HYDRAULIC GEOMETRY AND STREAMFLOW OF CHANNELS IN THE PICEANCE BASIN, RIO BLANCO AND GARFIELD COUNTIES, COLORADO

By John G. Elliott and Kenn D. Cartier

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For additional information
write to:

District Chief
U.S. Geological Survey
Water Resources Division
Box 25046, Mail Stop 415
Denver Federal Center
Denver, CO 80225

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CONTENTS

FIGURES

TABLES

CONVERSION TABLE

Inch-pound units used in this report may be converted to International System of Units (SI) by using the following conversion factors:

Multiply inch-pound units	*By*	*To obtain metric units*
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

SYMBOLS

A_f = bankfull cross-sectional flow area, in square feet (ft^2)

$\bar{D}$ = mean bankfull depth, in feet (ft)

DA = drainage area in square miles (mi^2)

d_{50} = median grain size of bed material, in millimeters (mm)

E = mean basin elevation, in feet (ft)

L_c = main channel length, in miles (mi)

P = sinuosity in feet per feet (ft/ft)

P_a = mean annual precipitation, in millimeters (mm)

$\bar{Q}_A$ = mean annual discharge, in cubic feet per second (ft^3/s)

Q_B = bankfull discharge, in cubic feet per second (ft^3/s)

Q_{MF} = mean annual flood, in cubic feet per second (ft^3/s)

Q_{PF} = peak flood of record, in cubic feet per second (ft^3/s)

Q_2 = two-year flood, in cubic feet per second (ft^3/s)

Q_{10} = ten-year flood, in cubic feet per second (ft^3/s)

Q_{25} = twenty-five-year flood, in cubic feet per second (ft^3/s)

R = correlation coefficient

R^2 = coefficient of determination, adjusted for degrees of freedom

S = channel slope, in feet per feet (ft/ft)

SE = standard error of estimate, in percent

S_v = valley slope, in feet per feet (ft/ft)

W = bankfull channel width, in feet (ft)

$W/\bar{D}$ = channel width-to-depth ratio, in feet per feet (ft/ft)

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ABSTRACT

The influence of streamflow and basin characteristics on hydraulic geometry was investigated at 18 perennial and ephemeral stream reaches in the Piceance basin of northwestern Colorado. Results of stepwise multiple-regression analyses indicated that the variabilities of mean bankfull depth ($\bar{D}$) and bankfull cross-sectional flow area (A_f) were predominantly a function of bankfull discharge (Q_B) and that most of the variability in channel slope (S) could be explained by drainage area (DA). None of the independent variables selected for the study could account for a large part of the variability in bankfull channel width (W).

Another phase of the study investigated indirect methods of estimating discharge in the Piceance basin and revealed that 95 percent of the variance in bankfull discharge was explained by the bankfull cross-sectional flow area. When channel-geometry variables were excluded from the analysis, 74 percent of the variance in bankfull discharge could be explained by the drainage area. Drainage area also accounted for a large percentage of the variance in mean annual discharge ($\bar{Q}_A$) and the two-year flood (Q_2). No predictive equations could be derived from basin characteristics for discharges of greater magnitude and lesser frequency, such as the ten-year flood (Q_{10}) or the twenty-five-year flood (Q_{25}).

INTRODUCTION

Surface mining of coal and development of oil-shale resources in the Rocky Mountain region may extensively alter the terrain of many semiarid watersheds. As a result, the streamflow characteristics and sediment yield of many streams may be drastically altered. If the disturbance is slight, a stream soon may adjust its morphology to a different sediment load and discharge regime. However, extensive land-use changes resulting from mining operations may cause stream channels to go through a prolonged period of instability characterized by accelerated channel erosion or deposition, deteriorated water quality, and potentially increased frequency of flooding.

Surface disturbances are likely in semiarid northwestern Colorado, either directly from surface mining, or indirectly from surface storage of tailings and waste products. Production of coal in Colorado has risen steadily through the last decade; total coal production in 1981 was 19.7 million tons. Sixty-five percent of the State's coal was produced in the counties of Routt, Moffat, Rio Blanco, and Garfield, mostly by strip mining (Colorado Division of Mines, 1981). Oil-shale reserves in the Piceance basin have been estimated at over one trillion barrels. Although no commercial production of shale oil currently occurs in this region, full-scale production of this resource could involve extraction of several hundred thousand tons of ore per day. Tailings and spoils would be stored, at least temporarily, on the surface in nearby areas (Glenn Miller, U.S. Bureau of Land Management, oral commun., 1985).

Energy companies are required by law to reclaim surface-mined areas to the approximate premined contours so that gully and channel erosion are minimized. Reclamation of extensively disturbed drainage basins involves reconstruction of valley-side slopes, valley bottoms, and often the stream channels draining these areas. The dimensions of a stream channel are dependent on the geomorphic characteristics of a basin and on the precipitation-runoff regime. A properly designed drainage system in which there is minimal channel erosion or deposition will include these factors. Hydraulic-geometry relations which express channel dimensions as functions of discharge and basin characteristics provide a framework for understanding the variables that control stable channel morphology.

Purpose and Scope

The purpose of this study was: (1) To identify hydraulic-geometry relations characteristic of stable stream channels in northwestern Colorado, and (2) to present methods of estimating discharge at ungaged sites using channel and basin characteristics.

Geomorphic and hydrologic characteristics were documented for stream channels in the Piceance basin in northwestern Colorado. The study sites were located in the drainage basins of Piceance, Yellow, Roan, and Parachute Creeks; these basins are part of the Piceance Creek structural basin (fig. 1). The Piceance Creek structural basin is an area of downwarped Tertiary sediments in Rio Blanco and Garfield Counties, Colorado. Most bedrock outcrops are marlstones, shales, siltstones, and sandstones of the Uinta and Green River Formations (Tweto, 1979; Cashion, 1973). Composition of bed-material samples from streams in this region reflects local lithology. Elevations range from about 5,000 ft above sea level near the mouth of Parachute Creek to more than 8,000 ft in the Cathedral Bluffs area. The climate is semiarid, and the Piceance basin is similar geographically to much of the area in northwestern Colorado.

Acknowledgments

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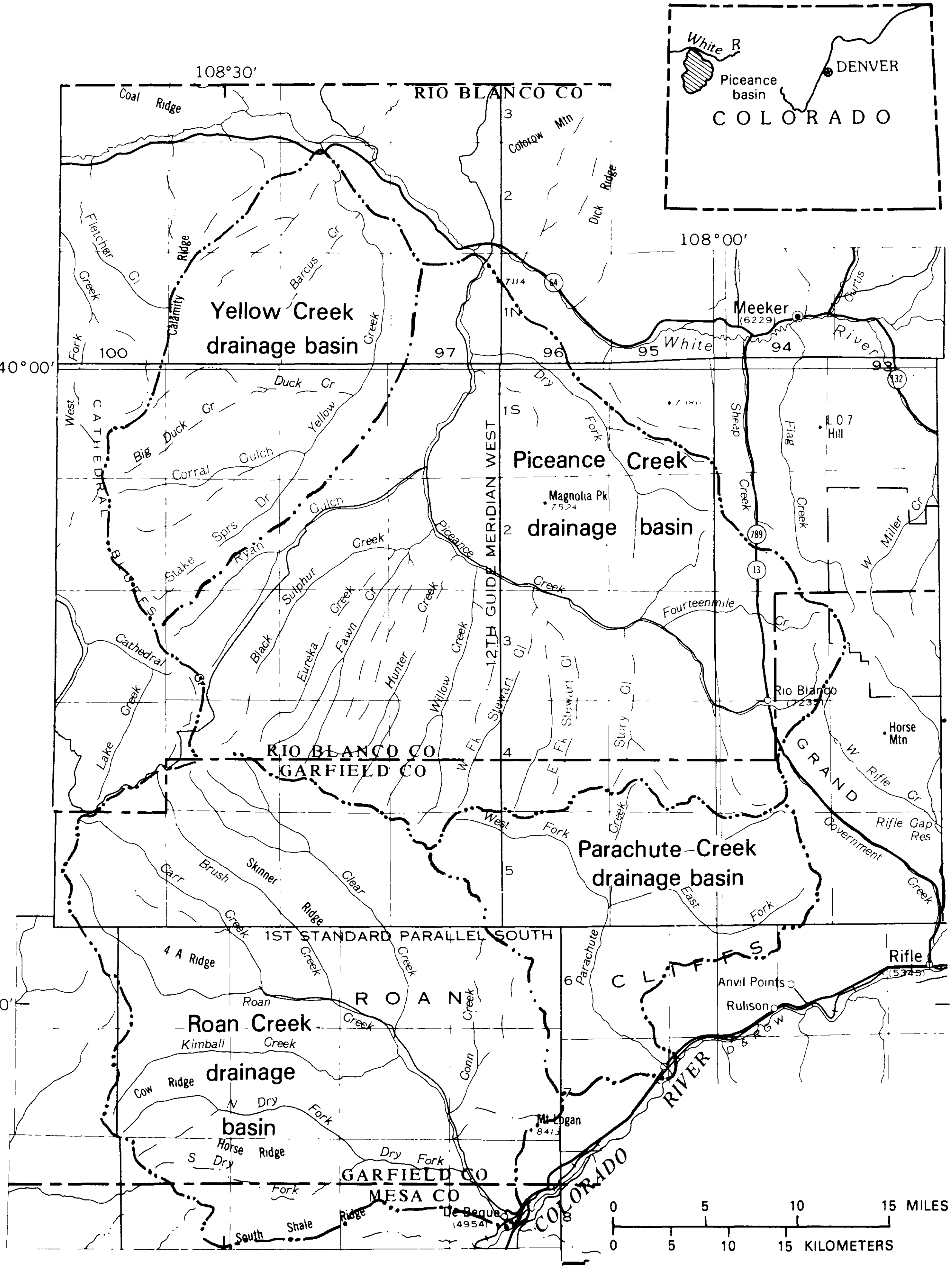

