DETERMINATION OF ROUGHNESS COEFFICIENTS FOR STREAMS IN COLORADO

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GLOSSARY

Water-resource terms are defined in the GLOSSARY and are italicized when first used in this report.

conveyance.--A measure of the carrying capacity of a channel section; it is directly proportional to channel discharge. Conveyance is that part of the Manning equation excluding the square root of the energy gradient or friction slope.

correlation coefficient.--A number that expresses the relation between two variables. The value of the correlation coefficient lies between +1 and -1. A positive correlation coefficient indicates one variable increases as the other increases. A negative correlation coefficient indicates one variable increases as the other decreases.

critical flow.--If the flow is critical, the Froude number is equal to unity, and the inertial forces balance the gravitational forces. This balance takes place at the depth at which flow is at its minimum energy with respect to the channel bottom.

flood plain.--An area in and adjacent to the stream that is built of sediments during the present regime of the stream and which is covered with water when the stream overflows its banks.

Froude number.--A dimensionless number used as an index to characterize the type of flow (subcritical, critical, and supercritical) in an open channel; the Froude number is the ratio of the inertial forces to gravitational forces. It is computed as the mean flow velocity divided by the square root of the product of the hydraulic depth times the gravitational constant.

high-gradient stream.--A high-gradient stream is defined as one having slopes greater than 0.01 (foot per foot).

higher-gradient stream.--For this report a higher-gradient stream is defined as one having slopes greater than 0.002 (foot per foot).

lower-gradient stream.--For this report a lower-gradient stream is defined as one having slopes less than 0.002 (foot per foot).

multiple-regression analysis.--A statistical technique by which a relation between a dependent variable and two or more independent variables can be derived. The result is usually expressed as a regression equation.

recurrence interval.--The average interval of time, in years, within which a given flood will be exceeded once.

standard error of estimate.--A measure of how well observed values agree with estimated values in a regression relation. The standard error of estimate is computed from the differences between the observed values and the values estimated using a regression equation.

stream power.--A measure of energy transfer used in computing the regime of flow in sand channels.

subcritical flow.--If the flow is subcritical, the Froude number is less than one and the inertial forces are less than the gravitational forces. The flow depth in subcritical flow is greater than the flow depth in critical flow.

supercritical flow.--If the flow is supercritical, the Froude number is greater than one and the inertial forces are greater than gravitational forces. The flow depth in supercritical flow is less than the flow depth in critical flow.

METRIC CONVERSIONS

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

Multiply inch-pound unit	*By*	*To obtain SI unit*
foot (ft)	0.3048	meter
square foot (ft^2)	0.093	square meter
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.0283	cubic meter per second
foot pound per second per square foot $(ft \cdot lb/s)/ft^2$	14.59	watt per square meter
inch (in.)	25.40	millimeter
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter

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ABSTRACT

Most hydraulic calculations of flow in channels and overbank areas require an evaluation of flow resistance, generally expressed as Manning's roughness coefficient, *n*. The degree of roughness depends on many factors. The report summarizes and relates several methods of estimating roughness and presents additional channel-roughness verification data on *higher-gradient streams* with slopes greater than 0.002. A procedure is outlined that enables the user to systematically evaluate the factors affecting natural, agricultural, and urban channel and overbank roughness. Two prediction equations are presented to aid in the calculation of roughness coefficients for natural stable channels in which roughness changes dramatically with depth of flow. Roughness coefficients can be determined from low-to-high flow conditions as long as the channel remains fairly stable, sediment concentrations are not so great as to result in mudflows or debris flows, and stream slopes are less than 0.05. Because of extreme turbulence, large energy losses, and hence large roughness coefficients, flow in high-gradient, cobble- and boulder-bed mountain streams generally is subcritical.

INTRODUCTION

Purpose and Scope

The purpose of this report is to provide guidelines in the evaluation and limitations of flow resistance in hydraulic analysis on streams in Colorado. First, this report describes the requirements for locating cross sections and reaches for a hydraulic study. Secondly, the report describes the factors that affect the roughness characteristics of channels and overbanks. Thirdly, flow resistance is described for the channel and overbank of a stream in the natural, agricultural, and urban condition. Fourth, a systematic procedure for calculating and selecting appropriate roughness coefficients is presented in addition to examples. The report incorporates additional channel-roughness verification data from a study of *higher-gradient streams* typical in Colorado.

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The author gratefully acknowledges assistance of Eugene I. Jencsok, Colorado Water Conservation Board, for help with project planning, data collection, and report preparation. Many helpful review comments were made by William P. Stanton, Colorado Water Conservation Board.

Hydraulic Analysis

Most hydraulic calculations of the magnitude and characteristics of flow in channels and overbank areas of *flood plains* require an evaluation of the roughness characteristics. These calculations are used in flood-plain studies and in instream-flow-requirement studies (minimum flow than preserves the natural environment) to evaluate the flow depth or discharge.

The degree of roughness depends on several factors, the most important of which in open-channel flow are surface roughness of the bed material, cross-section geometry, channel variations, obstruction to flow, type and density of vegetation, and degree of channel meandering. In general, all factors that tend to cause turbulence and retardance of flow, and hence energy losses, increase the roughness coefficient; those that cause smoother flow conditions tend to decrease the roughness coefficient.

Because of the lack of a satisfactory quantitative procedure, the ability to determine the roughness characteristics of flood plains needs to be developed through experience; however, a basic knowledge of the factors affecting the selection of roughness coefficients will greatly aid in the calculation and selection of n values.

Manning Equation

Most commonly, Manning's roughness coefficient, n, is used to describe the relative roughness of a channel or overbank areas, and it appears in the general Manning equation for open channel flow in the following form (Barnes, 1967):

$$V = \frac{1.486}{n} R^{2/3} S_f^{1/2}, \qquad (1)$$

where V is the mean velocity of flow, in feet per second;
R is the hydraulic radius, in feet;
S_f is the slope of the energy grade line; and
n is the Manning roughness coefficient.

The Manning equation was developed for uniform flow in which the water-surface profile and energy gradient are parallel to the streambed, and the area, hydraulic radius, and depth remain constant throughout the reach. It is assumed that the equation also is valid for the nonuniform reaches usually found in flood plains. The energy equation for a reach of nonuniform open-channel between sections 1 and 2 shown on figure 1 is

$$(h+h_v)_1 = (h+h_v)_2 + (h_f)_{1-2} + k(\Delta h_v)_{1-2}, \tag{2}$$

where

h = elevation of the water surface at the respective sections above a common datum,

h_v = velocity head at the respective section = $\alpha V^2/2g$,

α = the velocity head coefficient,

h_f = energy loss due to boundary friction in the reach,

Δh_v = upstream velocity head minus the downstream velocity head,

$k(\Delta h_v)$ = energy loss due to acceleration or deceleration in a contracting or expanding reach, and

k = a coefficient, generally taken to be 0.0 for contracting reaches and 0.5 for expanding reaches.

LIMITATIONS

Several limitations of the Manning equation and hydraulic calculations include streams subject to debris flow, very high-gradient streams, and modification of the channel during a flood.

Debris flows, mudflows, and debris and alluvial fans are common throughout Colorado mountain regions. The hydraulic characteristics of debris flows and mudflows are such that the selection of n values for them and subsequent conventional hydraulic analyses probably are not applicable because of the large sediment load, channel scour and deposition, and a lack of a well defined channel. These hazard areas can be identified from geomorphic and sedimentologic evidence that remains in the flood plain and generally are found in small, steep watersheds and at the confluence of these watersheds with larger streams (Costa and Jarrett, 1981).

A debris flow is a heterogeneous mixture of water and sediment of different sizes and has a high degree of fluidity. Evidence of past debris flows may consist of levees of poorly sorted debris that border the channel. Debris-flow deposits are more poorly sorted than water-flood deposits, and the largest rocks are concentrated near the surface and edges of the deposits. There is no evidence of excessive discharge downstream from the deposits. A mudflow is similar to a debris flow except the material is predominantly fine grained. An indication of a mudflow is a coating of mud on the ground surfaces, obstruction, and vegetation.

