TWO APPROACHES FOR ESTIMATION OF MANNING'S n IN MOUNTAIN STREAMS

Thomas A. Wesche
William T. Hill, Jr.
Victor R. Hasfurther

September, 1983

Wyoming Water Research Center
University of Wyoming

Research Project Technical
Report (A-030-WYO)
Agreement No. 14-34-0001-2154

Prepared for:
U. S. Department of the Interior

The research on which this report is based was financed in part by the U. S. Department of the Interior, as authorized by the Water Research and Development Act of 1978 (P.L. 95-467).

Wyoming Water Research Center
University of Wyoming
Laramie, Wyoming

ABSTRACT

An analysis of roughness coefficients for mountain streams in the Rocky Mountain Region was conducted to devise an empirical method for determination of Manning's n. Two approaches were developed. One procedure utilizes a diagrammatic key approach based upon water surface slope and observable channel characteristics, while the other attempts to relate the time-of-travel velocity of a dye cloud through a stream reach to channel roughness. The conclusions drawn indicate that good potential exists for the use of the diagrammatic key approach. A second significant conclusion of the study is that the estimation of n for steep, rough, tributaries at low flow by means of published tables and/or photographic comparisons can lead to erroneous results.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

INTRODUCTION

The determination of a roughness coefficient for a particular stream reach can be an extremely difficult task, especially in steep, rough channels. The selection of the proper coefficient can oftentimes be critical to the success of the river engineer in the determination of streamflow or the development of proper channel design and also to the habitat biologist working in the area of instream flow analysis or habitat improvement/modification. Unfortunately, the selection process has tended to remain an art rather than a science. Chow (1959) states that "at the present stage of knowledge, to select a value of n actually means to estimate the resistance to flow in a given channel, which is really a matter of intangibles. To veteran engineers, this means the exercise of sound engineering judgment and experience; for beginners it can be no more than a guess, and different individuals will obtain different results."

Generally, the roughness coefficient is estimated by one of three methods: (1) solving for n by rearrangement of the Manning equation; (2) consultation of a table of roughness coefficients for various types of channels; and (3) examination of and acquaintance with the appearance of channels whose coefficients are known, either through photographs or field visits. The widely applied Manning equation uses the resistance coefficient n as a major parameter for determination of flowrate. The Manning equation is given below:

$$Q = \frac{1.49\ AR^{2/3}\ S^{1/2}}{n}$$

where Q is the flowrate (cfs), A refers to the water cross-sectional area of flow (ft^2), R is the hydraulic radius (ft), S the energy slope (ft/ft), and n the Manning roughness coefficient. This equation can be rearranged and solved for n if all other parameters of the equation are known. Factors which affect the value of n for a particular stream reach include size and shape of side and bottom material, height of vegetative growth in channel, variations in channel cross section, straightness or degree of channel curvature, size and types of obstructions, and stage. In general, a straight, clear channel reach in alluvial material at high or design stage will have the lowest n-value of all natural channels. Application of the Manning equation to determine "n" is quite time consuming and in certain cases, such as the estimation of peak discharge of floods, cannot be used because all variables are not known (in this example, Q).

Chow (1959) has compiled one of the most complete tables of n values (Table 1) for natural stream channels. However, as will be shown later in this report, these tabled values are quite low when compared to the field measured values of the authors on small, steep, rough tributary streams in the Rocky Mountain region.

Barnes (1967) provides an in-depth pictorial analysis of bed forms influencing n values for extremely high or flood flows. This publication is restricted to stable channel sections primarily in a rock bottom environment, which is the type setting for this report. Use of the work covered in the USGS report is encouraged although the inexperienced field observer should be aware of the following limitations in its use. Values computed for n are based on flood flows and do not reflect channel resistance at the time of the photograph.

TABLE 1

VALUES OF THE ROUGHNESS COEFFICIENT n

Type of Channel and Description	Minimum	Normal	Maximum
D. Natural Streams			
D-1. Minor Streams (top width at flood stage ∿ 100 ft)			
a. Streams on plain			
1. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
2. Same as above, but more stones and weeds	0.030	0.035	0.040
3. Clean, winding, some pools and shoals	0.033	0.040	0.045
4. Same as above, but some weeds and stones	0.035	0.045	0.050
5. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
6. Same as 4 but more stones	0.045	0.050	0.060
7. Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
8. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
b. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
1. Bottom: gravel, cobbles and few boulders	0.030	0.040	0.050
2. Bottom: cobbles with large boulders	0.040	0.050	0.070

(Chow, 1959)

Because of this, the n value depicted represents the low value for a particular channel bottom type and should be used as the low starting point for n estimation at lower flows.

In addition to the three generally-applied methods described above, several other techniques appear in the literature. A systematic method of evaluating n for a reach of stream is discussed by Cowan (1956). He notes that, "n is used to indicate the net effect of all factors causing retardation of flow in a reach of channel under consideration." The approach recommends determining a reach length base n value and modifying this value by observable phenomena. Factors to be considered for modification include surface irregularities, variation in size and shape of cross section, modifying values for obstructions, a modifier for vegetation, and a multiplier for effects of meanders. His n equation takes the form:

$$n = (n_1 + n_2 + n_3 + n_4 + n_5)n_6$$

with n_1 being the basic reach n and the additions in the order mentioned previously. While seemingly somewhat limited, a relationship of this form has obvious merit provided the base, or n_1, value is properly selected. The inverse relationship of n with stage suggests that an additional parameter be added to Cowan's equation to account for stage.

Boyer (1954) derived an equation relating n to roughness height in open rocky channels. This relationship is:

$$n = \frac{0.105\ (y_o)^{1/6}}{\ln\ (30\ y_o/K)}$$

where y_o is the mean depth (ft) and K is the average roughness height (ft). The greatest estimation error encountered in Boyer's paper was 30 percent with most estimates being within 20 percent of n. Research conducted by Peterson and Mohanty (1960) also points to the ratio between roughness height and stage as being an important factor in flow resistance. Current work by Bathurst (1982) is continuing to explore the relationship of particle size and geometry to channel roughness.

Based upon this search of the literature and the preliminary findings of the authors regarding field measured values of n in small, steep, rough tributary streams of the Rocky Mountain region, research has been conducted to explore the development of two new methods for the estimation of channel roughness coefficients. One method is based upon easily measured and observed hydraulic properties arranged in a diagrammatic "key" format while the other method involves the determination of time-of-travel velocities using dye dilution technology. This report summarizes the findings of these two investigations.

METHODOLOGY

Selection of Stream Reaches

The selection of stream reaches was made based primarily upon the consideration of factors which can affect n as listed by Chow (1959) and described in the previous chapter of this report. Other factors also considered were streamflow and channel diversity, suitability for gaging, accessibility, and where possible, the presence of a USGS (United States Geological Survey) or WWRC (Wyoming Water Research Center) streamflow gaging station. Sections chosen ranged up to several hundred feet in length, were essentially straight with no in-channel vegetation, and were relatively free of channel obstructions other than natural channel bottom variations.

All stream reaches studied were located in the mountainous terrain of the upper Platte River basin of southeast Wyoming and northcentral Colorado. Typically, these streams could be described as relatively small, steep, rough tributaries. Table 2 presents the stream names and locations of the study reaches used for the Diagrammatic Key portion of this study, while those in Table 3 were sampled for the Time-of-Travel portion. More detailed descriptions of the study streams listed in Table 3 may be found in Eifert and Wesche (1982) and Kerr and Wesche (1983).