Figure 1.--Location of drainage basins and study sites.

STUDY APPROACH

This study documents the hydrologic and geomorphic character of relatively stable alluvial streams within the study area. Relatively stable streams are those in which, over a period of years, no progressive or rapid alteration of channel dimension, gradient, pattern, or shape occurs (Mackin, 1948; Schumm, 1977). Established hydraulic-geometry concepts were employed in an analysis of the independent variables considered to control alluvial channel form and stability.

Channel width, mean flow depth, channel cross-section area, and mean flow velocity of rivers vary as power functions of discharge (Leopold and Maddock, 1953). The relation of these channel-morphology variables to discharge is called hydraulic geometry. Hydraulic-geometry equations essentially describe both the channel morphology and the resistance to erosion associated with the character of the bed and banks (Leopold and others, 1964, p. 217). For example, in channels with cohesive banks, width changes little with increasing discharge, while greater adjustments occur in velocity and depth.

Equations in which channel-morphology variables are related to a range of discharges at a given river cross section are called at-a-station relations to differentiate them from similar equations that describe the way in which the variables change downstream as discharge increases by successive contributions of tributaries. Downstream hydraulic-geometry equations relate channel-morphology variables from cross sections at different locations to a standard streamflow characteristic, such as mean annual discharge, or to flows of a common return period. In this study, the standard streamflow characteristic was bankfull discharge, the discharge that just fills the channel to the top of its banks. Channel sections on main-stem streams and channel sections on tributaries were analyzed collectively in this study. Therefore, the resulting hydraulic-geometry equations are not precisely downstream relations; rather, they are composite equations representing basinwide trends in hydraulic geometry with increasing discharge.

In the first phase of the study, channel-morphology variables were described as a function of the bankfull discharge of streams in the Piceance basin by using least-squares regression analysis. The resulting hydraulic-geometry equations were of the form commonly found in the literature (for example, Leopold and Maddock, 1953). In the second phase of the study, channel-morphology variables were described as functions of sediment size, drainage basin characteristics, and discharge. The analyses in phase 2 attempted to identify additional independent variables that are significant in determining stable channel form. A multiple-regression technique was used in which the channel-morphology variables--bankfull channel width, mean bankfull depth, channel slope, and bankfull cross-sectional flow area--were each expressed as a function of the variables--drainage area, mean basin elevation, valley slope, main channel length, median grain size of bed material, mean annual precipitation, and bankfull discharge. In the resulting models, channel-morphology variables were explained by the best combination of discharge and basin-characteristic variables. These were generally the models in which R^2, the coefficient of determination, was maximized. R^2 values presented herein were adjusted for degrees of freedom (Draper and Smith, 1981) because of the small sample size. These models included only independent variables that explained a significant amount of variance in the channel-morphology variables.

Streamflow may be estimated from channel morphology (Hedman, Moore, and Livingston, 1972; Dury, 1976; Osterkamp and Hedman, 1979) or from basin characteristics (Kuiper, 1957; Leopold and others, 1964, p. 251; Black, 1972) when no discharge data are available. In the third phase of the study, indirect methods of estimating discharge were examined. Bankfull discharge was expressed as a function of channel morphology; and bankfull discharge, mean annual discharge, and the two-year flood were expressed as functions of basin characteristics.

Sources of Streamflow Data

More than 40 streams and tributaries in the Piceance basin are monitored for streamflow. Eighteen reaches at active streamflow-gaging stations have self-formed beds and banks and are only minimally affected by channel improvements; however, diversions for irrigation are moderate to great at some times of the year. These 18 study reaches are located in drainage basins whose areas range from 3.6 to 630 mi^2 and whose mean elevations range from 6,703 to 8,028 ft. Available data include daily mean discharges, peak discharges, and some water-quality information. When the data were collected in 1981, the period of record for 16 of these stations was less than 10 years.

Several of the studied streams had only a few days of significant discharge during the period of record; these were referred to as ephemeral streams. An ephemeral stream is one that flows only in direct response to precipitation (Langbein and Iseri, 1960) and may be defined as one in which discharge occurs on less than 10 percent of all days; that is, discharge occurs on fewer than an average of 36 days per year (Osterkamp and Hedman, 1979). Of the 18 study sites, 8 had daily mean discharges greater than 1 ft^3/s on less than 10 percent of all days; therefore, these 8 sites were classified as ephemeral-flow streams (table 1). The remaining 10 sites were perennial-flow streams, streams that flowed continuously. The ephemeral streams studied were located in drainage basins having areas less than 25 mi^2; whereas, the perennial streams studied were located in drainage basins having areas greater than 30 mi^2.

The most commonly cited discharge in hydraulic-geometry studies is the bankfull discharge. Bankfull discharge has been defined in several ways (Williams, 1978); generally bankfull discharge is the flow that fills the channel to the tops of the banks. The bankfull channel dimensions of streams in the Piceance basin were identified by a combination of topographic, sedimentologic, and vegetational features.

Bankfull stage at gaged sections was determined in the field by a survey of channel cross section. Bankfull discharge of perennial streams was identified from site-specific stage-discharge relations as the streamflow that

Table 1.--*Summary of discharge data for period of record through water year 1980*

[mi^2, square miles; ft^3/s, cubic feet per second; Per, perennial flow; Eph, ephemeral flow; *, gage established water year 1981; dashes indicate insufficient record]