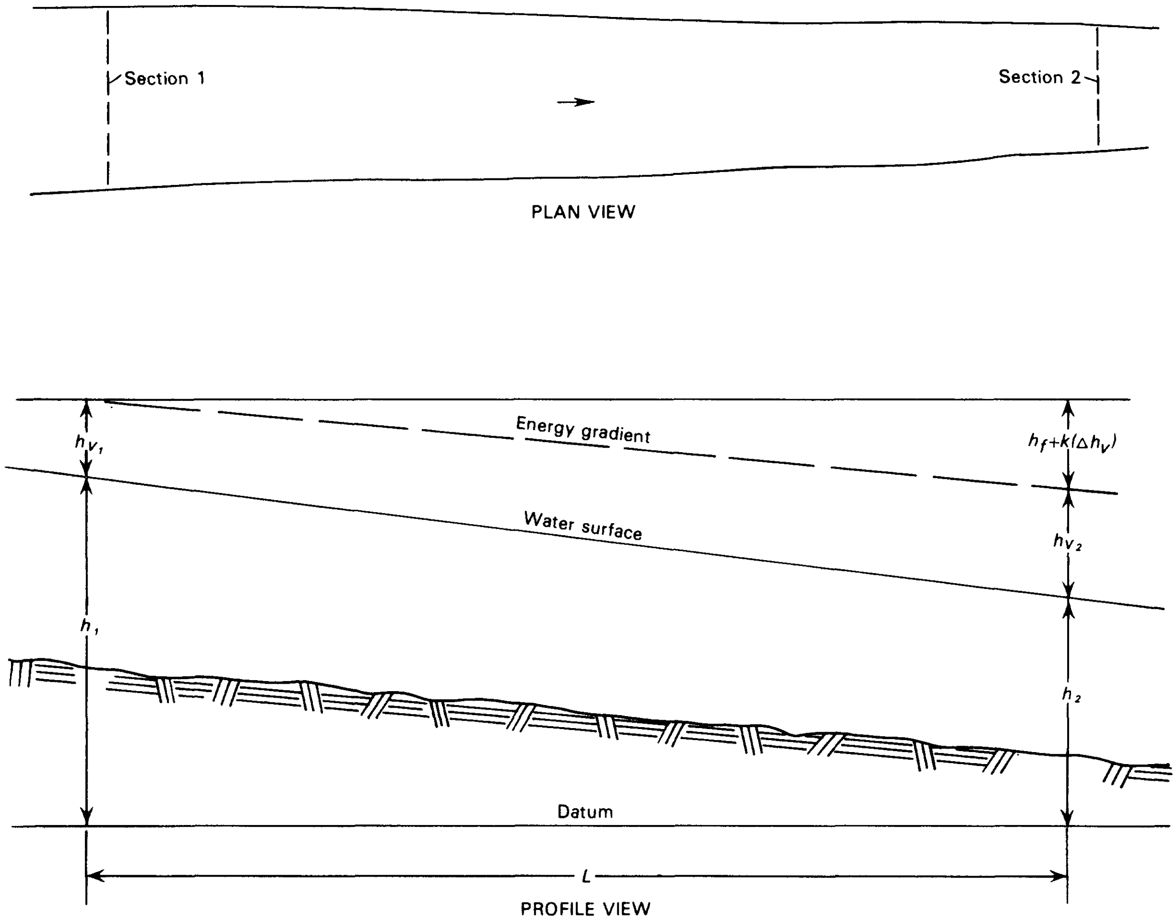


Figure 1.--Definition sketch of an open-channel flow reach.

Debris and alluvial fans are composed of clay, sand, gravel, cobble boulders, and other debris deposited at the foot of a steep channel where the channel gradient lessens, flow spreads on the fan, and flow velocity is decreased sufficiently to cause such deposits. These deposits are fan shaped and have relatively undersized channels. The channels generally are discontinuous and are subject to sudden relocation across the fan during runoff. Cross-sectional relief is relatively small and may slope away for some distance on either side of the sides of the channel. Gol'din and Lyubashevskiy (1966), Dawdy (1979), and Magura and Wood (1980) present alternative hydraulic methods to analyze the hazards for debris flows and debris and alluvial fans.

Except for sand-bed streams, the channel bottom is not uniform but is a series of steps or drops whose spacing and height are controlled by the slope (Judd and Petersen, 1969). As slope increases, spacing decreases and height increases. These steps develop as deposits of boulders across the channellike drop structures or as natural bedrock outcrops; these steps have been noticed on most high-gradient boulder-bed streams. Extreme care needs to be taken in making hydraulic calculations that span one or more of these steps because the flow usually passes through critical depth. Cross sections need to be placed immediately upstream and downstream from a critical depth control. High flows may drown out these steps.

Minimal verification exists in hydraulic computations beyond slopes of 0.05 in natural streams (Barnes, 1967). When stream slope exceeds 0.05, hydraulic computations may be inaccurate.

The passage of a flood can cause dramatic changes in channel geometry and roughness in a very short time. Contracting reaches are susceptible to scour at high-flow velocities, whereas deposition can occur in either contracting, uniform, or expanding channels. Although scour is a function of a number of flow, channel, and soil properties, the most dominant factor seems to be stream slope. As slope increases, particularly in excess of 0.03 to 0.04, scour increases greatly. In many high-gradient streams, almost their entire length can be scoured or filled. This is not meant to imply that erosion and channel enlargement cannot occur on flatter slope streams. A check for past flood erosion and depositional features needs to be made for all hydraulic computations.

CROSS SECTIONS

Location

Prior to the selection of the roughness coefficient values, an office study and an onsite investigation need to be made to properly locate the cross sections that would be used in the hydraulic analysis (Benson and Dalrymple, 1967; and Davidian, 1984). If low-level aerial photographs and detailed topographic maps or both are available, cross sections and study reaches need to be placed on them and then their location checked onsite.

Cross sections need to be located closely enough to accurately reflect the hydraulic characteristics of a channel and its adjacent overbanks between the cross sections. The sections need to extend across the entire flood plain and need to be at right angles to the anticipated direction of flow in both the main channel and overbanks. This may indicate the need for curved or angled sections at some locations. The location of the sections needs to ensure an accurate evaluation of energy losses between sections. For each reach, the energy gradient, water-surface slope, and streambed slope need to be as nearly parallel as possible. If any channel condition causes one of these profiles not to be parallel, it is an indication that additional cross sections are needed. A sufficient number of cross sections are needed to accurately reflect flood-plain geometry.

Some general criteria for locating cross sections are listed below. These criteria help satisfy the assumption of steady uniform flow in individual subreaches.

1. The cross sections need to be located at major changes in bed or water-surface profiles. If old flood profiles are available, they can be used to locate the breaks in water-surface profiles.
2. The cross sections need to be placed at points of minimum and maximum cross-sectional area, width, or depth. The number of cross sections needs to be greater in expanding reaches and in bends to minimize the relative degree of expansion between cross sections and leave the individual subreaches more nearly uniform.
3. The number of cross sections needs to be greater in reaches that have moderate to severe changes in cross-section shape, even though the total areas may differ only slightly from each other. An example would be sections that change shape from just a main channel to main channel with overbank flow.
4. The cross sections need to be located at abrupt changes in roughness characteristics, for example, where the flood plain is heavily vegetated in one subreach, but has been cleared and cultivated in the adjacent subreach. The use of a cross section twice, in close proximity and with different roughness values, must suffice for the present to evaluate the frictional losses.
5. The cross sections need to be located at control sections if critical or *supercritical flow* conditions exist. These controls include natural and manmade weirs, check dams, rock walls, fences, and severe obstructions.
6. The cross sections need to be located at tributaries where changes in discharge are anticipated. The exact placement of the cross sections varies, depending on the method of analysis and program requirements.

Where abrupt channel changes occur, several cross sections need to be established to accurately indicate the changes, regardless of the distance between the sections. At bridges and other hydraulic structures, a sufficient number of cross sections are needed to define the approach and outlet conditions as well as the geometry of the structure, but these conditions are not discussed in this report.

Reach Length

Although the cross section represents the hydraulic geometry at a specific location, the section needs to represent the typical conditions in a reach of the channel and its adjacent overbanks. In this context, a reach is a length of a channel and its adjacent overbanks that are reasonably uniform with respect to discharge, depth, slope, channel and flood-plain geometry, roughness characteristics, and cultural features. In figure 2, a hypothetical stream has been subdivided into three study reaches in which the cross sections represent typical conditions within that reach. The reach that includes any one section is considered to extend halfway to the next section, shown in figure 2. If channel flow is fairly steady and uniform, an upper limit of cross-section spacing needs to be about 75 to 100 times the mean depth for the largest discharge to be considered. Ideally, the fall between cross sections generally needs to be equal to or greater than the larger of 0.50 ft or the velocity head.

If water-surface profiles for several discharges are to be computed, the lengths between any two cross sections may have to be computed differently for different discharges. Small discharges would stay entirely within banks and follow the meanders of the main channel. The length for the subreach would be a maximum. Large discharges may have flood-plain flows, and their effective flow distances would be shorter.

For overbank flows, a weighted or effective subreach length needs to be used. The center of flow in the subsections of each cross section are determined and connected through the subreach by curvilinear or straight lines. One line will follow the main channel, and the others will be along the flood plains. The lengths of the main channel and overbank subareas are measured separately. Profile computations for a range of discharges may require one set of subreach lengths for all discharges within banks and another set of subreach lengths for discharges with overbank flow.

Subdivision

Cross-section subdivision usually is needed to satisfy the criteria for uniform flow. Under normal conditions, roughness can vary significantly between the main channel and the overbanks. Subdivision needs to be made primarily at major changes in cross-sectional geometry so that the velocity in each subarea is basically uniform in each stream reach. Typically, a cross-section subdivision is made where overbank flow first occurs, resulting in a channel and left and right overbank subareas as shown in cross-section 1 of figure 3. The cross section needs to be divided on the basis of geometry and separate n values assigned, even though roughness may be the same in the channel and overbanks.

