1964) suggest that the bankfull discharge might be approximated by a discharge which has a recurrence interval of 1.5 yr. on an annual peak series. Dury (1973) used discharges with a 1.58-yr. recurrence interval.

The recurrence interval of bankfull discharges in stream channels of the Yampa River basin are shown in Fig. 12. Note that the recurrence intervals are given for both the annual series (bottom scale) and the partial duration series (top scale). The Yampa River basin data are compared with the distribution of 36 bankfull-discharge-recurrence intervals presented by Williams (1978). His data were collected entirely in the western U.S.A. from Texas to Alaska.

The two distributions are generally comparable, although the data presented by Williams (1978) included a significant number of observations with bankfull-recurrence intervals greater than 4 yr. The modal bankfull discharge in the Yampa River basin is between 1.18 and 1.40 yr., while that for Williams' data is about 1.5 yr. Both sets of observations, however, show that there is a large variance in the distribution of bankfull-discharge-recurrence intervals. Fifty percent of the streams in the Yampa River basin had bankfull discharge recurrence intervals greater than 1.75 yr. or less than 1.25 yr. Consequently, there does not appear to be a common frequency of occurrence for bankfull discharge.

RECURRENCE INTERVAL OF BANKFULL DISCHARGE, IN YEARS
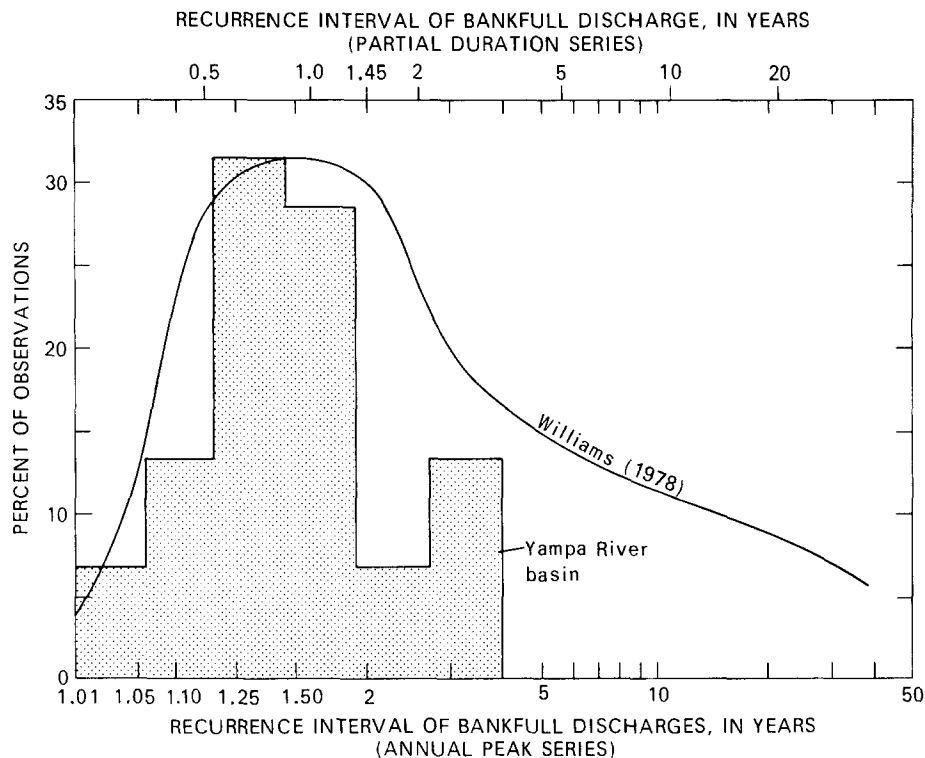(PARTIAL DURATION SERIES)

Fig. 12. Distribution of bankfull-discharge-recurrence intervals.