Site number (shown on figure 1)	Station number	Station name	Flow type	Drainage area (DA) (mi^2)	Mean annual discharge ($\bar{Q}_A$) (ft^3/s)	Bankfull discharge (Q_B) (ft^3/s)	Mean annual flood (Q_{MF}) (ft^3/s)	Peak flood of record (Q_{PF}) (ft^3/s)	2-year flood (Q_2) (ft^3/s)	10-year flood (Q_{10}) (ft^3/s)	25-year flood (Q_{25}) (ft^3/s)	Period of record (year)
1	09093000	Parachute Creek near Grand Valley-----------	Per	141	21.4	170	434	2,310	280	976	1,490	17
2	09095400	Dry Fork near DeBeque-----------------------	Per	109	5.47	35.0	480	784	426	930	1,200	6
3	09306007	Piceance Creek below Rio Blanco-------------	Per	177	13.1	76.0	234	520	184	467	658	6
4	09306015	Middle Fork Stewart Gulch near Rio Blanco----	Eph	24.0	---	20.8	.64	3.2	---	---	---	3
5	09306022	Stewart Gulch above West Fork near Rio Blanco	Per	44.0	1.58	4.24	10.6	38	8.5	31.6	51.2	6
6	09306025	West Fork Stewart Gulch near Rio Blanco------	Eph	14.2	---	4.24	.74	1.5	---	---	---	5
7	09306028	West Fork Stewart Gulch at mouth, near Rio Blanco---------------------------------	Eph	15.7	---	4.24	7.06	38	---	---	---	6
8	09306036	Sorgum Gulch at mouth near Rio Blanco--------	Eph	3.58	---	.92	16.9	59	5.2	71.7	163	6
9	09306045	Piceance Creek below Gardenhire Gulch--------	Per	255	---	56.0	---	---	---	---	---	*
10	09306050	Scandard Gulch near Rio Blanco---------------	Eph	6.61	---	4.94	3.00	11	.7	30.8	98.2	4
11	09306052	Scandard Gulch at mouth near Rio Blanco------	Eph	7.95	---	1.48	3.04	6.0	3.1	6.3	7.8	4
12	09306058	Willow Creek near Rio Blanco-----------------	Per	48.3	2.00	24.0	9.53	23	9.6	20.9	27.2	6
13	09306175	Black Sulphur Creek near Rio Blanco----------	Per	103	6.86	22.2	36.4	72	30.4	77.7	105	5
14	09306222	Piceance Creek at White River----------------	Per	630	25.3	167	226	628	119	426	568	12
15	09306235	Corral Gulch below Water Gulch near Rangely--	Eph	8.57	.23	6.71	47.3	272	4.3	75.3	220	6
16	09306240	Box Elder Gulch near Rangely-----------------	Eph	9.19	.27	16.6	8.83	30	5.7	18.7	29.2	6
17	09306242	Corral Gulch near Rangely--------------------	Per	31.6	1.52	14.0	42.7	183	20.5	112	200	6
18	09306255	Yellow Creek near White River----------------	Per	262	1.85	43.0	1,100	6,800	270	2,500	5,680	8

filled the channel to the top of its banks. The stage-discharge relations of most ephemeral streams did not include discharge measurements at or above the bankfull stage, therefore bankfull discharge was estimated by using the Manning equation:

$$Q_B = \frac{1.49}{n} A_f R_h^{0.67} S^{0.50} ; \tag{1}$$

where Q_B = bankfull discharge (ft^3/s);
n = Manning's roughness coefficient, estimated during field data collection;
A_f = bankfull cross-sectional flow area (ft^2);
R_h = hydraulic radius, approximated by mean depth (ft); and
S = friction slope, approximated by channel slope.

The percentage of time bankfull discharge was equaled or exceeded was determined for perennial streams in the Piceance basin study area by using individual station flow-duration curves based on recorded daily mean discharges. Values for perennial streams ranged from 0.1 to 3.0 percent and had a mean of 1.1 percent. The percentage of time bankfull discharge was equaled or exceeded could not be determined for ephemeral streams in the Piceance basin. Discharges comparable to the magnitude of estimated bankfull discharges rarely appeared in the short records of these tributaries. Absence of observed discharges in this range suggests that the channel-forming discharge of ephemeral streams occurs very infrequently; also, discharge that fills an ephemeral channel to the bankfull level may be of such short duration (a few hours) that its significance is obscured by the daily (24-hr) mean discharge used in the flow-duration computation.

Sources of Geomorphic and Sediment-Size Data

Basin characteristics, channel morphology, and sediment-size data were collected in 1981 for 18 stream reaches. Bankfull channel dimensions were surveyed in the field. Bankfull channels of several perennial streams were determined from the elevation of an active flood plain. Where an active flood plain was not present, the highest surface of point bars or the upper limit of fresh sand-sized particles on channel margins was used to determine bankfull stage. Identifying the bankfull channels of ephemeral streams was very difficult at some sites. In reaches where the bed and bank material was noncohesive, recent runoff had greatly influenced channel features. Berms and terraces along many of the ephemeral channels probably resulted from major floods and past periods of arroyo cutting. The bankfull channel dimensions of most ephemeral streams were defined by topography and a change in vegetation type from grass to other perennial species.

Bankfull channel width (W), mean bankfull depth ($\bar{D}$), bankfull cross-sectional flow area (A_f), and channel width-to-depth ratio ($W/\bar{D}$) were determined from the channel surveys. Channel slope (S) was surveyed over a length of the stream roughly equal to 15 to 20 channel widths. Median grain size of bed material (d_{50}) at each site was determined from a sieved bed-material sample. Additional basin and channel characteristics were determined from U.S. Geological Survey topographic maps. Drainage area (DA) was measured with a planimeter, valley slope (S_v) was determined from the change in elevation along the valley axis, main channel length (L_c) was the distance from headwater divide to basin mouth along the path of the major channel, sinuosity (P) was the ratio of stream channel length to valley length, and mean basin elevation (E) was determined as the average of numerous elevations measured at regular intervals on a grid. Mean annual precipitation (P_a) was determined from data published by the Colorado Climate Center (1984). Although mean flow velocity commonly is presented as a dependent variable in hydraulic-geometry studies, it is not included in this report. Bankfull-flow conditions were not observed in the study area, and thus no measurements of flow velocity could be made. A summary of basin and channel characteristics for the Piceance basin streams is presented in table 2.

Table 2.--*Summary of basin and channel characteristics*

[mi^2, square miles; ft, feet; ft/ft, feet per feet; mi, miles; mm, millimeters; ft^3/s, cubic feet per second; ft^2, square feet]

Site number (shown on figure 1)	Drainage area (DA) (mi^2)	Mean basin elevation (E) (ft)	Valley slope (S_v) (ft/ft)	Main channel length (L_c) (mi)	Median grain size of bed material (d_{50}) (mm)	Mean annual precipitation (P_a) (mm)	Bankfull discharge (Q_B) (ft^3/s)	Bankfull channel width (W) (ft)	Mean bankfull depth ($\bar{D}$) (ft)	Channel slope (S) (ft/ft)	Bankfull cross-sectional flow area (A_f) (ft^2)	Channel width-to-depth ratio ($W/\bar{D}$) (ft/ft)	Sinuosity (P) (ft/ft)
1	141	8,028	0.0106	12.4	8.67	572	170	38.0	1.24	0.0074	47.0	30.5	1.15
2	109	6,909	.0133	20.4	10.2	442	35.0	16.0	.67	.0069	10.7	24.4	1.46
3	177	7,326	.0064	25.2	3.99	607	76.0	16.8	1.58	.0024	26.6	10.7	1.10
4	24.0	7,566	.0132	10.8	.58	559	20.8	10.0	.72	.0116	7.2	13.6	1.03
5	44.0	7,484	.0167	13.4	1.92	559	4.24	4.1	.72	.0085	3.0	5.68	1.06
6	14.2	7,710	.0223	10.0	.87	544	4.24	10.0	.22	.0198	2.2	33.3	1.08
7	15.7	7,621	.0188	11.0	.95	544	4.24	11.0	.21	.0191	2.3	37.8	1.07
8	3.58	6,946	.0388	4.60	1.40	457	.92	9.4	.09	.0195	.83	107	1.13
9	255	7,536	.0046	28.1	3.66	577	56.0	16.9	2.15	.0049	36.4	7.80	1.28
10	6.61	7,234	.0226	5.70	.96	483	4.94	6.3	.29	.0196	1.8	21.6	1.07
11	7.95	7,165	.0272	7.40	.53	483	1.48	10.1	.13	.0168	1.3	77.5	1.07
12	48.3	7,530	.0162	15.0	2.15	560	24.0	10.1	.91	.0049	9.2	11.0	1.10
13	103	7,241	.0129	20.7	2.11	553	22.2	15.8	.79	.0006	12.5	20.1	1.32
14	630	7,208	.0053	57.0	7.48	521	167	16.7	2.32	.0024	38.0	7.20	1.36
15	8.57	7,756	.0272	3.98	2.91	521	6.71	4.8	.46	.0254	2.2	10.7	1.10
16	9.19	7,513	.0185	6.53	6.41	521	16.6	6.5	.85	.0157	5.5	7.69	1.08
17	31.6	7,323	.0155	8.39	3.20	533	14.0	9.6	.49	.0089	4.7	19.5	1.09
18	262	6,703	.0094	30.0	5.63	438	43.0	14.6	1.09	.0081	15.9	13.5	1.27

Preliminary analyses of the basin and channel characteristics involved computation of correlation coefficients (table 3); several basin-characteristic variables exhibited a significant amount of interrelation. *DA* and L_c were highly correlated (R=0.97), as were E and P_a (R=0.73). To avoid computational problems, basin characteristics exhibiting a high degree of interrelation were not grouped together as independent variables in subsequent multiple-regression analyses.