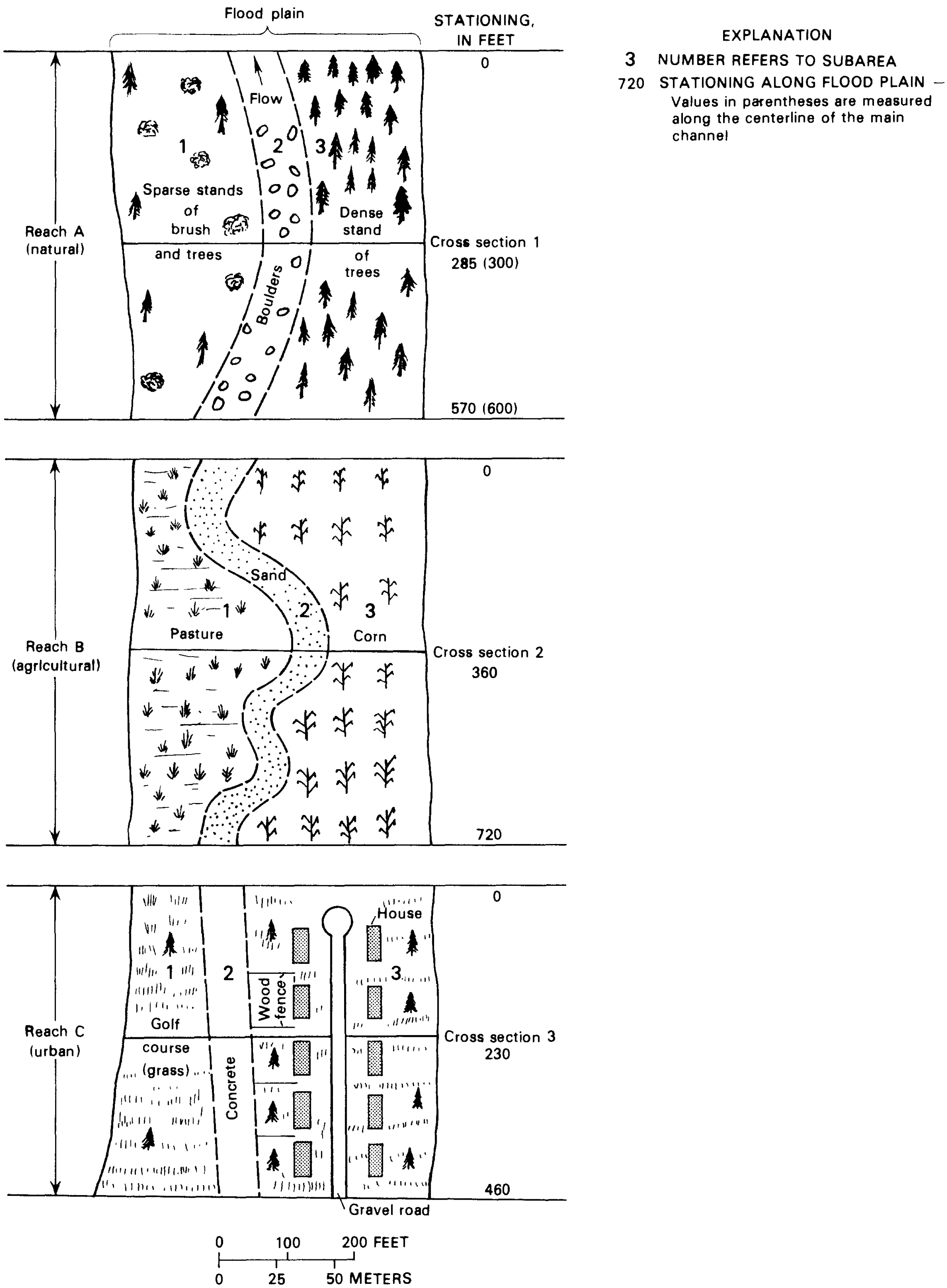


Figure 2.--Plan view of a hypothetical channel and flood plain showing types of reaches, subareas used in assigning n values, and location of cross sections.

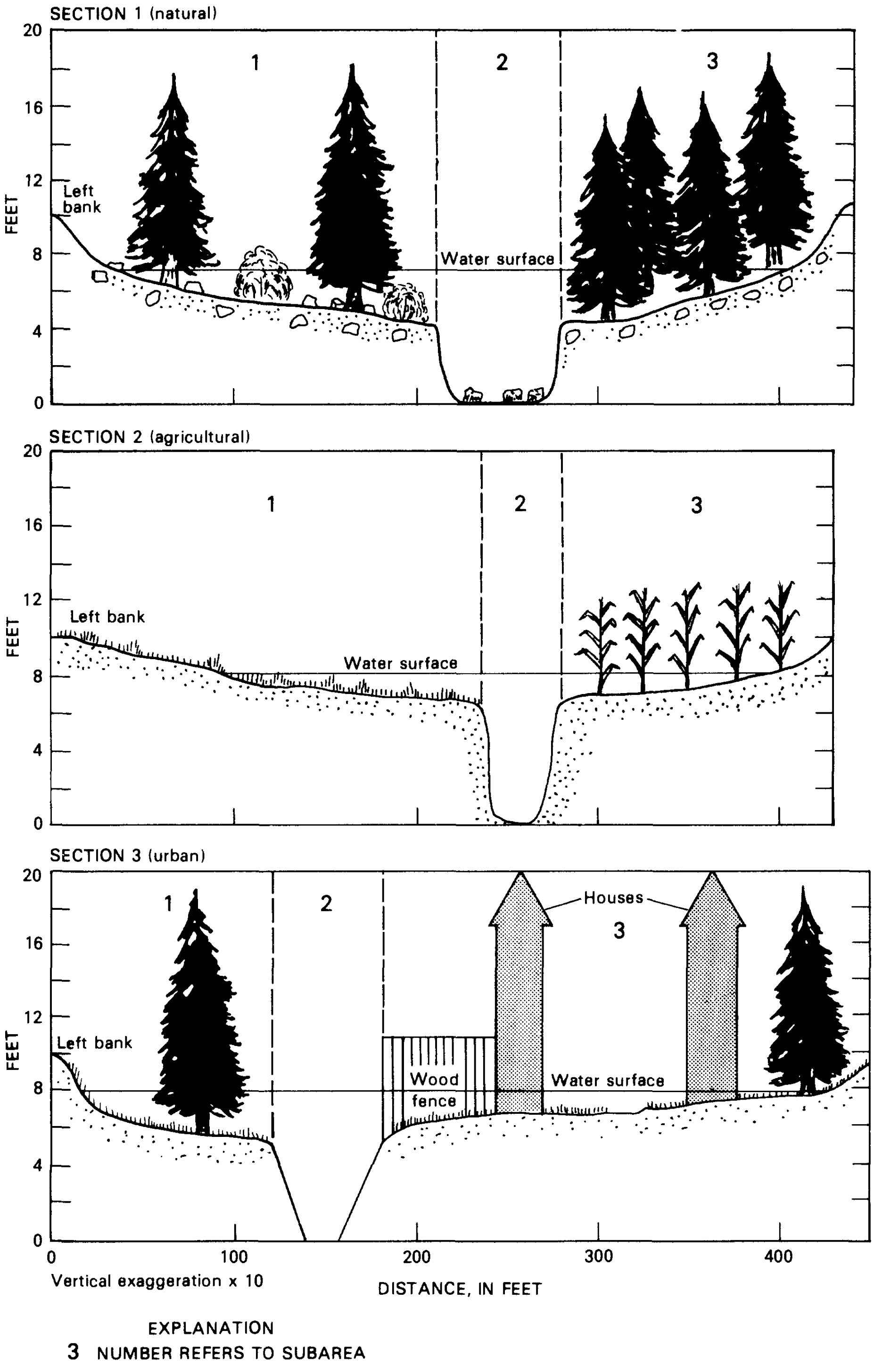


Figure 3.--Cross sections of a hypothetical channel and flood plain.

In some cases, a more detailed subdivision may be needed. Verification studies have shown that the proper method of subdividing the cross section based on roughness is as follows (Davidian, 1984; and Chow, 1959).

The channel is not subdivided for changes in bed roughness at the low water edge because of the variation between bed and bank roughness. A cross section of a hypothetical main channel and flood plain showing proper subdivision based on geometry and roughness is shown in figure 4. The channel bed consists of gravel having an n value of 0.030. A dense growth of willows on the sides of the low-water channel has an n value of 0.15. A single composite roughness value needs to be calculated for the main channel (subarea 3) using equation 3, simplified from Chow (1959).

$$n_c = \frac{(P_1 n_1 + P_2 n_2 + \ldots P_m n_m)}{P} \tag{3}$$

where n_c is the composite n value for the channel;
P_1, P_2, P_m are the wetted perimeter, in feet, for each roughness area;
n_1, n_2, n_m are the roughness coefficients corresponding to each wetted perimeter; and
P is the total wetted perimeter, in feet, for the channel.

The composite roughness often is approximated by weighting with wetted perimeter, width, or subarea rather than *conveyance* (Chow, 1959).