Data Collection and Analysis (Diagrammatic Key Approach)

Each site was gaged at the same location, contingent on flow depth, over as wide a range of flows as possible. Permanent control sections

TABLE 2

STREAM SECTIONS STUDIED FOR
DIAGRAMMATIC KEY APPROACH

1. North Fork of Little Laramie River near Centennial, Wyoming.
   NE , Sec 17, T 16 N, R 78 W.

2. North Fork of Little Laramie River near Centennial, Wyoming.
   SE , Sec 16, T 16 N, R 78 W.

3. Douglas Creek near Keystone, Wyoming.
   SE , Sec 9, T 14 N, R 74 W.

4. Douglas Creek near Keystone, Wyoming.
   SE , Sec 34, T 13 N, R 79 W.

5. Little South Fork of Cache La Poudre River, Colorado.
   NW , Sec 16, T 7 N, R 73 W.

6. Little South Fork of Cache La Poudre River, Colorado.
   NE , Sec 36, T 8 N, R 73 W.

7. Little South Fork of Cache La Poudre River, Colorado.
   NE , Sec 11, T 7 N, R 73 W.

8. Sand Creek near Chimney Rock, Wyoming, Colorado.
   Sec 1, T 12 N, R 75 W.

9. Laramie River near Woods Landing, Wyoming.
   NE , Sec 36, T 14 N, R 77 W.

10. Pioneer Canal near Woods Landing, Wyoming.
    NE , Sec 36, T 14 N, R 77 W.

11. Little Laramie River near Filmore, Wyoming.
    SE , Sec 4, T 15 N, R 77 W.

TABLE 3

STREAM SECTIONS STUDIED FOR TIME-OF-TRAVEL APPROACH

1. North Fork of Horse Creek - Site #4
   Sec 8, T 17 N, R 70 W.

2. North Fork of Horse Creek - Site #6
   Sec 8, T 17 N, R 70 W.

3. North Fork of Horse Creek - Site #9
   Sec 7, T 17 N, R 70 W

4. North Fork of Horse Creek - Site #10
   Sec 18, T 17 N, R 70 W.

5. North Fork of Horse Creek - Site #15
   Sec 13, T 17 N, R 71 W

6. North Fork of Horse Creek - Site #17
   Sec 12, T 17 N, R 71 W.

7. North Fork of Horse Creek - Site #18
   Sec 14, T 17 N, R 71 W.

8. North Fork of Horse Creek - Site #19
   Sec 14, T 17 N, R 71 N.

SNOWY RANGE STREAMS

9. Nash Fork Creek below Medicine Bow Ski Area
   Sec 20, T 16 N, R 78 W.

10. Nash Fork Creek above Brooklyn Lodge
    Sec 14, T 16 N, R 79 W.

11. Telephone Creek above Millpond (below Middle Pond)
    Sec 15, T 16 N, R 79 W.

12. Telephone Creek above Tower Lake
    Sec 15, T 16 N, R 79 W.

were established upstream and downstream of the gaging section to eliminate excessive cross-sectional computations. Water levels at the upstream and downstream stakes were marked for later surveying or slopes were determined at the time of gaging. Control sections were established for reaches containing only riffles or pools to limit difficulties associated with conflicting channel types.

Sites in Colorado were gaged in cooperation with personnel from Colorado State University and the water levels staked at the time of gaging. USGS sites in Wyoming were similarly treated with additional low flow gaging as deemed necessary. Sites on Douglas Creek and the North Fork of the Little Laramie River were monitored on a weekly basis and gaged to reflect the widest possible range of flowrates. Gaging was accomplished with Price AA and pygmy current meters using procedures discussed by Linsley, Kohler and Paulhus (1975).

Areas for upper and lower ends of the control sections and water surface slopes were determined by level traverses based upon the staked water levels. The cross-sectional flow area was determined using the techniques discussed by Linsley, Kohler and Paulhus (1975), based upon 1-foot spacings. Wetted perimeter length was computed by summing the incremental triangle hypotenuses between the adjacent 1-foot verticals. The hydraulic radius, R, was then computed using the cross-sectional area divided by wetted perimeter. The measured parameters were entered into the Manning equation as follows:

$$n = \frac{1.49\ AR^{2/3}\ S_f^{1/2}}{Q}$$

where:

$$S_f = \frac{h_f}{L} = \frac{h + h_v - K(h_v)}{L}$$

and, h_f = energy loss due to friction; L = length of stream reach; h = vertical change in water surface elevation; h_v = change in velocity head; K = constant = 0 for contractions, = 0.5 for expansions; A = average cross-sectional area of flow obtained by adding area of flow at upstream and downstream ends of the control section and dividing by 2; R = average hydraulic radius for the control section, averaged as above; Q = flowrate; and n = Manning's roughness coefficient (Barnes, 1967). Detailed photographs were taken at the time of gaging to later assist in correlating values of n with observable channel and streamflow characteristics.

Reduced data from 71 stream sections were analyzed using the SPSS-Statistical Packages for the Social Sciences program on the University of Wyoming's computer system. Data considered appropriate for analysis included flowrate, cross-sectional area, wetted perimeter, hydraulic radius, width of flow, slope, mean depth, and n-value. The water surface slope was utilized to evaluate possible correlations to a field situation. Initial analysis was aimed at evaluating relationships between parameters while subsequent analysis was utilized to determine the relative value of n in the Manning equation and to explore the possibility that n was in some way related to one or more of the other channel parameters.

Slides of individual control sections were subdivided into pool and riffle sections and evaluated as to prominent visual characteristics.

Stream sections with similar n-values were segregated into groups and were viewed to determine which of the factors controlling n discussed in the previous chapter could be identified and correlated with a particular n-value. A diagrammatic key was developed for use in determining the n-value within groups.

Data Collection and Analysis (Time-of-Travel Approach)

The hypothesis that the time-of-travel of a dye cloud through a reach of montane stream could be used as a parameter from which n could be predicted originated from analysis of preliminary data collected by Wesche (1973, 1974 and 1980). While these data had not been specifically collected to test the hypothesis and as a result were not as comprehensive as desired, the significant relationship found between time-of-travel velocity and n indicated that further testing could be of value.

Two sets of stream reaches were utilized for the study reported herein. During 1981, eight sites were sampled on the North Fork of Horse Creek, while in 1982, 4 reaches were selected on two gaged streams in WWRC's Snowy Range Observatory (Research Watershed). North Fork sites were only sampled at one discharge level (low flow) while each of the Snowy Range sites was sampled 3 or 4 times over a range of flows. This was done not only to determine the fluctuation of n with discharge, but also to test the relationship of time-of-travel and n for a specific reach as flow is reduced.

Hydraulic parameters necessary to calculate n using the rearranged form of Manning's equation were measured using techniques similar to those described above for the Diagrammatic Key approach. Somewhat larger reaches (up to several hundred feet) were needed however, to obtain accurate time-of-travel data through each reach.

Time-of-travel measurement at each study site was made by means of slug injection of Rhodamine WT fluorescent dye a sufficient distance above the reach to allow adequate mixing, followed by timed water sample collection at both the upper and lower ends of the reach. The procedures used were as outlined by Cobb and Bailey (1965) and Turner Designs (1976). Samples were collected at 10 second intervals until the dye cloud had passed the sampling points. The fluorescent content (parts per billion) of each sample was then measured on site using a Turner Designs Model 10-000 Fluorometer and time-concentration curves were developed. From these curves, leading edge, peak and centroid time-of-travel through the reach were determined. Reach length (ft) was then divided by each respective time (seconds) to determine leading edge velocity, peak velocity, and centroid velocity. Where possible, visual estimates of the dye cloud's leading edge time-of-travel were made, as well as the float velocity of a pencil through the reach. These latter two measurements were made to investigate their relationship to the more time-consuming and equipment-intensive peak and centroid measurements, thereby possibly facilitating the field estimation of n.

To determine the statistical relationship between calculated channel roughness coefficients (independent variable) and the variety of time-of-travel velocity measures (dependent variables), regression analysis was applied. Logarithmic transformation of the variables was also attempted.

RESULTS

Diagrammatic Key Approach

The range of n-values calculated from the measured flowrates at the site locations are presented in Table 4. The range of flowrates indicated are matched with the corresponding n values, with high flowrate and low n-value occurring together. One exception was found at one pool section (site number 4) where low flow corresponds to low n. This phenomenon at site 4 is believed to be due to low velocity and very uniform channel roughness. It should be noted that the n-values presented in Table 1 are considerably lower than those in Table 4 or those indicated by Barnes (1967). The only obvious explanation for these large differences would be the lower flowrates encountered in the streams studied for similar bottom and side materials. Another condition affecting n observed while making field measurements, was that stream sections with no flow zones (dead water areas) within the cross-sectional area resulted in unusually high n-values. The no flow zones cause larger cross-sectional areas than actually should be used in calculation of n, thus resulting in an underestimated value of flowrate and an increase in n-value. For this reason, several sets of data were deleted from the analysis where this type of section was encountered.

Stepwise regression performed on the data indicated that the cross-sectional area was the most significant parameter in determining flowrate, with n being next in importance. Linear and logarithmic linear regression was performed to determine if n could be correlated with any of the hydraulic parameters. This analysis, while very inconclusive, did indicate that n was at least partially dependent upon water surface slope.