DATA ANALYSES

Discharge-Equated Hydraulic Geometry

Leopold and Maddock (1953) state that a river system tends to develop in a manner that produces approximate equilibrium between the stream channel and the water and sediment that it transports. They describe channel morphology as a power function of water discharge. Hydraulic-geometry equations were calculated from data collected on main-stem streams and tributaries in the Piceance basin. The dependent channel-morphology variables W, $\bar{D}$, S, and A_f were expressed as power functions of Q_B (table 4). Data points for perennial and ephemeral streams and regression curves were plotted in figures 2, 3, 4, and 5.

Table 3.--*Matrix of correlation coefficients for basin and channel characteristics*

[*DA*, drainage area, in square miles; *E*, mean basin elevation, in feet; S_v, valley slope, in feet per feet; L_c, main channel length, in miles; d_{50}, median grain size of bed material, in millimeters; P_a, mean annual precipitation, in millimeters; Q_B, bankfull discharge, in cubic feet per second; *W*, bankfull channel width, in feet; $\bar{D}$, mean bankfull depth, in feet; *S*, channel slope, in feet per feet; A_f, bankfull cross-sectional flow area, in square feet; $W/\bar{D}$, channel width-to-depth ratio, in feet per feet; *P*, sinuosity, in feet per feet; numeric value is correlation coefficient (*R*); absolute values greater than 0.47 are significantly different from zero at the 95-percent level; sample size is 18]

	DA	*E*	S_v	L_c	d_{50}	P_a	Q_B	*W*	$\bar{D}$	*S*	A_f	$W/\bar{D}$	*P*
DA	1.00												
E	-.23	1.00											
S_v	-.66	-.06	1.00										
L_c	.97	-.30	-.72	1.00									
d_{50}	.53	-.12	-.50	.48	1.00								
P_a	.03	.73	-.44	.06	-.18	1.00							
Q_B	.77	.18	-.62	.68	.67	.26	1.00						
W	.41	.21	-.50	.35	.59	.23	.81	1.00					
$\bar{D}$	.85	.04	-.82	.84	.52	.39	.76	.48	1.00				
S	-.60	.19	.81	-.69	-.43	-.35	-.55	-.50	-.72	1.00			
A_f	.74	.20	-.73	.67	.61	.38	.93	.84	.86	-.64	1.00		
$W/\bar{D}$	-.33	-.27	.74	-.38	-.30	-.40	-.25	-.02	-.55	.43	-.31	1.00	
P	.64	-.48	-.46	.68	.67	-.33	.42	.39	.50	-.55	.47	-.16	1.00

Table 4.--*Hydraulic-geometry equations from least-squares regression analysis*

[n, sample size; R^2, coefficient of determination, adjusted for degrees of freedom; SE, standard error of estimate, in percent; W, bankfull channel width, in feet; $\bar{D}$, mean bankfull depth, in feet; S, channel slope, in feet per feet; A_f, bankfull cross-sectional flow area, in square feet; and Q_B, bankfull discharge, in cubic feet per second]

Equation	n	R^2	SE	
$W = 5.72\ Q_B^{0.24}$	18	0.44	41	(2)
$\bar{D} = 0.13\ Q_B^{0.57}$	18	0.84	38	(3)
$S = 0.027\ Q_B^{-0.38}$	17	0.60	49	(4)
$A_f = 0.72\ Q_B^{0.81}$	18	0.95	29	(5)

Large R^2 values in table 4 suggest that Q_B may be a reasonably good estimator of $\bar{D}$ and A_f for Piceance basin channels. The variance of S was marginally explained by Q_B, because channel slope is influenced more by basin characteristics than by hydraulic factors. Q_B was inadequate in explaining the variance of W, reflecting a large degree of variability in the data (illustrated in fig. 2). Some of this variability may be attributable to inaccuracy in estimating bankfull dimensions in ephemeral channels, or because the variability of ephemeral channel width in the Piceance basin was controlled by factors such as flood flows, local vegetation, bank erodibility, valley slope, or the amount of sediment stored in the channel. Ephemeral streams in the Piceance basin generally were associated with smaller drainage basins that tended to have steeper valley slopes. Schumm (1977) reports that, as valley slopes become increasingly steep in some smaller ephemeral-flow watersheds, streams have wider, shallower, or nearly braided channels that are an adjustment to steeper gradients. In a study of gravel streams, Chang (1979) found a greater $W/\bar{D}$ ratio on increasingly steep slopes. The relations among channel morphology, streamflow characteristics, and drainage-basin size and slope may be significant in ephemeral streams in the Piceance basin, but additional analysis of data is necessary to confirm this.

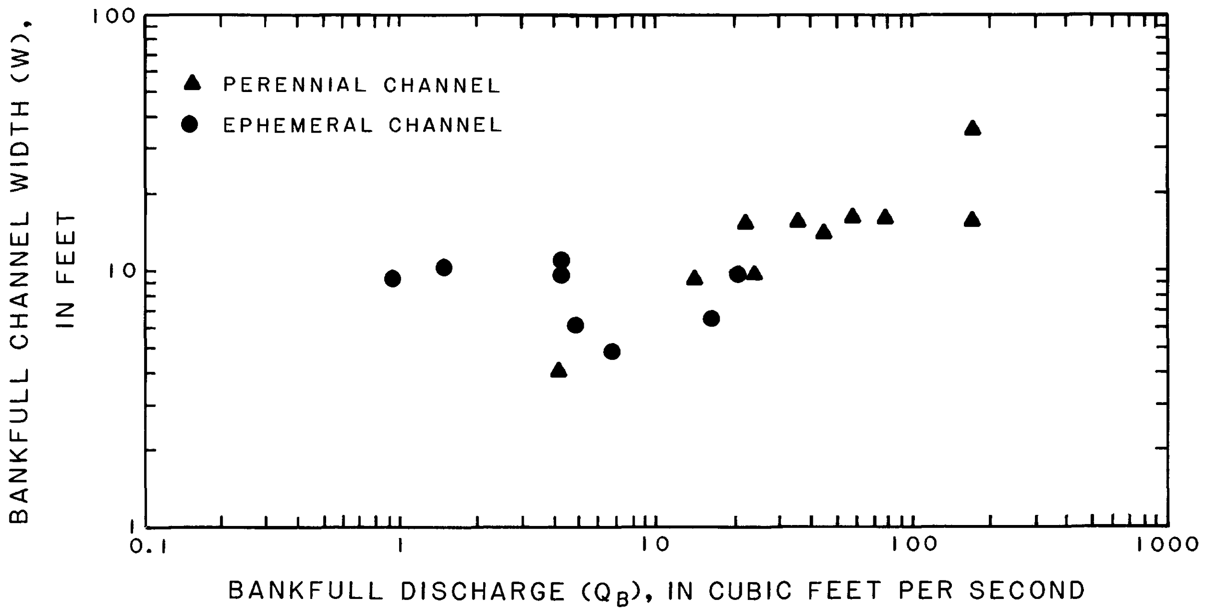

Figure 2.--Bankfull channel width as a function of bankfull discharge.