For channel subarea 3 shown in figure 4, $n_1 = 0.15$, $P_1 = 15$ ft, $n_2 = 0.030$, $P_2 = 165$ ft, $n_3 = 0.15$, $P_3 = 22$ ft, and $P = 202$ ft. Using equation 3, the composite roughness value for subarea 3 is

$$n_c = \frac{0.15(15\text{ ft})+0.030(165\text{ ft})+0.15(22\text{ ft})}{202\text{ ft}} = 0.052 .$$

If the roughness varies with depth, several composite n values may need to be computed and used in the hydraulic analysis.

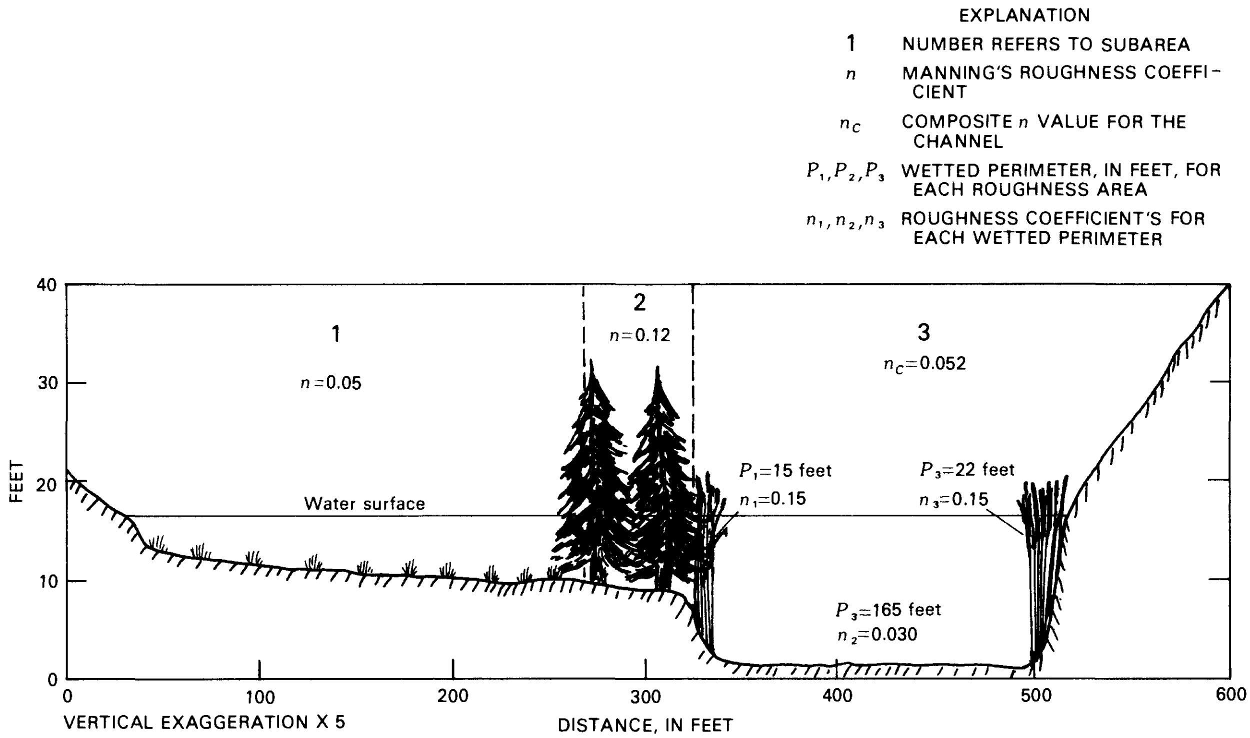


Figure 4.--Cross section of a hypothetical channel and flood plain showing subdivisions based on geometry and roughness.

In wide, flat sections of the overbanks, subdivisions based on roughness need to be made where the roughness changes, if they occur throughout the reach. The left overbank shown in figure 4 needs to be subdivided into subarea 1 (pasture) having an n value of 0.05 and subarea 2 (dense growth of trees) having an n value of 0.12.

ROUGHNESS COEFFICIENTS

An understanding of the basic factors that affect roughness coefficients in channels and overbanks are needed for the selection of Manning's n. In general, the roughness coefficient is a measure of the effect that bed material, channel geometry, vegetation type and density, and other factors have on flow resistance. Consequently, any factors that increase flow resistance increase the roughness coefficient, and factors that decrease flow resistance decrease the roughness coefficient.

The roughness can vary greatly with changes in stage and discharge and the seasonal changes in vegetation. The variation with stage and discharge is particularly important in higher-gradient mountain streams. The general approach to evaluate roughness outlined in this section consists of evaluating the channel roughness (base n value), modifying the base value by adjustment factors, and evaluating the roughness of the overbanks. The discussion is further divided into natural, agricultural, and urban conditions.

General Approach

The general approach for estimating n values consists of the selection of a base roughness value for a straight, uniform, smooth channel in the materials involved, then, through a consideration of various factors, modifying values are added to the base n value to obtain the n value for the channel under consideration (Chow, 1959; Cowan, 1956).

The n value for a given depth of flow may be calculated by the general equation

$$n = (n_0+n_1+n_2+n_3+n_4)\,m \tag{4}$$

where

n_0 is the base value for a straight uniform channel;
n_1 is the additive value due to the effect of cross-section irregularity;
n_2 is the additive value due to variations of the channel;
n_3 is the additive value due to the relative effect of obstructions;
n_4 is the additive value due to the type and density of vegetation; and
m represents a value for the degree of meandering used to multiply the sum of the previous values.

Although the base and modifying values are interrelated to some extent, it is important that each factor be examined and considered independently and the effects not duplicated. Cowan (1956) indicates this method has not been verified on channels where hydraulic radius exceeds 15 ft.

The selected *n* values need to apply not only to the cross section they are assigned to, but also need to be representative of the study reach under consideration. Consequently, the selection of cross-section locations and reach lengths needs to be carefully considered.

Base Value

The base roughness value of a streambed depends on the size, shape, spacing, and spacing pattern of the bed-material particles, channel gradient in natural stable channels, depth of flow, suspended material, and the bed level. Tables of base *n* values have been developed independently by several sources (Chow, 1959; Benson and Dalrymple, 1967; Aldridge and Garrett, 1973), but they are for different settings, such as stable, movable bed, and urban channels. These tables of *n* values will be presented in later sections.

Particle Size

Generally, roughness increases with increasing particle size; sand-bed channels have the smallest roughness values. Shape, spacing, and spacing pattern of the larger particle sizes are extremely difficult to quantify in terms of their effects on roughness and, therefore, are not considered directly in the evaluation of roughness.

The size and size distribution of the bed material can be determined by either of the following methods, as described in detail by Benson and Dalrymple (1967). If the bed material is composed of material of about 2 in. or smaller in diameter, small samples of the bed material needs to be collected at representative sites throughout the stream reach. A sieve analysis is made on the composite sample, the volume of material in each sieve size range is converted to a percentage of the total, and a size-distribution curve of the composite sample is prepared.

If the material is too large for a sieve analysis, a grid system of 50 to 100 points per stream reach is used (Wolman, 1954). The width or intermediate diameter of a particle at each grid is measured and recorded. The sizes are grouped into a minimum of five ranges, and the number of particles in each range is recorded and converted to a percentage of the total. In both methods, the size that corresponds to the 50th percentile or median diameter (d_{50}) is obtained from a distribution curve derived by plotting particle size versus the percentage of sample smaller than the indicated size.

It often is not possible to physically measure the bed material because of deep or fast-flowing water or time constraints. In these cases, the median particle size needs to be visually estimated and recorded during inspection of the stream reach.

Channel Gradient

Studies by Golubtsov (1969), Riggs (1976), and Ayvazyan (1979) indicate that base *n* values are directly related to channel gradient in natural stable channels. This relation is due, in part, to the interrelation between channel slope and particle size. The effect of increased turbulence and resistance results in increased friction slope. For similar bed-material size, channels having low gradients have much smaller *n* values than stable channels having high gradients. Values of *n* as small as 0.032 have been obtained for stable channels having very low gradients, shallow flow depths, and large boulders.

Depth of Flow

Many hydraulic studies involve evaluating flow resistance over a range of depth from low to high. In many cases, *n* values need to be selected to reflect the change in flow resistance with depth of flow.

Based on a review of verified channel roughness data, the base *n* value in a uniform channel does not vary with depth of flow if the ratio of the mean depth (usually hydraulic radius) of flow to bed-material size (usually the median diameter) is greater than 5 and less than 276. This can be expressed as

$$276 > \frac{R}{d_{50}} > 5$$

It is assumed the channel widths are large relative to depth of flow, and the bed and bank materials are the same. This condition generally exists for sand- and gravel-bed channels, but not for cobble- and boulder-bed channels.

Ratios less than 5 generally apply to mountain streams having relatively large median bed-particle sizes. In these streams, *n* values vary significantly with depth of flow. Ratios of greater than 276 generally are found in sandbed streams where significant variations in *n* values are due to changes in bed-form configuration.