TABLE 4

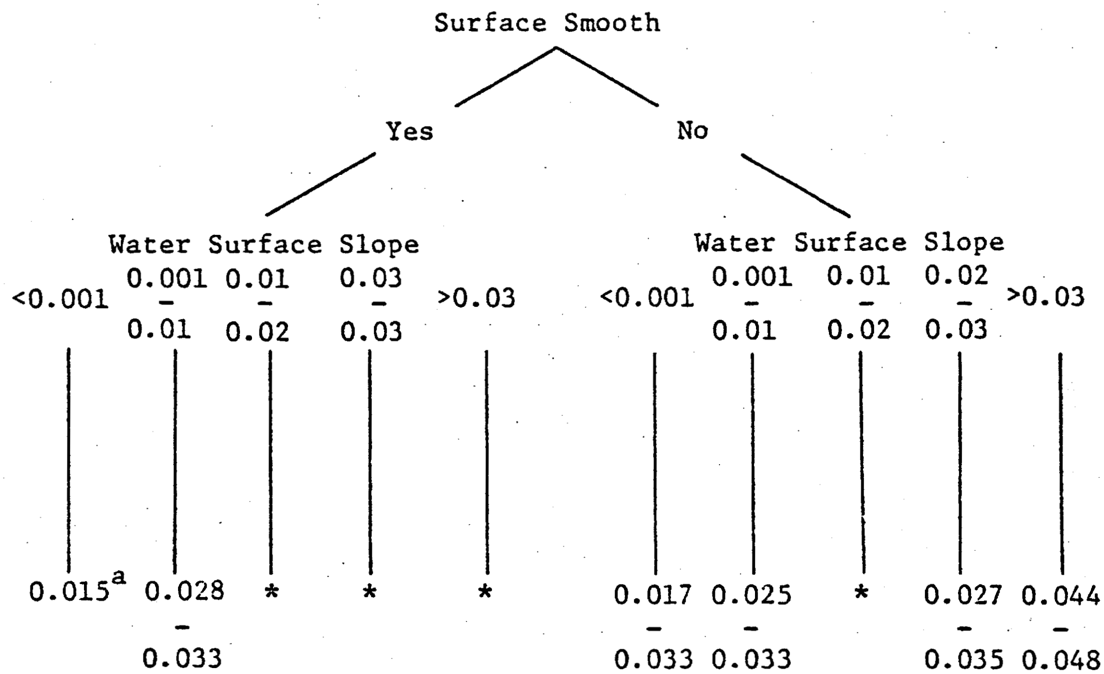
STREAMFLOW DATA

Site Number*	Flow Range (cfs)	n Range	No. of Flow Measurements at Site	Number of Section Measurements Used in Analysis
1	68-6	0.067-0.147	3	5
2	60-2	0.029-0.135	6	12
3	18-2	0.219-0.663	4	6
4	145-17	0.048-0.012	5	9
5	43-17	0.055-0.134	5	11
6	76-40	0.062-0.095	3	5
7	98-38	0.046-0.086	3	6
8	16-5	0.119-0.785	3	2
9	61-1	0.044-0.173	5	7
10	133-32	0.050-0.073	6	4
11	402-18	0.028-0.094	3	4

*Site numbers as presented in Table II.

Results of the analysis of the slides taken for evaluation indicated that a reasonable method of determining n based on channel characteristics can be developed. Pool and riffle classifications, discussed in the previous chapter, were defined according to water surface irregularities. A pool is defined as a stream section with a smooth or slightly irregular surface with obvious slowing of streamflow throughout the reach. This means the channel bed material is not affecting the water surface appreciably and the presence of random large bottom elements will generate little or no surface disturbance. A riffle refers to a stream section with an irregular water surface possibly having whitecaps and/or thinly covered bottom elements causing surface disturbance within the section. Plate 8 (page 35) shows a riffle-pool sequence with the upper zone classified as a riffle due to the disturbances caused by the near surface bottom elements. The classifications for pool and riffle sections were also broken down into high and low flow categories based upon the groupings of similar n values. For purposes of this paper, high flow refers to a higher than normal flow condition, but the flow is still contained within the streambanks. The water surface level intersects the channel banks and average bottom size elements are completely covered by the flow. Low flow is characterized by normal or lower than normal flow. Water level is at or below the line of intersection of the channel banks and channel bottom material. Bottom elements will generally be visible along the sides in low flow situations.

It was found that a diagrammatic key was the most convenient way for an inexperienced individual to systematically evaluate n. For pool sections (Figures 1 and 2) it was determined by evaluation of the



Modifying Conditions

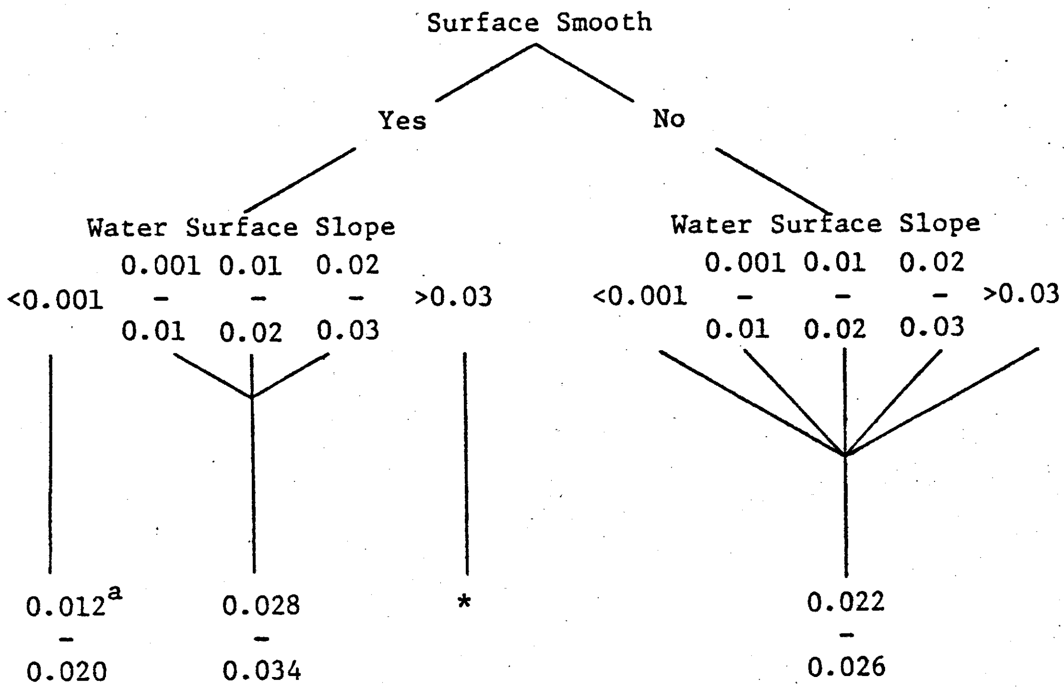
1. For n-ranges - (a) Uniform bottom material - lower value.
   (b) Non-uniform bottom material - higher value.

Note: Uniform refers to height of roughness.

[a]Denotes the range of n values for the above conditions.

*For these water surface slopes, no data were available from the study.

Figure 1. Pool section with high flow.



Modifying Conditions

1. For n-ranges - (a) Uniform bottom material - lower value.
   (b) Non-uniform bottom material - higher value.

Note: Uniform refers to height of roughness.

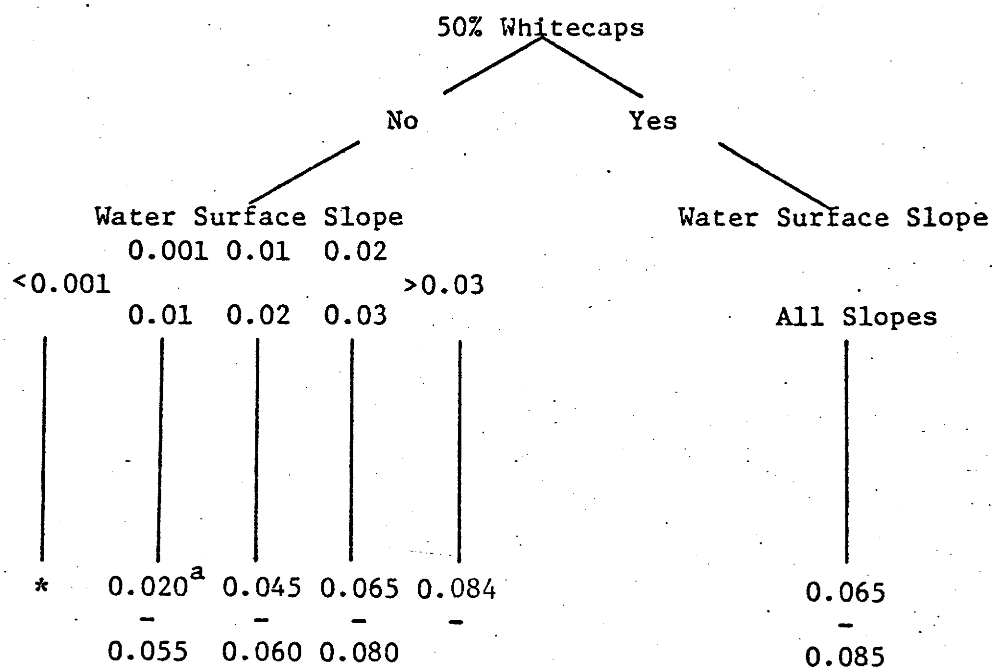
[a]Denotes the range of n values for the above conditions.