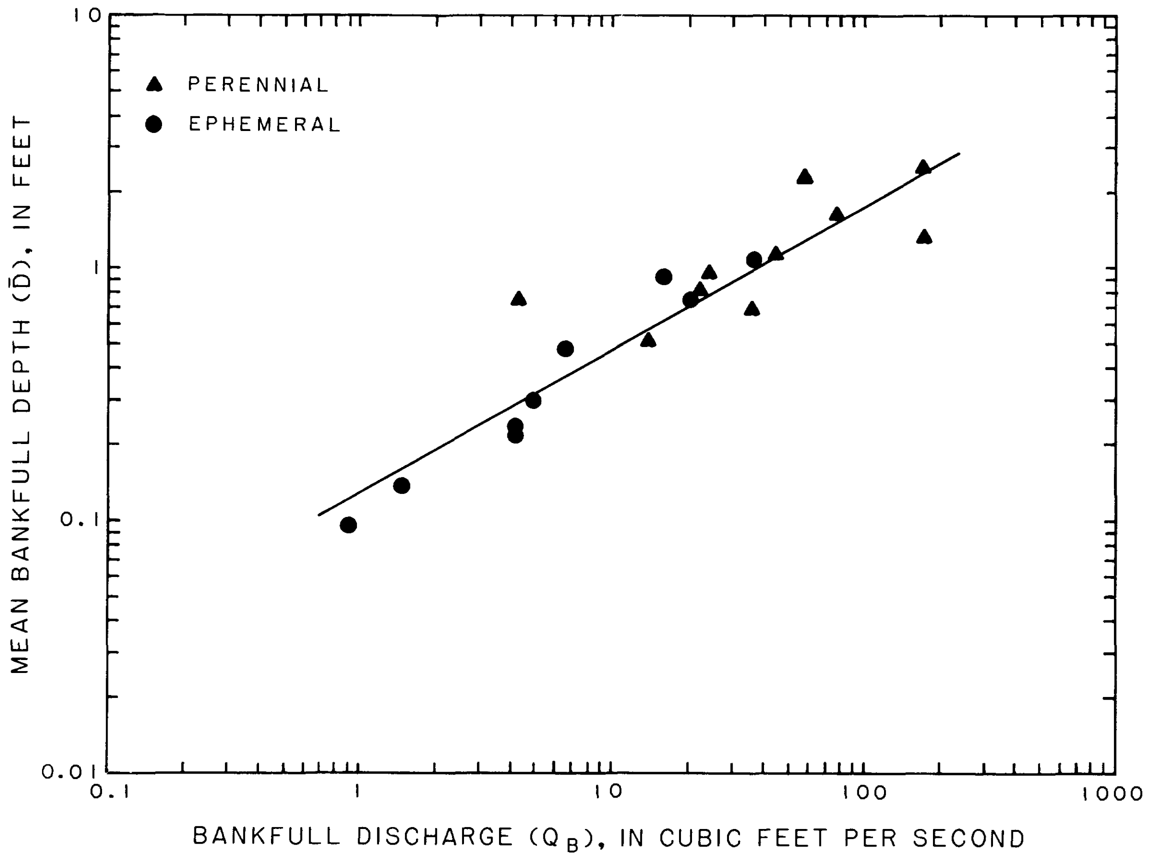

Figure 3.--Mean bankfull depth as a function of bankfull discharge.

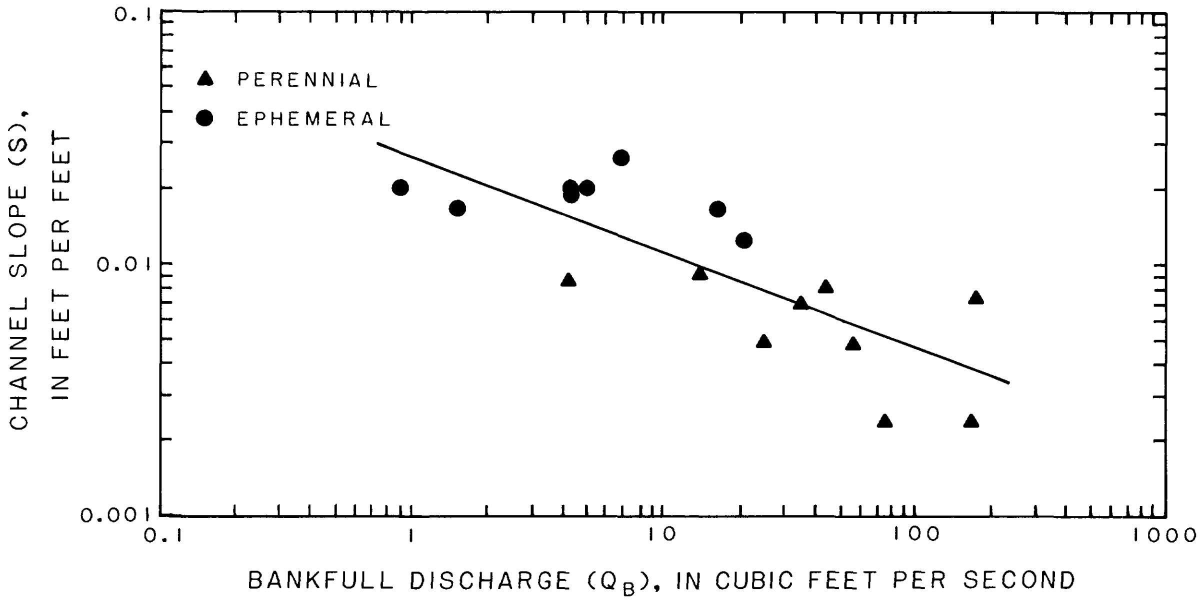

Figure 4.--Channel slope as a function of bankfull discharge.

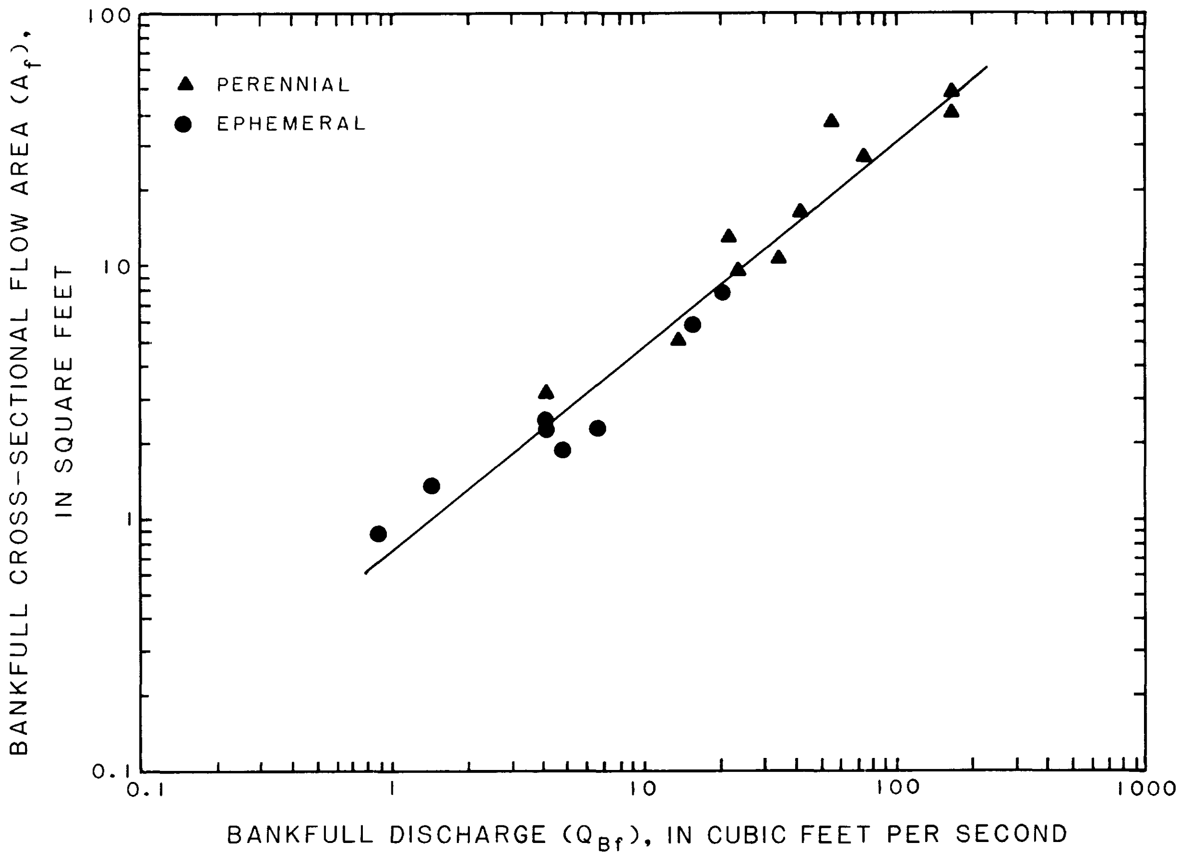

Figure 5.--Bankfull cross-sectional flow area as a function of bankfull discharge.