Prediction equations provided later in this report aid in evaluating change of roughness with depth of flow in natural channels. Subjective judgment is needed for other types of channels and overbank areas.

As the depth of flow increases, the effect of streambed particle size generally decreases, and channel roughness decreases. Channels not fitting this relation consist of those whose banks are much rougher than the bed material, channels in which a dense growth of vegetation impedes the main channel flow, and channels whose cross sections are extremely irregular.

Sediment load

Limited laboratory and field data indicate that small suspended-sediment concentrations result in appreciable reduction in turbulence and roughness in stable channels. The relative effect is hard to assess because information on particle size, settling velocity, and amount of sediment present in the flow are needed. In addition, if sufficient sand is available, large changes in roughness result from changes in bed configuration associated with sand-bed channels. As the flow increases, larger bed material, as bed load, is moved by rolling or sliding along or temporary suspension above the streambed; this consumes energy, and roughness increases. These problems have not been studied sufficiently for adequate guidelines to be developed.

Adjustment Factors

Base *n* values may need to be adjusted to reflect other factors that increase flow resistance. The base *n* value for channel roughness selected from tables or computed from regression equations may need adjustments for cross-section irregularities, channel variations, effects of obstructions, channel vegetation, degree of meandering, and other factors.

The adjustments for base *n* values for channels to determine the entire channel *n* value are shown in table 1 and discussed below. Examples of applying these adjustment factors are given in the section "Procedure for Assigning *n* Values."

Chow's (1959) adjustments (table 1) are applicable when the base *n* is selected for the smoothest reach attainable for a given bed material. The base *n* values of Benson and Dalrymple (1967) generally apply to conditions that are closer to the average and, therefore, their base values need smaller adjustments than do the base values of Chow (1959). Aldridge and Garrett (1973) suggest an adjustment of about two-thirds of the adjustment factors given in table 1. The base *n* values of equations 5 and 6 generally would need adjustment only if the respective channel adjustment was for the severe channel condition. For this condition, the adjustment needs to be about half of the respective maximum value given in table 1.

Extremely rough conditions may need larger adjustments than the largest values given in table 1. The conditions may occur in steep mountain channels or during extreme flood conditions.

Cross-Section Irregularities, n_1

Surface irregularities such as eroded and scalloped stream banks, exposed tree roots, and rock outcrops increase the wetted perimeter, create turbulence, and increase roughness. Generally, the effect of these irregularities increases with depth of flow. Where the ratio of channel width to depth is small, larger adjustments are needed.

Table 1.--*Adjustment factors for the determination of n values for the entire channel*
[Modified from Aldridge and Garrett, 1973]

Channel conditions		*n* value adjustment[1]	Example
Cross-section irregularities, n_1.	Smooth	0.000	Compares to the smoothest channel attainable in a given bed material.
	Minor	0.001-0.005	Compares to carefully dredged channels in good condition but having slightly eroded or scoured side slopes.
	Moderate	0.006-0.010	Compares to dredged channels having moderate to considerable bed roughness and moderately sloughed or eroded side slopes.
	Severe	0.011-0.020	Badly sloughed or scalloped banks of natural streams; badly eroded or sloughed sides of canals or drainage channels; unshaped, jagged, and irregular surfaces of channels in rock.
Channel variations, n_2 (Do not reevaluate channel variation in the hydraulic computations).	Gradual	0.000	Size and shape of channel cross sections change gradually.
	Alternating occasionally.	0.001-0.005	Large and small cross sections alternate occasionally, or the main flow occasionally shifts from side to side owing to changes in cross-sectional shape.
	Alternating frequently.	0.010-0.015	Large and small cross sections alternate frequently, or the main flow frequently shifts from side to side owing to changes in cross-sectional shape.
Effect of obstructions, n_3.	Negligible	0.000-0.004	A few scattered obstructions, which include debris deposits, stumps, exposed roots, logs, piers, or isolated boulders, that occupy less than 5 percent of the cross-sectional area.
	Minor	0.005-0.015	Obstructions occupy less than 15 percent of the cross-sectional area, and the spacing between obstructions is such that the sphere of influence around one obstruction does not extend to the sphere of influence around another obstruction. Smaller adjustments are used for curved smooth-surfaced objects than are used for sharp-edged angular objects.
	Appreciable	0.020-0.030	Obstructions occupy from 15 to 50 percent of the cross-sectional area, or the space between obstructions is small enough to cause the effects of several obstructions to be additive, thereby blocking an equivalent part of a cross section.
	Severe	0.040-0.060	Obstructions occupy more than 50 percent of the cross-sectional area, or the space between obstructions is small enough to cause turbulence across most of the cross section.

Table 1.--*Adjustment factors for the determination of n values for the entire channel*--Continued

Channel conditions		*n* value adjustment[1]	Example
Channel vegetation, n_4.	Small	0.002-0.010	Dense growths of flexible turf grass, such as Bermuda, or weeds growing where the average depth of flow is at least two times the height of the vegetation; supple tree seedlings such as willow, cottonwood, arrowweed, or saltcedar growing where the average depth of flow is at least three times the height of the vegetation.
	Medium	0.010-0.025	Turf grass growing where the average depth of flow is from one to two times the height of the vegetation; moderately dense stemmy grass, weeds, or tree seedlings growing where the average depth of flow is from two to three times the height of the vegetation; brushy, moderately dense vegetation, similar to 1- to 2-year-old willow trees in the dormant season, growing along the banks and no significant vegetation along the channel bottoms where the hydraulic radius exceeds 2 feet.
	Large	0.025-0.050	Turf grass growing where the average depth of flow is about equal to the height of vegetation; 8- to 10-year-old willow or cottonwood trees intergrown with some weeds and brush (none of the vegetation in foliage) where the hydraulic radius exceeds 2 feet; bushy willows about 1 year old intergrown with some weeds along side slopes (all vegetation in full foliage) and no significant vegetation along channel bottoms where the hydraulic radius is greater than 2 feet.
	Very large	0.050-0.100	Turf grass growing where the average depth of flow is less than half the height of the vegetation; bushy willow trees about 1 year old intergrown with weeds along side slopes (all vegetation in full foliage) or dense cattails growing along channel bottom; trees intergrown with weeds and brush (all vegetation in full foliage).
Degree of meandering[1], *m* (Adjustment values apply to flow confined in the channel and do not apply where down-valley flow crosses meanders.)	Minor	1.00	Ratio of the channel length to valley length is 1.0 to 1.2.
	Appreciable	1.15	Ratio of the channel length to valley length is 1.2 to 1.5.
	Severe	1.30	Ratio of the channel length to valley length is greater than 1.5.

[1]Adjustment for cross-section irregularities, channel variations, effect of obstructions, and channel vegetation are added to the base *n* value (tables 2 or 5 or the prediction equations) before multiplying by the adjustment for degree of meandering.

Channel Variations, n_2

Although the shape of a channel has little effect on roughness, changes in the size of cross sections and side-to-side shifting of the low-water channel in successive cross sections (also called channel alignment) will increase hydraulic losses. Gradual changes in channel dimensions do not increase turbulence; however, abrupt variations along the channel increase turbulence and need to be evaluated.

Care needs to be taken not to reevaluate energy losses due to channel variations when making hydraulic computations with available computer models. Several models enable the user to calculate energy losses due to channel variations as a function of contraction or expansion coefficients and the variation of velocity head between successive cross sections.

Obstructions, n_3

Obstructions such as trees, stumps, large boulders, and debris deposits increase roughness and cause backwater upstream and eddy losses downstream. The degree of increased roughness can be evaluated in terms of reduction in cross-sectional area, which depends on the type, size, shape, number, and distribution of the obstructions. The effect of the obstruction increases with velocity as the area of the disturbance surrounding the obstruction increases and may overlap with nearby obstruction disturbances. Chow (1959) did not define the adjustments; therefore, adjustments for the four degrees of obstruction given in table 1 are based on guidelines provided by Aldridge and Garrett (1973).

Free fall may result from the combined effect of several severe obstructions that act like a weir; under these conditions Manning's equation is invalid. This problem can be avoided by the proper location of cross sections.

Channel Vegetation, n_4

The effect of bank vegetation is to increase turbulence and roughness and reduce channel capacity. At three of the sites (fig. 11), as the depth of flow in the main channel increased and encompassed bank vegetation, channel roughness increased. This is particularly true for narrow channels. The magnitude of this effect depends on the vegetation height related to depth of flow, the capacity of the type of vegetation to resist bending, the amount of vegetation that reduces channel capacity, and the time of year. Generally, the effect of the vegetal cover on resistance is greater during the growing season, which corresponds to the flood season in Colorado. During flood flows, floating debris commonly lodges in the vegetation and increases roughness.

The criteria given in table 1 are based on the assumption that vegetation is uniformly distributed in the channel. If the vegetation grows in bands or is prevalent throughout a subarea in the reach, a composite n value needs to be assigned to each subarea and weighted according to the size of the wetted perimeter (eq. 3).

Where the channel vegetation is well established, covers most of the channel, and controls channel roughness, guidelines for overbank flow resistance given in the section "Overbank Flow Resistance" needs to be used to assign *n* values.