*For these water surface slopes, no data were available from the study.

Figure 2. Pool section with low flow.

photographs that the stage and slope were the critical factors. This condition implies that a pool with flow at high level would be evaluated using Figure 1. A low flow situation would be represented by Figure 2.

Riffle sections (Figures 3 and 4) were found to depend on stage, surface roughness and slope. They were subdivided in the same manner as pools according to stage, defined as high and low flow. Depth of flow in relation to roughness height is subdivided into covered, thinly covered, and protruding categories. Thinly covered implies that large bottom elements are visible, yet still covered by a thin film of water in a majority of cases. A protruding condition indicates that bottom elements are above the mean flow depth (Plates 7 and 10; pages 34 and 37). A condition that could not be explained was related to slope range. A slope in the lower 25 percent of the slope range resulted in an n-value at the lower end of the n range, with no linear relationship between n and slope in the upper 75 percent of the slope range. An additional consideration in riffle sections is the presence of whitecaps over more than 50 percent of the reach (Plate 5, page 32) which results in a separate category in Figures 3 and 4. Use of Figures 3 and 4 will, in many cases, result in a procedure similar to that of Cowan (1956). In this instance an n-value is determined for each modifying condition and the values averaged to arrive at the reach n-value. A special riffle case identified as a chute must be considered. For purposes of this study, a chute is defined as a straight, structurally or vegetatively controlled stream section of generally high slope with steep banks, low width variation between high and low flows, and some vegetative infringement on flow (Plate 10).



Modifying Conditions

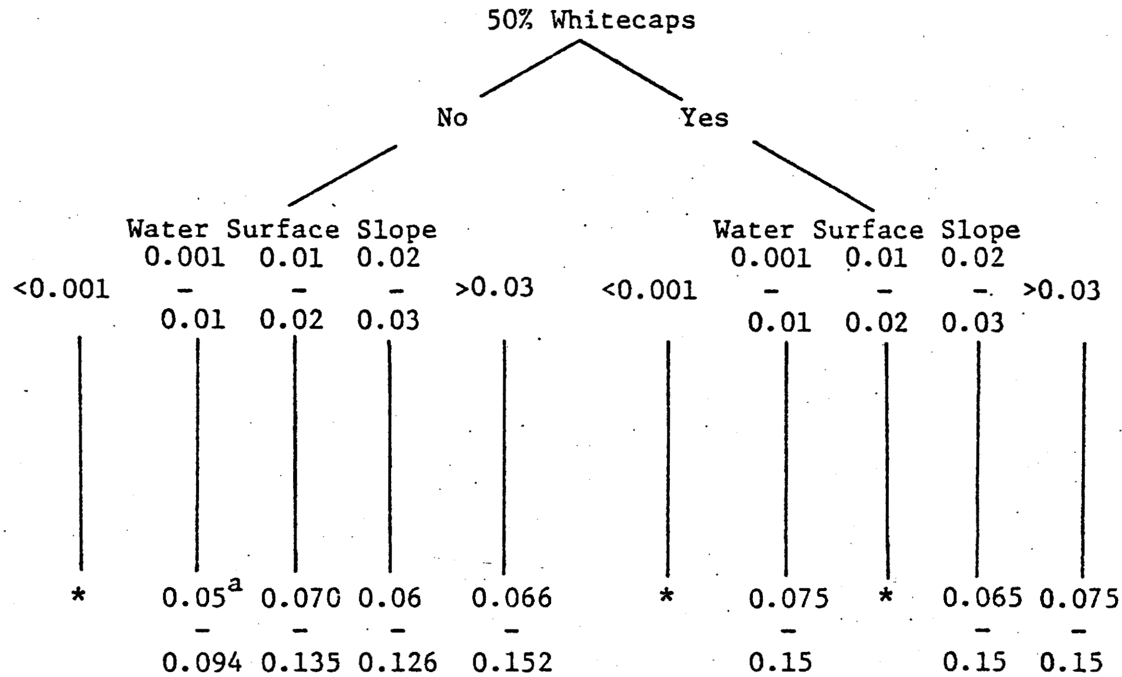
1. If slope is in lower 25 percent of slope range, use n at 1/4 of range. If in upper 75 percent, use n at 3/4 of range.
2. Isolated whitecaps throughout reach associated with surface undulations use n slightly lower than high value given.
3. For n-ranges above - (a) Uniform bottom material - lower value.
   (b) Non-uniform bottom material - higher value.

Note: Uniform refers to height of roughness.

[a]Denotes the range of n values for the above conditions.

*For these water surface slopes, no data were available from the study.

Figure 3. Riffle section with high flow.



Modifying Conditions

1. "Chutes" - use high n values.
2. Boulders protruding through flow across width - high in n-range.
3. Isolated boulders protruding through flow - lower to intermediate of n-range.
4. Low flow (average bottom size covered to thinly covered) - midrange of n-values.
5. Very low flow (average bottom size protruding across width) - n is in 0.2-0.5 range. Cannot be computed by methods in this paper.
6. Random boulders thinly covered with associated whitecaps - lower 25 percent of n-range.

Note: Boulders are 5 to 10 times average bottom material size.

[a]Denotes the range of n values for the above conditions.

*For these water surface slopes, no data were available from the study.

Figure 4. Riffle section with low flow.

Use of the diagrammatic key procedure for estimating n is illustrated in Plates 1 through 4 (pages 28 to 31). No pool sections were discussed in these examples due to the limited range of n-values encountered. Examination of Figures 1 and 2 shows that the n-value is dependent on slope and bottom conditions and can be estimated with very little error.

The n-values in the examples presented were estimated by two students with no coursework or previous experience in estimating roughness coefficients. To assist in evaluation of n-values by the preceding method, particularly in evaluating the modifying conditions, additional stream sections illustrating these conditions are presented in Plates 5-12 (pages 32 to 39), with the n-value measured also indicated.

Time-of-Travel Approach

Hydraulic data collected at the North Fork of Horse Creek study reaches during 1981 are presented in Table 5, while the 1982 data for the Snowy Range streams appears in Table 6. As discussed in the previous section, it is important to note the high range of roughness coefficients calculated for these reaches in comparison to Chow's values shown in Table 1. Also, inspection of the data obtained at the Telephone Creek above Towner Lake site again indicates the assumption cannot always be made that n increases as flow decreases, even when the range of flows considered is less than bankfull. In this case, an embedded log bridging the channel may have contributed to this phenomenon. The water surface at the highest stage measured was in contact with the log, while the surface water elevation at reduced discharges was lower than its underside.