The nature of streamflow may considerably influence the processes that determine channel morphology in the Piceance basin. Wolman and Miller (1960) state that the variability of streamflow is inversely proportional to drainage area, and that, in smaller drainage basins, more geomorphic work is accomplished by less frequent streamflows. In emphemeral streams, here associated with smaller drainage areas, streamflows of broadly varying magnitude and frequency may abruptly alter an existing channel morphology. A channel morphology, continuously adjusting to long-term changes in the flow regime, is observed in perennial streams, whereas a transient response to a wide range of streamflows of varying intensity is characteristic of ephemeral streams (Thornes, 1977). It follows that ephemeral-channel morphology may reflect larger or more recent streamflows, while perennial channel morphology is conditioned, in the long run, by a series of integrated streamflows.

Visual inspection of channel morphology and flow-duration trends of Piceance basin streams also suggest differences between perennial and ephemeral streams. Consequently, the Piceance basin data set was subdivided on the basis of flow type, and hydraulic-geometry equations were recomputed for perennial streams and for ephemeral streams. An analysis of covariance was performed on the slope (exponent) and intercept (coefficient) of the subgroup-regression equations to test for significant differences between the hydraulic-geometry equations of perennial and ephemeral streams. The analysis of covariance indicated some differences between perennial and ephemeral hydraulic geometry equations at the 95-percent level; but, because the sample size of subgroup-regression equations was very small, results of these analyses are unreliable, and they are not included in this report. Separate analyses of data from perennial and ephemeral streams may be desirable in future studies if a larger data set is available.

Multiple-Regression Analyses

Leopold and Wolman (1957) stated that flow velocity and channel depth adjust to a discharge-dependent width and to a slope that is more or less predetermined, thus implying that basin characteristics are important in some aspects of channel morphology. The variability of streamflow, sediment size and rate of sediment transport, basin characteristics, and climate probably all affect channel morphology. Low R^2 values from equations 2 and 4 in table 4 suggested that Piceance basin channel morphology was not solely dependent on Q_B and legitimized an attempt to develop additional hydraulic-geometry equations that explained more variance of the dependent channel-morphology variables. Sediment size and basin-characteristic variables were included with Q_B as independent variables in stepwise multiple-regression analyses. All stepwise multiple-regression models of channel-morphology variables were determined by a maximum R^2 improvement procedure (Statistical Analysis System, 1979) in the analyses that follow. In these analyses, the best one, two, or more independent variable models were computed, but only those models were considered whose variables were significant at the 95-percent level. Therefore, it was possible to attain the "best" model for a channel-morphology variable with one or multiple independent variables. When more than one independent variable was significant, the stepwise procedure included them in order of decreasing significance.

The dependent channel-morphology variables--W, $\bar{D}$, S, A_f--were related to several "independent" variables describing basin and sediment characteristics, as well as streamflow. Those variables were DA, E, d_{50}, P_a, and Q_B. S_v and L_c were not included in the analyses because of their high correlation with other variables (table 3). In the resulting models, channel-morphology variables were explained by the best individual, or combination of, independent variables. If an original univariate hydraulic-geometry equation had a low R^2 value or a high SE value (table 4), Q_B could be replaced or supplemented with one or more other independent variables that explained more of the variance of the channel-morphology variable.

Stepwise multiple-regression analyses indicated that Q_B was the only significant variable in explaining the variance of Piceance basin channel W and $\bar{D}$. No other variable isolated in this study contributed significantly to explaining the variance of W and $\bar{D}$, when included in the analyses. DA and Q_B

were both significant in the equation for A_f, but the addition of DA to equation 5 improved R^2 minimally. It can be assumed that the contribution of DA in explaining the variance of A_f was negligible. Therefore, the hydraulic-geometry relations represented by equations 3 and 5 in table 4 appear to be the best available for channels in the Piceance basin. A satisfactory hydraulic-geometry equation for W could not be derived with available data, as previously discussed.

DA replaced Q_B in the equation for S as shown by:

$$S = 0.044\ DA^{-0.42}\ ; \tag{6}$$

where R^2 = 0.76; SE = 37 percent; and n = 17. When included in the group of "independent" variables, DA was the only significant variable, and it accounted for 76 percent of the variance in S. A plot of channel slope and drainage area is presented in figure 6.

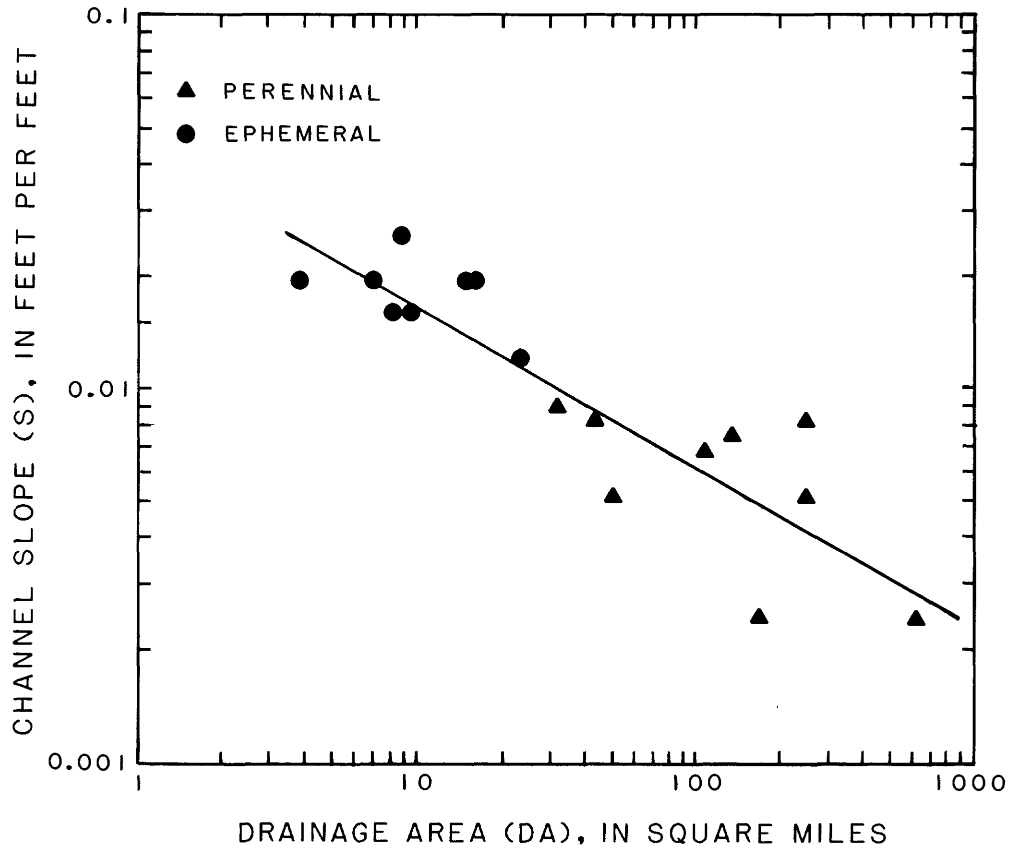

Figure 6.--Channel slope as a function of drainage area.

Entering additional independent variables in stepwise multiple-regression equations did not improve the explanation of variance of W, $\bar{D}$, and A_f beyond that accounted for in traditional discharge-equated hydraulic-geometry analyses (table 4). R^2 was improved and SE was reduced for the slope equation when another independent variable was added, replacing Q_B (eq. 4 and 6). The slope of channels in the study area is predominantly a function of DA, but the importance of Q_B in determining stream-channel cross-sectional morphology is indicated by its occurrence as the only significant variable in equations 2, 3, and 5.

Derivation of equations for width-to-depth ratio and sinuosity was not attempted in these analyses. The variance in sinuosity was poorly accounted for by Q_B, or basin characteristics, as indicated by low R^2 values. The $W/\bar{D}$ ratio also failed to exhibit a strong dependence on Q_B, although it was significantly correlated with S_v (table 3). Schumm (1960, 1963) studied channel width-to-depth ratio ($W/\bar{D}$) and sinuosity (P) of streams in the Great Plains and concluded that both are highly dependent on the percentage of silt and clay in the channel bed and banks. Schumm's index of sediment type was not determined for Piceance basin streams. No relation could be detected in the Piceance basin between $W/\bar{D}$ and bed material d_{50}, nor between $W/\bar{D}$ and the percent of bed material finer than 0.063 millimeters (mm), the conventional division between fine sand and silt.