Degree of Meandering, *m*

The increase in channel roughness due to small curves and bends generally is considered to be insignificant. The effects of sharp bends may extend for some distance downstream. Streams containing sharp bends need to be divided into a typical reach as previously discussed. The degree of meandering is computed as the ratio of the straight length of the reach under consideration (L_s) divided by the meander length (L_m) of the channel in the reach. The modified value for meandering is obtained by multiplying the total additive effects of the other factors for this reach by L_s/L_m.

When floods in meandering channels are out of the banks and flow down-valley across the meanders, the *n* value is larger. Wormleaton and others (1982) indicate that the traditional methods of calculating the discharge in compound channels (main channel and subdivided overbank flow) do not fully account for energy losses, and that channel discharge capacity is considerably overestimated. Their study indicates that the tendency is further exaggerated when overbank roughness is greater than main channel roughness. No guidelines are presently available for determining the effects of varying roughness in compound channels nor these effects on *n* values, although most floods occupy the overbanks.

CHANNEL FLOW RESISTANCE

Natural Channels

Median particle size generally is used to classify natural stream channels as either stable or movable (sand) bed. A sand-bed channel is comprised of an unlimited supply of particles less than about 0.079 in. (2 millimeters) in diameter. For sand channels, bed-form roughness associated with movable or sand-bed channels is important and needs to be considered.

Channels composed of coarse material having a median particle size greater than 0.079 in. (2 millimeters) generally are relatively stable; however, even stable channels may be subject to significant bank and bed erosion and act as a movable bed stream at high discharges. If channel erosion has occurred in the past or is anticipated during high flows, it needs to be accounted for in subsequent hydraulic analysis.

Sand-Bed Channels

Resistance to flow in sand-bed (movable) streams varies greatly, depending on the velocity of flow, grain size, shear, and other variables, because the moving bed material takes on different bed forms. The flows that produce the bed forms are classified as lower, transition, and upper regime (Simons and Richardson, 1966). Bed forms of lower regime flows consist of plane bed, ripples, and dunes. Bed forms of upper regime flows consist of moving plane bed, standing waves, and antidunes.

The roughness coefficients for the lower and transition regimes depend on grain size and bed-form roughness at a particular time and are very difficult to assess. Generally, as the flow increases dune formation greatly increases, and the roughness is much greater than the upper-regime flow roughness.

Manning *n* values for upper-regime flow are given in table 2. This table indicates that *n* values in sand channels increase directly with particle size. To determine the roughness of a sandbed stream, an initial *n* value based on the median particle size is selected from table 2.

After the hydraulic properties of the channel section are computed using the Manning equation, the flow regime is checked by computing the ***stream power*** to determine the reliability of the assigned *n* value. Stream power is computed as $62RS_wV$, where 62 is the approximate specific weight of water, in pounds per cubic foot; R is the hydraulic radius, in feet; S_w is the water-surface slope, in foot per foot; and V is the mean velocity, in feet per second.

Table 2.--*Base values of the Manning's n for natural channels*

Channel type and bed material	Median size of bed material: Millimeters	Median size of bed material: Inches	Base *n* value: Benson and Dalrymple (1967)[1]	Base *n* value: Chow (1959)[2]
Sand channels (Upper-regime flow only):				
	0.2	--------	0.012	-----
	.3	--------	.017	-----
	.4	--------	.020	-----
	.5	--------	.022	-----
	.6	--------	.023	-----
	.8	--------	.025	-----
	1.0	--------	.026	-----
Stable channels:				
Firm earth--------	------	--------	0.025-0.032	0.020
Coarse sand-------	1-2	--------	.026- .035	-----
Fine gravel-------	------	--------	-----------	.024
Gravel------------	2-64	0.08-2.5	.028- .035	-----
Coarse gravel-----	------	--------	-----------	.028
Cobble------------	64-256	2.5-10.5	.030- .050	-----
Boulder-----------	>256	>10	.040- .070	-----

[1]Straight uniform channel.
[2]Smoothest channel attributable in indicated material.

The relation of stream power and median grain size to the type of regime flow (modified from Benson and Dalrymple, 1967) is shown in figure 5. If the value $62RS_wV$ plots above the upper line, it may be assumed the upper-regime flow occurs.

If the stream power plots below the upper-regime line, a reliable *n* value cannot be assigned. Methods for evaluating depth-discharge relations for the lower- and transition-regime flows, which are beyond the scope of this report, are discussed in Simons and Senturk (1977).

Stable Channels

The base *n* values for a stable channel normally range from about 0.025 for firm earth to about 0.070 or larger for large-boulder channels and shallow depths as shown in table 2. These values are based on verification studies; however, the values have a wide range because the effects of bed roughness are difficult to separate from the effects of other roughness factors. The roughness of a reach in exposed bedrock can be evaluated in terms of the average height of rock protrusions above the bedrock surface and by using this value as an indicator of median diameter in table 2. Large boulders scattered in a stream need to be considered as channel obstructions. Personal experience and judgment will influence the selection of the base *n* value.

Analysis of available verified stream *n* value data indicates *n* values vary with depth of flow (see section "Depth of Flow"). This is true for many streams in Colorado. Prediction equations have been developed to assess the base channel roughness to assist in the determination of *n* values from onsite inspection or from photographs. Two equations are presented, one by Limerinos (1970) for generally lower-gradient channels and one developed in this study for higher-gradient channels. In this report, a higher-gradient stream is defined as one having slopes greater than 0.002. The Limerinos equation is, however, valid on streams steeper than 0.002, but its upper limit has not been ascertained.

Equation for predicting roughness coefficients of lower-gradient natural channels

Limerinos (1970) related *n* to hydraulic radius and particle size, based on samples from 11 predominantly *lower-gradient stream* channels having bed material ranging from small gravel to medium-size boulders. Particles have three different diameters or dimensions--length, width, and thickness--and generally are oriented so that length and width are about parallel to the plane of the streambed. Limerinos (1970) related *n* to minimum diameter (thickness) and to intermediate diameter (width); his equation using intermediate diameter seems to be the most useful because this dimension is the one most easily measured by screening, by photographs, and by onsite evaluation.

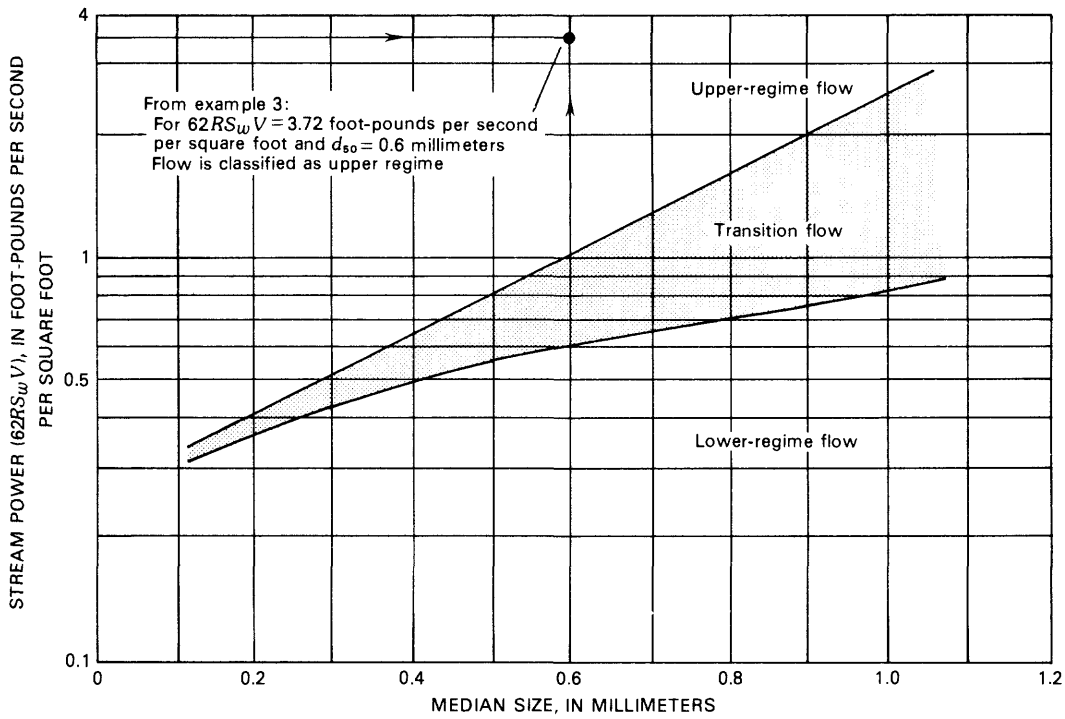


Figure 5.--Relation of stream power and median grain size to type of regime flow. Modified from Benson and Dalyrymple (1967).

The equation for n, using the intermediate diameter is

$$n = \frac{(0.0926)R^{1/6}}{1.16 + 2.0 \log \frac{R}{d_{84}}} \quad , \qquad (5)$$

where

d_{84} = the particle intermediate diameter, in feet, that equals or exceeds that of 84 percent of the particles.