SUMMARY AND CONCLUSIONS

The effective discharge is defined as the increment of discharge that transports the largest fraction of the annual total sediment load over a period of years. The effective discharge was computed at 15 gaging stations in the Yampa River basin. As suggested by Wolman and Miller (1960), the effective discharge is a relatively frequent event. At the stations studied, the effective discharges were equaled or exceeded on the average between 1.5 days per year (0.4% of the time) and 11 days per year (3.0% of the time).

The variation in the duration of the effective discharge between stations is explained, in part (about 50%), by the skewness of the distribution of daily streamflows. As the size of the contributing drainage area decreases, the relative abundance of high flows or skew of the distribution of streamflows increases. As a result, the effective discharge becomes less frequent as drainage area decreases.

Conceptually, the duration of the effective discharge should also be influenced by the threshold of sediment transport. For the streams studied, however, there was no apparent correlation. In all streams, regardless of how coarse the median diameter of bed material, there was some relatively fine

material that was transported by moderate flood flows. Thus, the threshold discharge for transport for at least a fraction of the bed material was relatively small in all streams.

Cross-sections surveyed in self-formed reaches of the channel showed that the bankfull discharge was equivalent to the effective discharge. Thus, the bankfull stream channels studied in this investigation appeared to be adjusted to and formed by the effective discharges.

REFERENCES

Andrews, E.D., 1978. Present and potential sediment yields in the Yampa River basin, Colorado and Wyoming. U.S. Geol. Surv., Water-Resour. Invest. 78-105, 33 pp.

Baker, V.R., 1977. Stream-channel response to floods, with examples from central Texas. Geol. Soc. Am. Bull., 88: 1057—1071.

Dury, G.H., 1973. Magnitude—frequency analysis and channel morphometry. In: M. Morisawa (Editor), Fluvial geomorphology. N.Y. State Univ. Publ. Geomorphol., pp. 91—121.

Einstein, H.A., 1950. The bed-load function for sediment transportation in open channel flow. U.S. Dep. Agric., Tech. Bull. 1026, 70 pp.

Emmett, W.W., 1975. The channels and waters of the upper Salmon River area, Idaho. U.S. Geol. Surv., Prof. Pap. 870-A: 1—116.

Harvey, A.M., 1969. Channel capacity and the adjustment of streams to hydrologic regime. J. Hydrol., 8: 82—98.

Leopold, L.B., Wolman, M.G. and Miller, J.P., 1964. Fluvial Processes in Geomorphology. Freeman, San Francisco, Calif., 522 pp.

Meyer-Peter, E. and Mueller, R., 1948. Formulas for bed-load transport. Int. Assoc. Hydrol., Res., 2nd Congr. Proc. Stockholm, pp. 39—64.

Miller, C.R., 1951. Analysis of flow duration sediment rating curve method of computing sediment yields. U.S. Bur. Reclam., Washington, D.C., 55 pp.

Pickup, G. and Warner, R.F., 1976. Effects of hydrologic regime on magnitude and frequency of dominant discharge. J. Hydrol., 29: 51—75.

Shields, A., 1936. Application of similarity principles and turbulence research to bed-load movement. Mitt. Preuss. Versuchsanst. Wasserbau Schiffbau, Berlin. In: W.P. Ott and J.C. Uchelen (translators), W.M. Kech Laboratory of Hydraulics and Water Resources, Calif. Inst. Technol., Pasadena, Calif., Rep. No. 167.

White, W.R., Milli, H. and Crabbe, A.D., 1975. Sediment transport theories: a review. Proc. Inst. Civ. Eng., Part 2, pp. 265—292.

Williams, G.P., 1978. Bankfull discharge of rivers. Water Resour. Res., 14(6): 1141—1154.

Wolman, M.G. and Leopold, L.B., 1957. River flood plains — Some observation on their formation. U.S. Geol. Surv., Prof. Pap. 282—C: 87—109.

Wolman, M.G. and Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. J. Geol., 68: 54—74.