Estimating Discharge at Ungaged Sites

Information concerning streamflow characteristics is essential to land-use planning and reclamation. When adequate discharge records are not available, discharge estimation techniques can be used. Dury (1976) derived predictive equations for the "most probable annual flood" in humid region streams, using channel width, cross-sectional flow area, channel slope, mean velocity, and meander wavelength. Hedman, Moore, and Livingston (1972) found channel width and mean depth to be important variables in predicting mean annual runoff and peak discharges in Colorado mountain streams.

Bankfull discharge of Piceance basin streams was related to channel-morphology variables and sediment size in a stepwise multiple-regression analysis. Of six possible variables, only A_f was significantly related to Q_B, but it accounted for 95 percent of the variance of Q_B. The relation between these variables is described by the equation:

$$Q_B = 1.67\ A_f^{1.18}\ ; \tag{7}$$

where $R^2 = 0.95$; $SE = 35$ percent; and $n = 18$. Q_B for streams in the Piceance basin may be estimated with reasonable accuracy using equation 7, if bankfull cross-sectional flow area is known.

If no channel-morphology data are available, discharge can be estimated from drainage-basin variables. Discharge has been related to drainage-basin characteristics with varying degrees of success (Carlston, 1963; Livingston, 1970; Black, 1972; Emmett, 1975). In this study of the Piceance basin, an attempt was made to relate discharge characteristics to basin characteristics. Discharge characteristics--Q_B, bankfull discharge; $\bar{Q}_A$, mean annual discharge; Q_{MF}, mean annual flood; Q_{PF}, peak flood of record; Q_2, two-year flood; Q_{10}, 10-year flood; and Q_{25}, 25-year flood--were regressed against several basin characteristics. DA was the most significant individual independent variable in explaining variance in discharge characteristics; but adequate equations (with a high R^2) could be derived for only a few discharge characteristics.

Q_B for the 18 study sites correlated well with drainage area. A least-squares regression of all stream channels resulted in the equation:

$$Q_B = 0.62\ DA^{0.87}\ ; \tag{8}$$

where $R^2 = 0.74$, and $SE = 87$ percent. A similar analysis of mean annual discharge data produced the equation:

$$\bar{Q}_A = 0.034\ DA^{1.05}\ ; \tag{9}$$

where R^2 = 0.74, and SE = 94 percent. Discharge records were sufficient to compute $\bar{Q}_A$ for only two of the ephemeral streams and nine of the perennial streams (table 1); as a result, equation 9 was computed from a total sample size of 11. The discharge of two-year recurrence interval, or the two-year flood (Q_2), was regressed against DA. Drainage area accounted for 72 percent of the variance in this discharge characteristic and is represented by the equation:

$$Q_2 = 0.39\ DA^{1.09}\ ; \tag{10}$$

where R^2 = 0.72, SE = 144 percent; and n = 14. Data used to derive equations 8, 9, and 10 are plotted in figures 7, 8, and 9.

Discharges of greater magnitude and less frequent occurrence also were regressed against drainage area. Although Kuiper (1957) found that peak run-off per unit area decreased with basin size, neither the mean annual flood (Q_{MF}), defined as the average of yearly peak discharges, nor the peak flood of record (Q_{PF}) from streams in the Piceance basin could be related to drainage area with a high coefficient of determination. DA was the only significant variable in explaining variance in Q_{10} and Q_{25}; however, R^2 values for the regression equations were low.

Failure to define predictive equations for higher discharges and flood flows in the Piceance basin is due in part to the poor definition of these flow characteristics derived from short records (table 1) and to the variable nature of rainfall and peak discharge in the region. Equations successfully relating lower discharges, Q_B, $\bar{Q}_A$ and Q_2, to channel and drainage-basin characteristics may be used to estimate discharge characteristics of other streams in the Piceance basin. These relations are not usable as predictive equations for streams outside the Piceance basin area until their validity has been proven for a wider range of conditions. Also, these relations are not applicable in areas where surface disturbances have altered rainfall-runoff relations.

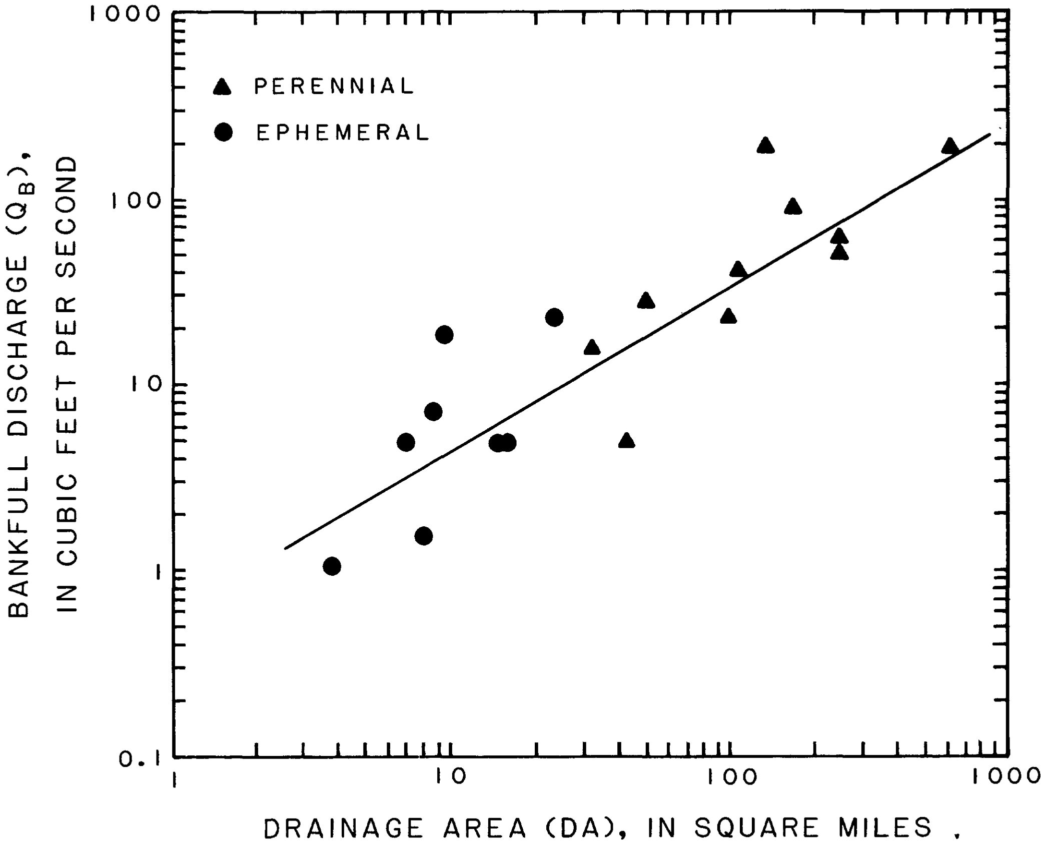

Figure 7.--Bankfull discharge as a function of drainage area.

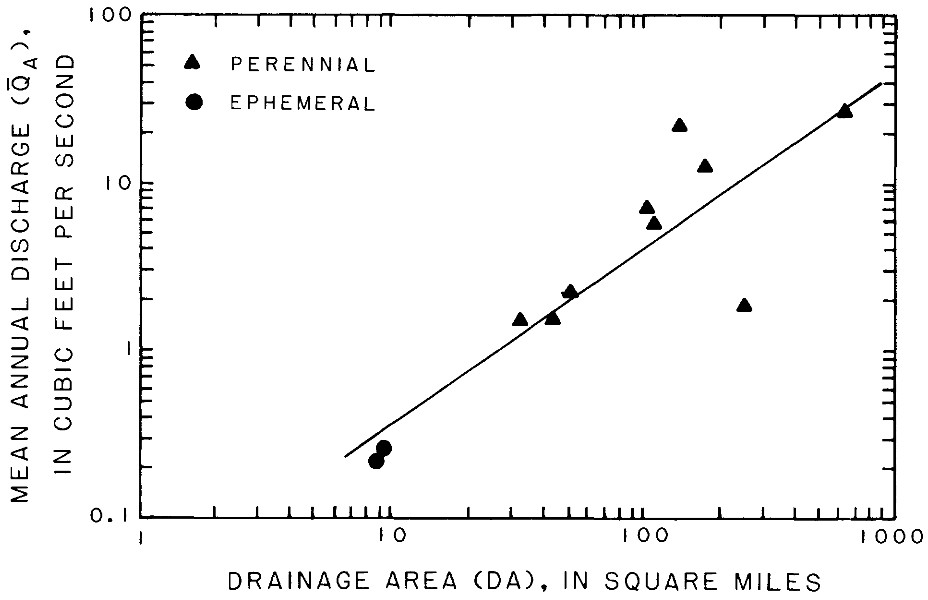

Figure 8.--Mean annual discharge as a function of drainage area.