Limerinos (1970) selected reaches having a minimum roughness other than that caused by bed material. Therefore, his values correspond to the base values given by Benson and Dalrymple (1967) and shown in table 2.

Equation for predicting roughness coefficients of higher-gradient natural channels

Existing guidelines for selecting roughness coefficients were developed primarily for lower-gradient streams having relatively large flow depths. Many streams in Colorado have higher-gradient channels (slopes greater than 0.002) and shallow flow depths. In these streams, most of the flow is in the main channel.

Available verified data are very limited for high-gradient streams (slopes greater than 0.01); however, many streams channels in Colorado are much steeper. Estimating n values using existing guidelines are difficult for these steeper streams. Therefore, for this report, additional verification data were collected on streams with slopes greater than 0.002 in Colorado to complement existing data. This report summarizes hydraulic studies of hydraulics on high-gradient streams (Jarrett, 1984).

Current-meter discharge measurements and onsite surveys were made at 21 higher-gradient natural stream sites in Colorado to compute channel roughness by the Manning formula. These sites, shown in figure 6, were selected to provide a wide range in channel types and flow depths and to represent average main channel flow resistance. Photographs of typical higher-gradient stream channels studied are shown on figures 7 to 9. The maximum discharges at these sites were equivalent to floods having about a 1 to 25-year *recurrence interval*. A detailed description of fieldwork and computational procedures used in computing the discharges are discussed in Benson and Dalrymple (1967), Wolman (1954), and Barnes (1967).

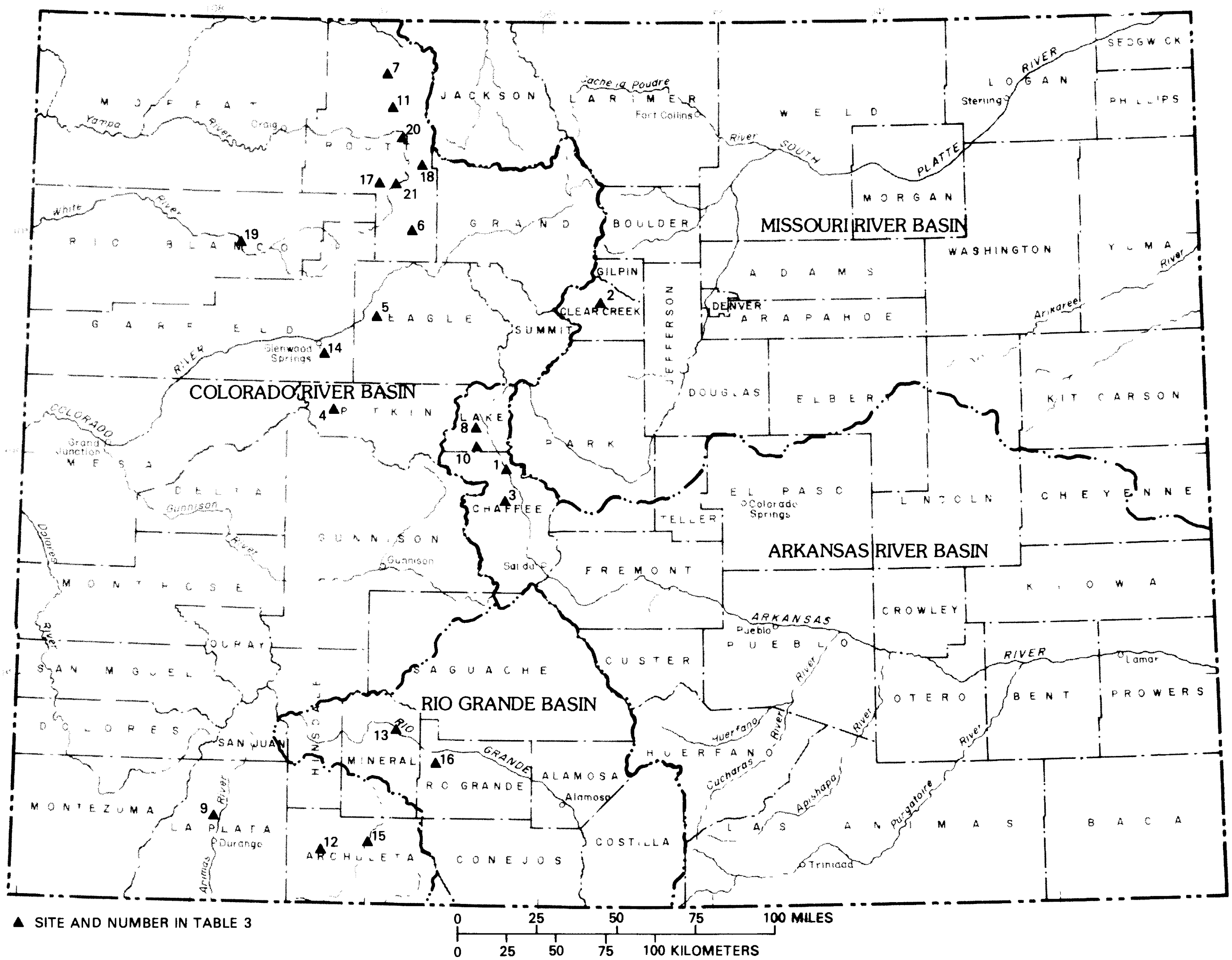


Figure 6.--Location of *n*-verification sites.

A.

B.

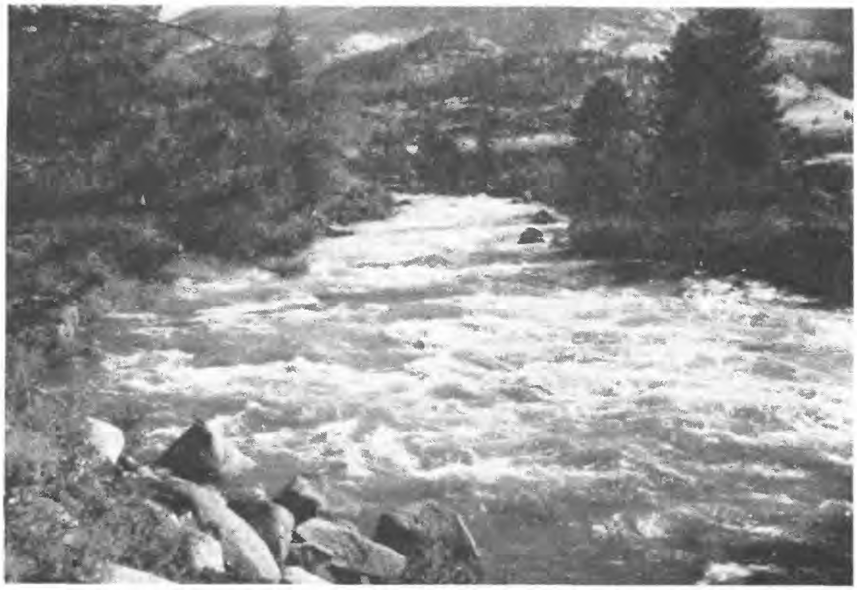
Figure 7.--Downstream view of Trout Creek near Oak Creek: A, at low flow; B, at high flow.

A.

B.

Figure 8.--Upstream view of Lake Creek above Twin Lakes Reservoir: A, at low flow; B, at high flow.

A.



B.

Figure 9.--Upstream view of Arkansas River at Pine Creek School, above Buena Vista: A, at low flow; B, at high flow.

A summary of *n*-verification data for hydraulic variables for the 21 sites is given in table 3. The few inconsistencies in the data (for example, the slopes at site 11) are due to difficulties in data collection as a result of the extremely turbulent flow conditions. These data indicate the wide range of channel roughness accompanying depth of flow (in terms of hydraulic radius) for seven sites as shown in figures 10 and 11. Where channel roughness changes dramatically with depth of flow, it is difficult to select *n* values by any of the available methods. These roughness-depth relations indicate the need for an accurate and reliable method of estimating *n* values on higher-gradient streams.

Standard hydraulic theory and analysis indicate that when slope exceeds critical slope, that is, when the ***Froude number*** exceeds unity, greater velocities and supercritical flow result. The onsite data collected for this study (table 3) and that of Barnes (1967), Limerinos (1970), and Thompson and Campbell (1979), and other data for slopes as steep as 0.052, indicate that Froude numbers computed from average section properties are less than unity, subcritical flow, in higher-gradient mountain streams. Davidian (1984) indicates Froude numbering rarely exceed unity for any time period in a natural stream with erodible banks. At velocities greater than those listed in table 3, the combined effects of channel and cross-section variations seem to create extreme turbulence and energy losses that result in increased flow resistance. Studies of the flow resistance of boulder-filled streams by Herbich and Shulits (1964) and Richards (1973) indicate that there is a spill-resistance component with increasing flow. Spill resistance is a result of increased turbulence and roughness resulting from the velocity of water striking the large area of protruding bed-roughness elements and eddy currents set up behind the larger boulders. Aldridge and Garrett (1973) believe the effect of the disturbance of water surrounding boulders and other obstructions increases with velocity and may overlap with nearby obstruction disturbances and further increase turbulence and hence roughness. In larger magnitude floods, additional energy is consumed transporting bed material.