TABLE 5

HYDRAULIC DATA FOR NORTH FORK OF HORSE CREEK STUDY SITE

Site No.	Discharge (cfs)	Slope (ft/ft)	Mean Cross-Sectional Area (ft^2)	Mean Hydraulic Radius (ft)	Manning's n	Mean Cross-Section Velocity (ft/sec)	Peak Time-of-Travel Velocity (ft/sec)	Centroid Time-of-Travel Velocity (ft/sec)	Leading Edge Time-of-Travel Velocity (ft/sec)	Float Velocity (ft/sec)	Visual Dye Velocity (ft/sec)
#4	1.06	.008	1.08	0.19	0.044	0.98	1.05	1.02	1.43	1.80	1.42
#6	0.85	.007	1.51	0.27	0.094	0.56	0.67	0.60	0.80	1.02	0.91
#9	0.76	.005	1.52	0.20	0.085	0.50	0.59	0.50	0.71	0.89	0.72
#10	0.81	.022	1.85	0.27	0.210	0.44	0.31	0.32	0.49	0.83	0.48
#15	1.09	.035	2.01	0.30	0.231	0.54	0.31	0.32	0.57	0.72	0.42
#17	0.45	.015	1.05	0.20	0.144	0.43	0.51	0.47	0.67	0.77	0.67
#18	0.68	.007	1.49	0.28	0.120	0.46	0.44	0.40	0.59	0.85	0.63
#19	0.53	.007	0.92	0.20	0.074	0.58	0.53	0.48	0.74	1.00	0.77

TABLE 6

HYDRAULIC DATA FOR SNOWY RANGE STUDY SITES

SITE	DISCHARGE (cfs)	SLOPE (ft/ft)	MEAN CROSS-SECT. AREA (ft^2)	MEAN HYDRAULIC RADIUS (ft)	MANNING'S n	MEAN CROSS-SECT. VELOCITY (ft/sec)	PEAK TIME-OF-TRAVEL VELOCITY (ft/sec)	LEADING EDGE T-OF-T VELOCITY (ft/sec)	FLOAT VELOCITY (ft/sec)
Nash Fork Ck below Ski Area	56.6	.006	25.8	1.09	.053	2.22	2.56	3.60	3.60
" " " " " "	23.2	.005	17.0	0.79	.067	1.39	1.82	2.39	2.88
" " " " " "	14.6	.006	13.5	0.66	.077	1.12	1.38	1.69	2.04
Nash Fork Ck-Brooklyn Lodge	20.2	.042	9.1	0.72	.111	2.28	2.80	-	5.85
" " " " "	9.4	.042	5.9	0.48	.118	1.67	1.45	2.24	3.32
" " " " "	5.9	.042	5.1	0.43	.149	1.24	1.12	1.82	2.84
" " " " "	3.6	.042	3.6	0.31	.139	1.07	0.82	-	1.87
Telephone Ck above Millpond	17.8	.019	8.0	0.80	.079	2.38	2.75	3.30	3.93
" " " "	9.7	.019	5.3	0.60	.079	1.88	1.65	2.28	2.95
" " " "	5.9	.020	4.0	0.47	.088	1.55	1.38	2.13	2.09
" " " "	2.6	.021	2.8	0.36	.119	0.98	0.94	1.47	1.79
Telephone Ck above Towner Lake	14.0	.035	6.6	0.57	.090	2.05	1.92	2.88	4.11
" " " " "	8.6	.034	4.4	0.41	.077	2.00	2.56	3.07	3.29
" " " " "	4.7	.035	3.2	0.31	.087	1.52	1.28	1.59	2.67
" " " " "	2.3	.034	2.0	0.22	.089	1.18	1.02	1.31	1.89

The relationships found between the time-of-travel velocities of the peak concentration of the dye cloud (V_{TT-P}) through the study reaches and Manning's n are illustrated in Figure 5. The results of the 1981 sampling on the North Fork of Horse Creek were encouraging with the regression analysis indicating that only 17% of the total variation was not explained by the regression (coefficient of determination, $r^2 = 0.83$ and correlation coefficient, $r = 0.91$). Based upon these results, further testing was carried out in 1982 on the four Snowy Range study reaches over a range of flow levels (all less than bankfull stage). In total, 15 additional data points were collected, as shown on Figure 5. For the Snowy Range reaches, the regression was found to explain only 35% of the total variation ($r^2 = 0.35$, $r = 0.59$). The combining of 1981 and 1982 data points ($n = 23$) resulted in a coefficient of determination of 0.42 with a correlation coefficient of 0.65. Analysis using only the 12 low flow data points (one for each study site) resulted in an r^2 of 0.57, with $r = 0.75$.

Based upon the relationship found between slope and roughness coefficient described earlier in this chapter, stratification of the 23 data points by the slope classes outlined on Figures 1, 2, 3 and 4 was attempted. Results were very inconclusive as no strong relationships were found.

As described in the previous chapter of this report, the centroid time-of-travel, leading edge time-of-travel, mean cross-sectional, and float velocities were also measured at each study reach. Regression analysis of these dependent variables against n resulted in weaker relationships than were found using V_{TT-P} as the dependent. Logarithmic transformations of the data were also attempted with little additional success.

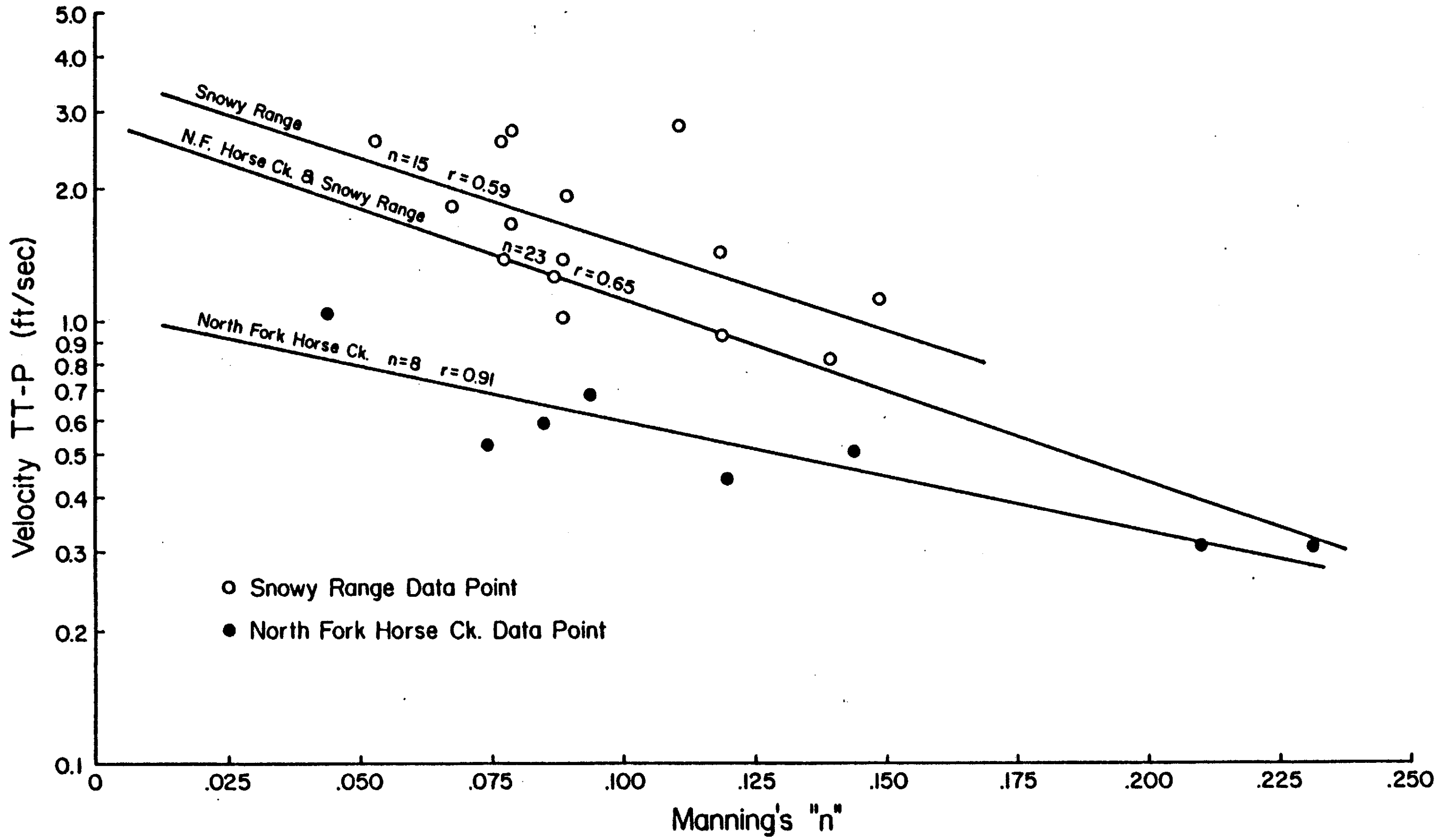


Figure 5. Relationship between the peak time-of-travel velocities and Manning's n for the North Fork of Horse Creek study sites, the Snowy Range sites, and combined.