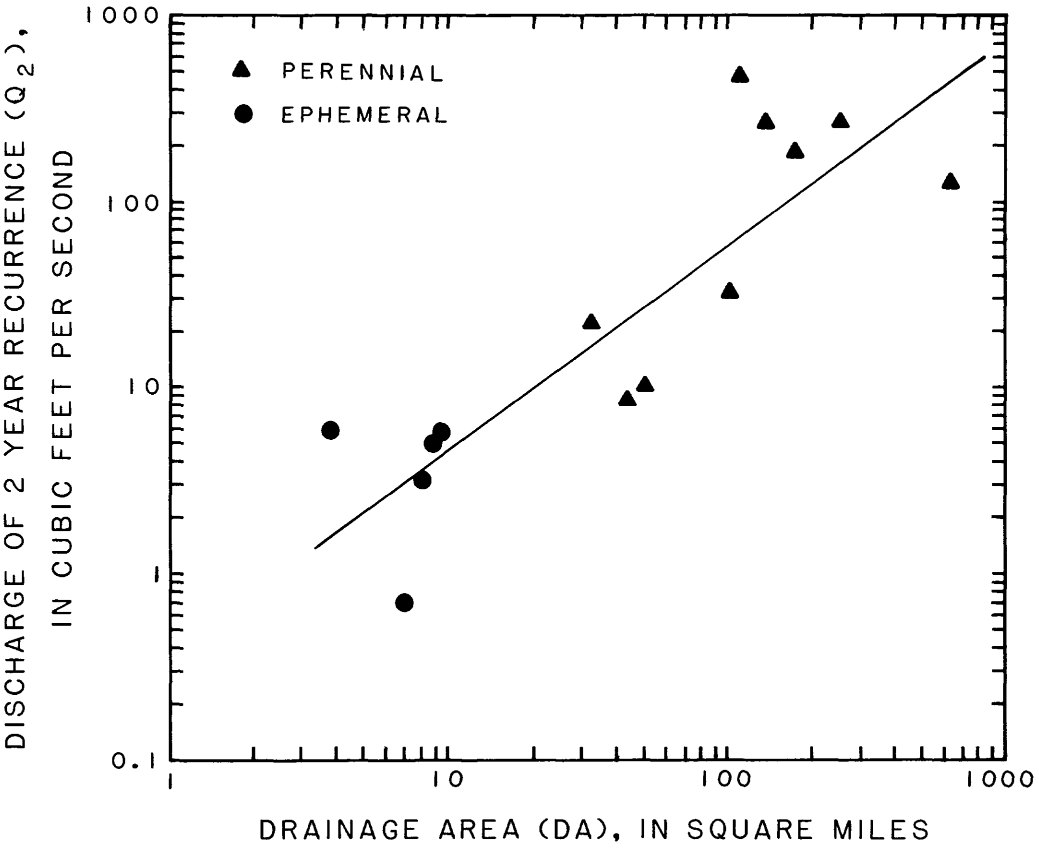

Figure 9.--Two-year flood as a function of drainage area.

SUMMARY AND CONCLUSIONS

This study documented the geomorphic and hydrologic character of relatively stable and undisturbed alluvial streams in a semiarid shale-lithology region of northwestern Colorado. Channel morphology was expressed as a function of Q_B. Channel-morphology variables of 18 perennial and ephemeral streams in the Piceance basin were regressed against Q_B, and the resulting hydraulic-geometry equations are presented in table 4. The variabilities of $\bar{D}$ and A_f were adequately accounted for by Q_B, based on high values of R^2. Low R^2 values indicated that the independent variable, Q_B, was neither the most appropriate nor perhaps the only variable that accounted for the variance in other channel-morphology variables. The variance in S was marginally explained by Q_B, and the variance of W was poorly explained by Q_B. A plot of W against Q_B (fig. 2) revealed a large amount of scatter in the data from ephemeral streams. The poor relation between W and Q_B in the Piceance basin may have resulted because the variability of channel width in ephemeral streams was controlled by factors such as flood flows, local vegetation, bank erodibility, valley slope, or the amount of sediment stored in the channel, rather than by a frequently occurring streamflow, such as Q_B.

Visual inspection of 18 Piceance basin stream channels, data plots, and flow-duration records suggested that the streams were members of two populations, dominated by different geomorphic processes or process rates. The data set was subdivided on the basis of flow type, and hydraulic-geometry equations were computed for perennial streams and ephemeral streams. An analysis of covariance of regression coefficients and exponents indicated significant differences between perennial and ephemeral streams in some aspects of hydraulic geometry; but, because the sample size of subgroup-regression equations was small, results of these analyses were unreliable and were not reported. Distinction between perennial and ephemeral streams in future studies may be desirable if a larger data set is available.

Multiple-regression analyses were performed with additional data from the Piceance basin to examine more thoroughly the independent variables affecting stable channel morphology. In this phase of the study, dependent channel-morphology variables were expressed in terms of basin characteristics (DA, E, P_a), sediment size (d_{50}), and discharge (Q_B). A stepwise multiple-regression technique that maximized R^2 values was employed to determine the most appropriate predictive model for a given channel-morphology variable. The stepwise multiple-regression technique also permitted replacement of Q_B by another independent variable if it improved the R^2 value and reduced SE. This occurred in the equation for S, where DA was found to be more significant than Q_B in explaining the variance of S (eq. 6).

Additional independent variables included in the multiple-regression analyses did not contribute significantly to the explanation of variance of channel-morphology variables in the Piceance basin. Q_B remained the only significant variable explaining the variance of Piceance basin channel W and $\bar{D}$. DA and Q_B were both significant in the equation for A_f, but the addition of DA improved R^2 minimally. Therefore, hydraulic-geometry equations 3 and 5 appear to be the best available for predicting $\bar{D}$ and A_f in the Piceance basin. No suitable equation could be derived for predicting W. Although basin characteristics appear to be a significant factor affecting channel slope, the presence of Q_B in the equations for W, $\bar{D}$, and A_f in table 4 indicated the importance of bankfull discharge in determining the cross-sectional dimensions of stream channels.

Some streamflow characteristics may be estimated when discharge measurements are not available. Q_B in Piceance basin streams can be estimated from A_f with a high degree of reliability if bankfull cross-sectional flow area is known (eq. 7). Earlier studies have attempted to relate streamflow characteristics to basin characteristics. Several Piceance basin streamflow characteristics were regressed against basin characteristics in a stepwise multiple-regression analysis. DA was the most significant individual independent variable in explaining the variance of all streamflow characteristics. Predictive equations were derived for Q_B (eq. 8), $\bar{Q}_A$ (eq. 9), and Q_2 (eq. 10). DA accounted for 72 to 74 percent (SE of 87 to 144 percent) of the variance in these three streamflow characteristics.

Efforts to derive predictive equations for discharges of greater magnitude and lesser frequency were unsuccessful. DA was still the most significant independent variable tested, but it accounted for a relatively small percentage of variance in Q_{MF}, Q_{PF}, Q_{10}, and Q_{25}. Inability to relate discharges of long recurrence interval to basin characteristics in the Piceance basin may have resulted from the poor definition of those discharges obtained from the short periods of discharge records or from the variable nature of rainfall and high-discharge events in this region.

The hydraulic-geometry equations and the equations relating streamflow characteristics to basin characteristics presented in this report are representative of stable stream channels in the Piceance basin area. The relations are not necessarily functional; that is, they do not define absolute physical relations between dependent and independent variables. However, those with relatively high R^2 values (eqs. 3, and 5 through 10) may have limited use as predictive equations within the range of conditions sampled. The equations also may be useful as guidelines for additional investigations of hydraulic geometry and streamflow in semiarid regions.

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