While investigations into the relationship between the various measures of stream velocity obtained during the course of this study were not a primary objective, these data do merit further consideration, especially in light of increased water development activity in Wyoming and the Rocky Mountain region, and the subsequent interest in stream habitat evaluation and instream flow analysis. The results of correlation analysis between these velocity variables are presented in Table 7. As the measurement of V_{TT-P} and $V_{\overline{x-s}}$ for a stream reach are both time-consuming and equipment-intensive, the equations provided can be used to estimate these variables based upon more easily measured parameters such as V_F and V_{LE}, which under suitable conditions can both be measured by visual observation. Such prediction capability can be of value to a variety of river scientists, including hydraulic engineers, habitat biologists, and water quality specialists.

TABLE 7

RELATIONSHIP BETWEEN VARIOUS MEASURES OF STREAM VELOCITY DETERMINED BY CORRELATION ANALYSIS

Variables	n	Equation	r
V_{TT-P}, V_F	23	$V_F = 0.30 + 1.54\ V_{TT-P}$	0.92
V_{TT-P}, V_{LE}	21	$V_{LE} = 0.11 + 1.27\ V_{TT-P}$	0.98
V_{TT-P}, $V_{\overline{x-s}}$	23	$V_{\overline{x-s}} = 0.24 + 0.79\ V_{TT-P}$	0.95
V_F, $V_{\overline{x-s}}$	23	$V_{\overline{x-s}} = 0.20 + 0.46\ V_F$	0.93
V_{LE}, $V_{\overline{x-s}}$	21	$V_{\overline{x-s}} = 0.13 + 0.64\ V_{LE}$	0.97

V_{TT-P} = Time-of-travel velocity of the dye cloud peak

V_F = Float velocity of a pencil

V_{LE} = Time-of-travel velocity of dye cloud leading edge

$V_{\overline{x-s}}$ = Mean cross-sectional velocity of all cross-sections measured

n = Sample size

r = Correlation coefficient

Plate 1. Pioneer Canal near Woods Landing, Q = 32.3 cfs, S = 0.0062.

Plate 1 is a riffle with low flow. Water surface is irregular, water surface slope is 0.006 ft/ft. From Figure 6, the range of n is from 0.05 to 0.94. Flow is low; therefore, from condition 4, n is at the midrange or 0.072. Actual n = 0.073.

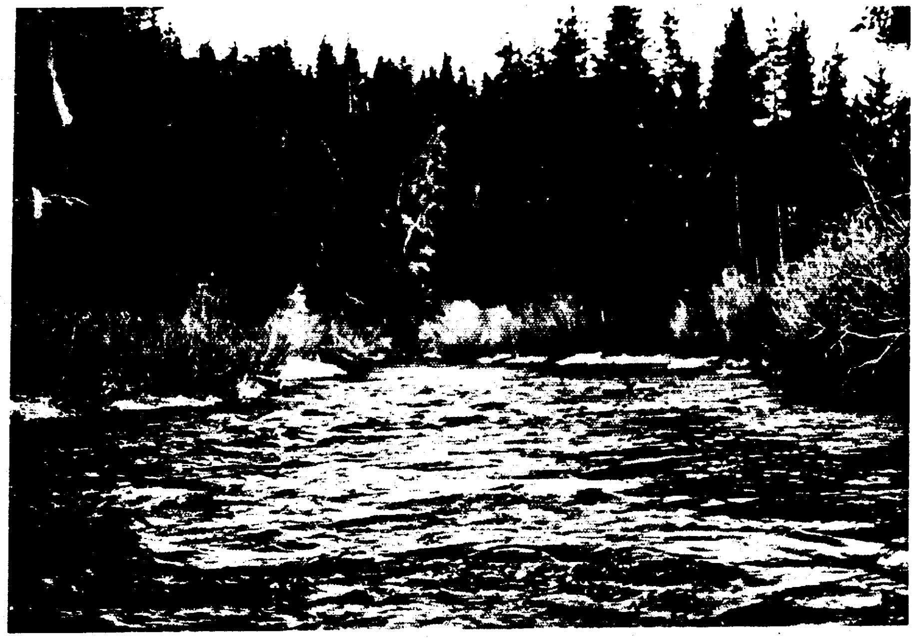


Plate 2. Douglas Creek #4, Q = 138 cfs, S = .0042

Plate 2 is a riffle with high flow. Water surface is irregular, slope is 0.0042. Isolated whitecaps are present. From Figure 5, the n range is 0.02 to 0.055. Modifying condition 1 applies; therefore, use n at 3/4 of the range or 0.046. Modifying condition 2 applies; use n at 0.053. Condition 3a states that for uniform bottom material use the lower value, therefore n (estimated) = 0.046. Actual n = 0.044.

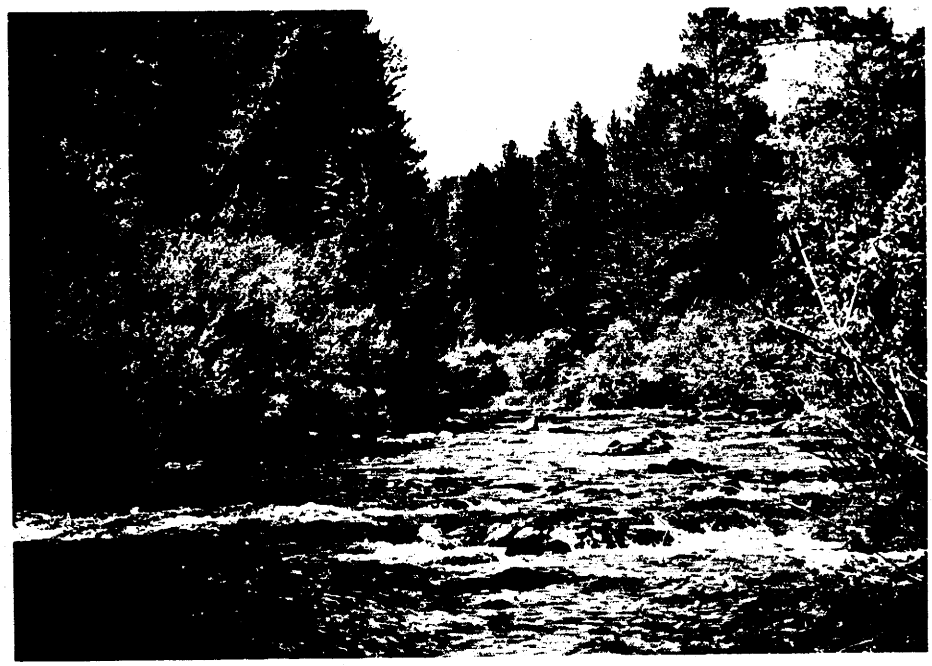


Plate 3. South Fork of Cache La Poudre River #6, Q = 41 cfs, S = 0.022.

Plate 3 is a riffle with low flow, slope is 0.022. From Figure 6, n range is 0.06 to 0.126. Modifying condition 2 exists; therefore, use n_1 at 3/4 of range or 0.1095. Condition 3 exists; use n_2 at 1/4 of range or 0.0765. Condition 4 applies, use n_3 at 1/2 of range or 0.093. Compound n (estimated) = 0.093. Actual n = 0.095.

Plate 4. North Fork of Little Laramie River #1, Q = 22 cfs, S = 0.023.

Plate 4 is a riffle with low flow and greater than 50 percent whitecaps, Slope is 0.023. From Figure 6, n range is 0.065 to 0.15. Modifying condition 1 applies, n_1 = 0.15. Condition 3 applies, n_2 = 0.09375. Condition 4 applies, n_3 = 0.1125. Compound n (estimated) = 0.119. Actual n = 0.127.

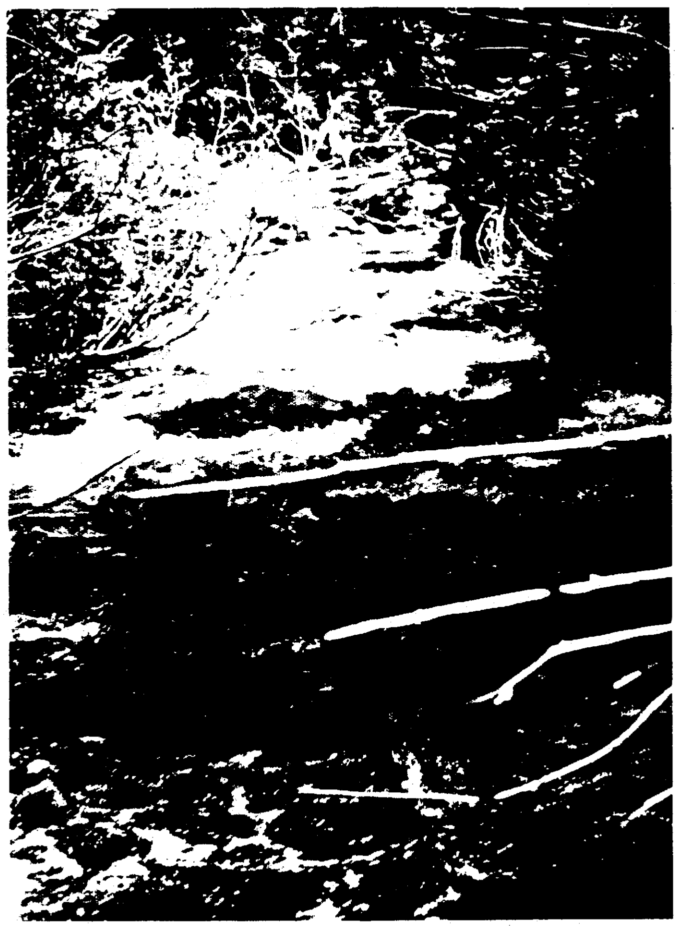


Plate 5. North Fork of Little Laramie River #1.

Plate 5 is a riffle section at high flow in a chute with greater than 50% whitecaps. Q = 59.7 cfs, S = 0.033, n = 0.082.

Plate 6. Little Laramie River near Filmore.

Plate 6 is a riffle section at low flow with boulders across the flow width. Q = 18.5 cfs, S = 0.0077, n = 0.094.

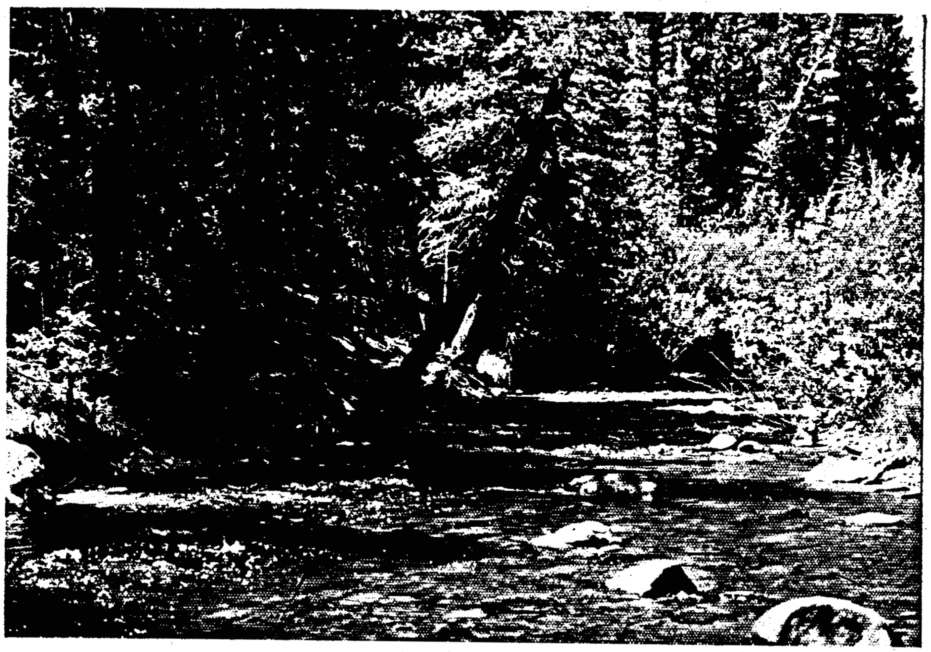


Plate 7. South Fork of the Cache La Poudre River #6.

Plate 7 is a riffle section at low flow with isolated boulders protruding through the flow. Q = 40.6 cfs, S = 0.0094, n = 0.064.

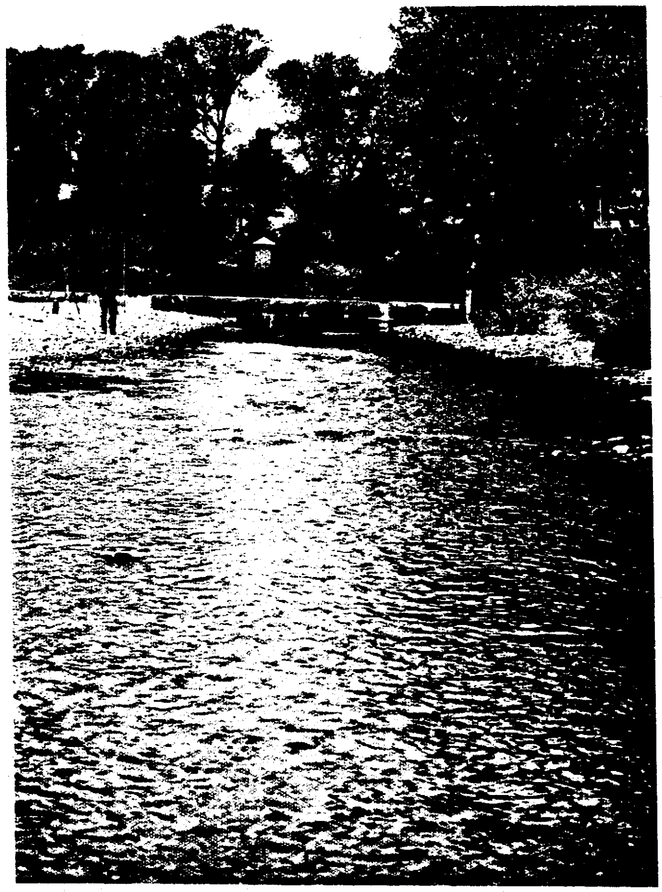


Plate 8. Laramie River near Woods Landing.

Plate 8 is a riffle section at low flow with pool in foreground. Disturbances in relatively smooth riffle section in background. $Q = 10.5$ cfs, $S = 0.004$, $n = 0.066$.

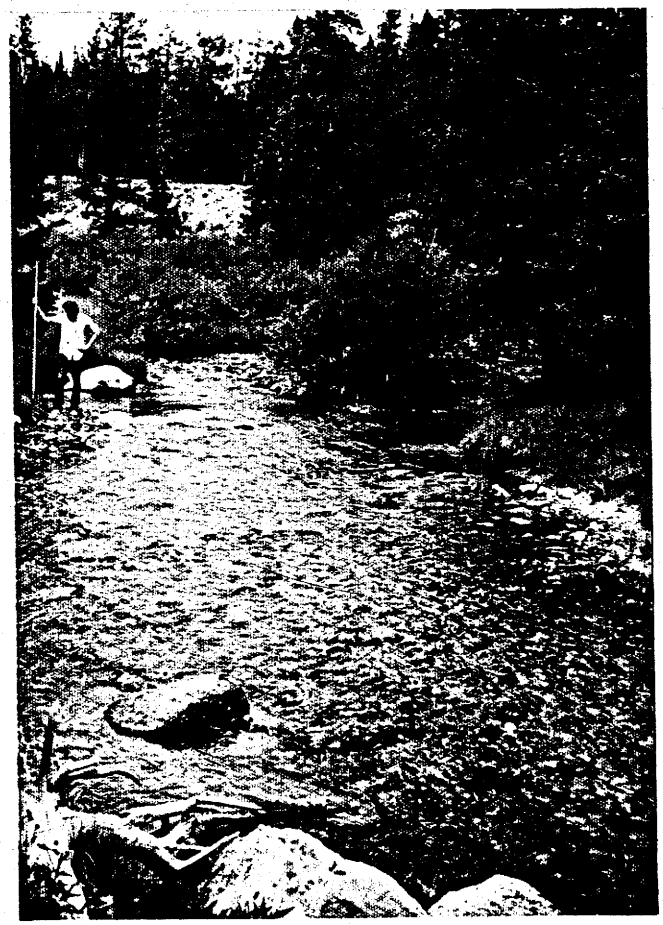


Plate 9. North Fork of Little Laramie River #2.

Plate 9 is a riffle section at very low flow. n cannot be determined by the technique presented. Q = 6.61 cfs, S = 0.011, n = 0.310.

Plate 10. North Fork of Little Laramie River #1.

Plate 10 is a riffle in a chute at low flow with greater than 50% whitecaps. Bottom covered to thinly covered. Q = 19.9 cfs, S = 0.021, n = 0.134.

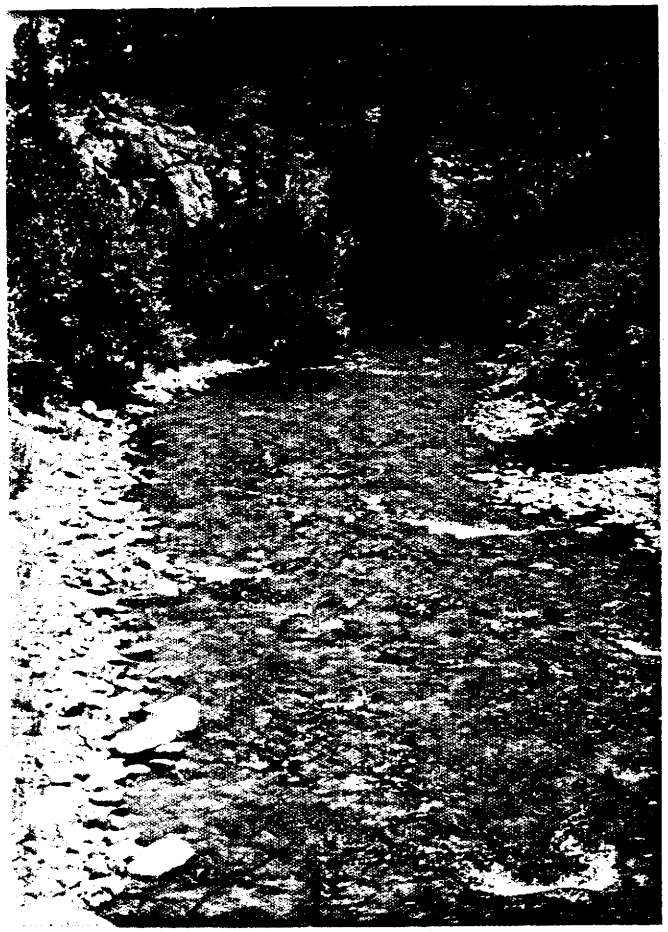


Plate 11. South Fork of the Cache La Poudre River #7.

Plate 11 is a riffle section at low flow. Random boulders thinly covered with associated whitecaps are shown. Q = 38.4 cfs, S = 0.014, n = 0.086.

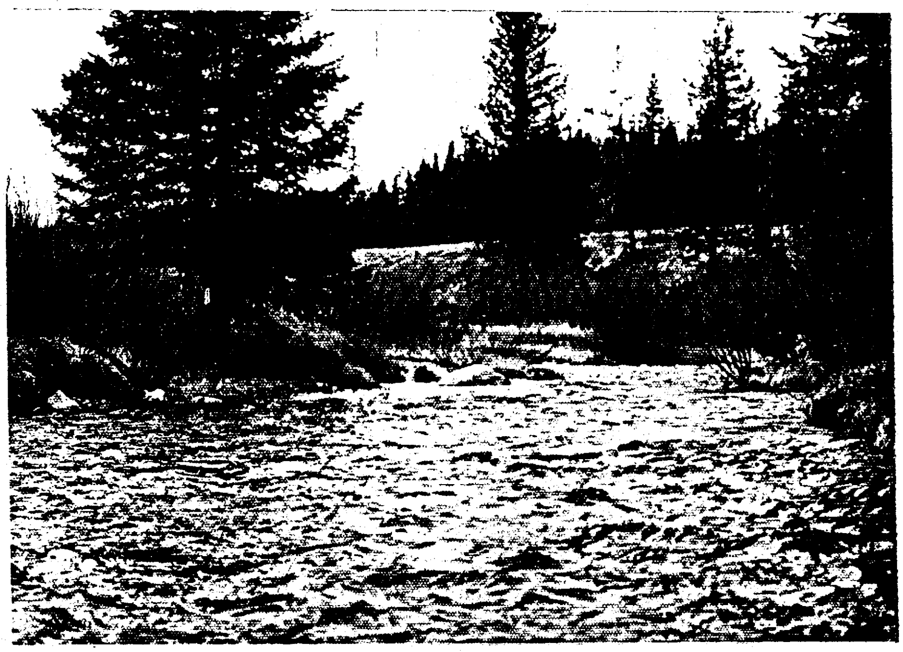


Plate 12. North Fork of Little Laramie River #2.

Plate 12 is a pool with riffle in foreground and background at high flow. Q = 68 cfs, S = 0.0045, n = 0.029. For riffle in foreground, S = 0.011, n = 0.053.

CONCLUSIONS AND RECOMMENDATIONS

1. In steep, rough, tributary channels, especially at low flow, the use of tabled roughness coefficients and/or photographic comparisons can lead to erroneous estimation of Manning's n.

2. Under field conditions n was generally found to increase as flow was reduced, a few examples were found where the reverse occurred. Thus, any analysis which makes this assumption should also include a detailed inspection of the study channel to attempt to eliminate the possibility of such exceptions as described herein.

3. Based upon our findings to date, the diagrammatic key approach appears to have good potential for estimating roughness coefficients in relatively straight reaches of steep, rough tributary channels. It is felt that additional research efforts strengthening the approach, especially under higher flow conditions and over a broader range of slopes, is desirable.

4. Based upon the 1981 data, the time-of-travel approach to roughness coefficient estimation had a high degree of merit and warranted additional investigation. Verification studies conducted during 1982 on differing stream types and over a wider range of flows failed to duplicate the strong relationship found from the 1981 data. Hence, further study of the approach cannot be recommended at this time.

5. Strong correlations have been found between the several measures of stream velocity investigated for the time-of-travel approach portion of this study. Predictive equations have been developed for the estimation of such time- and equipment-intensive measures as peak

time-of-travel and mean cross-sectional velocities from less intensive variables such as leading edge and float velocities.

6. Throughout the course of this study, a comprehensive photographic collection has been built of mountain stream reaches with documentation of their associated n values. We hope that sometime in the future funding can be obtained to publish this collection in a format similar to that of Barnes (1967).

REFERENCES

Barnes, H.H., Jr. 1967. Roughness Characteristics of Natural Channels, U.S. Geol. Survey Water Supply Paper 1849.

Bathurst, J.C. 1982. Flow Resistance in Boulder-Bed Streams. In: Fluvial Processes Engineering and Management. Hey, R.D., J.C. Bathurst, and C.R. Thorne, Editors. p. 443-465. John Wiley and Sons, Inc. N.Y.

Boyer, M.C. 1954. Estimating the Manning Coefficient from an Average Bed Roughness in Open Channels, Am. Geophysical Union Trans., v. 35, pp. 957-961.

Chow, V.T. 1959. Open Channel Hydraulics, McGraw-Hill Book Company.

Cobb, E.D. and J.F. Bailey. 1965. Measurement of Discharge by Dye-Dilution Methods. Book 1, Ch. 14, U.S.G.S. Surface Water Techniques. 27 p.

Cowan, W.L. 1956. Estimating Hydraulic Roughness Coefficients, Agricultural Engineering, vol. 37, no. 7, pp. 473-475.

Eifert, W.H. and T.A. Wesche. 1982. Evaluation of the Stream Reach Inventory and Channel Stability Index for Instream Habitat Analysis. Water Res. No. 82, University of Wyoming, Laramie. 106 p.

Kerr, G.L. and T.A. Wesche. 1983. The Snowy Range Observatory: Climatological and Streamflow Data Report 1982. Wyoming Water Research Center Report, University of Wyoming, Laramie. 85 p.

Linsley, R.K., Jr., M.A. Kohler and J.L.H. Paulhus. 1975. Hydrology for Engineers, McGraw Hill, Inc.

Peterson, D.K. and P.K. Mohanty. 1960. Flume Studies in Steep Rough Channels. Proc., Journal of Hydraulics Division, ASCE 86(HY9), pp. 55-76.

Turner Designs. 1976. Fluorometric Facts, Flow Measurement. Mountain View, Calif. 16 p.

Wesche, T.A. 1973. Parametric Determination of Minimum Stream Flow for Trout. Water Resources Series No. 37, University of Wyoming, Laramie. 102 p.

Wesche, T.A. 1974. Relationship of Discharge Reductions to Available Trout Habitat for Recommending Suitable Streamflows. Water Res. Series No. 53, University of Wyoming, Laramie. 71 p.

Wesche, T.A. 1980. The WRRI Trout Cover Rating Method - Development and Application. Water Res. Series No. 78, University of Wyoming, Laramie. 46 p.