Several investigators have noted supercritical flow under certain conditions. These conditions have included flow in concrete, sand, or smooth rock channels. Dobbie and Wolf (1953), Thompson and Campbell (1979), and the author believe *n* values for cobble- and boulder-bed streams are much greater than those normally selected, and flows approach, but do not exceed, ***critical flow*** for any significant length of stream. For these conditions of steep slopes, cobble- and boulder-bed material channels, and extreme flows, a limiting assumption of subcritical to critical flow in subsequent hydraulic analyses seems reasonable. If supercritical flow is indicated in the hydraulic analysis for long lengths of channel, a reevaluation of roughness coefficients probably will show all energy losses were not accounted for.

Most equations used to predict channel roughness need streambed particle-size information, which often is time-consuming and difficult to obtain. ***Correlation coefficients*** for selected hydraulic characteristics of the Colorado data are shown in table 4. The correlation coefficient for Manning's *n* is greater for friction slope than for streambed particle size. This implies that the channel roughness associated with streambed material size can be evaluated in terms of the more easily obtained friction slope.

Table 3.--*Summary of basic data and results of using the prediction equation for Colorado streams*

Site number	Discharge[1] (cubic feet per second)	Average values for reach: Area (square feet)	Width (feet)	Velocity (feet per second)	Froude number	Friction slope	Water slope	Hydraulic radius (feet)	Hydraulic depth (feet)	Manning's *n*	Predicted *n* (equation 6)	Deviation of computed from observed value (percent)
1	Arkansas River at Pine Creek School, above Buena Vista (lat 38°58'38", long 106°12'46") (Miscellaneous site)											
	925	249	69	3.72	0.35	0.026	0.026	3.24	3.61	0.142	0.081	-43
	1,450	340	73	4.30	.35	.023	.022	3.99	4.66	.132	.074	-44
	2,120	407	78	5.27	.40	.021	.020	4.46	5.22	.112	.071	-37
	2,760	454	79	6.11	.45	.025	.024	4.85	5.75	.110	.074	-32
	4,530	526	80	8.65	.60	.026	.023	5.51	6.58	.086	.074	-14
2	Clear Creek near Lawson (lat 39°45'57", long 105°37'32") (Station 06716500)											
	53	43	42	1.25	0.22	0.015	0.015	1.02	1.02	0.138	0.079	-43
	214	71	46	3.00	.42	.017	.017	1.50	1.54	.084	.078	-7
	360	102	49	3.58	.44	.018	.018	2.00	2.08	.084	.076	-10
	765	141	52	5.48	.59	.019	.020	2.60	2.71	.067	.074	11
3	Cottonwood Creek below Hot Springs, near Buena Vista (lat 38°48'46", long 106°13'18") (Station 09089000)											
	31	21	24	1.48	0.28	0.030	0.030	0.90	0.88	0.159	0.104	-34
	115	36	29	3.24	.51	.034	.034	1.20	1.24	.097	.104	7
	281	43	30	6.61	.97	.033	.039	1.51	1.43	.052	.100	92
	[2]465	67	33	6.98	.86	.030	.028	1.85	2.03	.058	.093	60
4	Crystal River above Avalanche Creek, near Redstone (lat 39°13'56", long 107°13'36") (Station 09081600)											
	83	60	82	1.40	0.29	0.003	0.003	0.72	0.73	0.045	0.046	2
	272	112	88	2.44	.38	.004	.005	1.27	1.27	.046	.047	4
	530	161	95	3.32	.45	.004	.005	1.70	1.70	.041	.045	11
	1,220	220	94	5.58	.65	.004	.006	2.24	2.34	.028	.042	50
5	Eagle River below Gypsum (lat 39°38'58", long 106°57'11") (Station 09070000)											
	204	123	101	1.66	0.27	0.003	0.003	1.21	1.21	0.054	0.041	-24
	224	125	92	1.89	.29	.004	.004	1.35	1.36	.051	.045	-13
	233	135	94	1.82	.28	.004	.002	1.42	1.44	.052	.043	-17
	577	226	112	2.60	.33	.004	.004	2.02	2.02	.050	.043	-14
	2,300	443	125	5.19	.48	.004	.004	3.51	3.54	.041	.038	-7
	3,710	528	129	7.04	.61	.004	.005	4.03	4.09	.037	.040	8
6	Egeria Creek near Toponas (lat 40°02'12", long 106°46'56") (Miscellaneous site)											
	14	14	26	0.98	0.24	0.003	0.003	0.60	0.54	0.057	0.046	-19
	26	19	27	1.36	.28	.003	.003	.70	.70	.044	.043	-2
	111	42	36	2.63	.42	.002	.002	1.17	1.17	.030	.038	-29
7	Elk River at Clark (lat 40°43'03", long 106°54'55") (Station 09241000)											
	39	39	59	1.01	0.22	0.003	0.003	0.60	0.66	0.058	0.047	-18
	254	105	72	2.42	.35	.004	.004	1.50	1.46	.052	.046	-10
	1,050	185	81	5.73	.66	.006	.005	2.30	2.28	.034	.048	41
	1,410	272	90	5.21	.53	.006	.005	2.98	3.02	.044	.045	2

Table 3.--*Summary of basic data and results of using the prediction equation for Colorado streams*--Continued

Site number	Discharge[1] (cubic feet per second)	Average values for reach: Area (square feet)	Width (feet)	Velocity (feet per second)	Froude number	Friction slope	Water slope	Hydraulic radius (feet)	Hydraulic depth (feet)	Manning's *n*	Predicted *n* (equation 6)	Deviation of computed from observed value (percent)
8	Halfmoon Creek near Malta (lat 39°10'20", long 106°23'19") (Station 07083000)											
	12	14	29	0.88	0.23	0.011	0.011	0.50	0.48	0.109	0.079	-28
	94	35	32	2.73	.46	.016	.016	1.05	1.09	.062	.080	28
	242	48	32	5.06	.73	.014	.015	1.42	1.50	.042	.072	73
9	Hermosa Creek near Hermosa (lat 37°25'19", long 107°50'40") (Station 09361000)											
	493	122	53	4.05	0.47	0.019	0.019	2.23	2.30	0.087	0.076	-13
	1,380	224	78	6.26	.66	.014	.014	2.85	2.87	.052	.065	26
	1,580	252	82	6.36	.65	.014	.014	3.03	3.07	.054	.065	20
	1,800	264	84	6.94	.70	.014	.014	3.36	3.14	.049	.063	28
10	Lake Creek above Twin Lakes Reservoir (lat 39°03'47", long 107°50'40") (Station 07084500)											
	148	68	53	2.21	0.35	0.019	0.019	1.20	1.28	0.098	0.084	-15
	830	147	64	5.70	.67	.023	.023	2.12	2.30	.062	.083	33
	1,360	185	68	7.41	.79	.024	.024	2.53	2.72	.056	.082	47
11	Mad Creek near Steamboat Springs (lat 40°33'56", long 106°53'19") (Miscellaneous site)											
	48	32	54	1.53	0.35	0.026	0.026	0.60	0.59	0.117	0.106	-10
	92	46	56	2.03	.39	.026	.026	.80	.82	.108	.100	-7
	331	91	61	3.72	.54	.025	.027	1.40	1.49	.082	.091	11
	409	127	63	3.27	.41	.021	.023	1.92	2.02	.105	.081	-22
12	Piedra River at Piedra (lat 37°13'20", long 107°20'32") (Station 09349500)											
	2,920	419	109	6.97	0.63	0.004	0.004	3.80	3.84	0.034	0.039	15
	3,170	451	110	7.03	.61	.004	.005	4.03	4.10	.037	.040	9
13	Rio Grande at Wagonwheel Gap (lat 37°46'01", long 106°49'51") (Station 08217500)											
	151	103	116	1.47	0.28	0.004	0.004	0.89	0.89	0.058	0.049	-15
	2,060	453	152	4.56	.46	.004	.004	2.97	2.98	.041	.039	-3
	4,040	680	170	5.94	.52	.003	.004	3.98	4.00	.035	.036	1
14	Roaring Fork River at Glenwood Springs (lat 39°32'37", long 107°19'44") (Station 09085000)											
	571	245	145	2.34	0.32	0.002	0.003	1.73	1.69	0.044	0.037	-16
	650	256	147	2.56	.35	.002	.003	1.80	1.74	.041	.036	-11
	1,170	366	158	3.19	.37	.003	.003	2.32	2.32	.043	.037	-13
	3,260	559	170	5.83	.57	.003	.004	3.29	3.29	.032	.037	14
15	San Juan River at Pagosa Springs (lat 37°15'58", long 107°00'37") (Station 09342500)											
	2,700	396	119	6.84	0.66	0.008	0.008	3.34	3.33	0.042	0.050	20
	3,175	434	126	7.34	.70	.007	.007	3.43	3.44	.038	.049	32

Table 3.--*Summary of basic data and results of using the prediction equation for Colorado streams*--Continued

Site number	Discharge[1] (cubic feet per second)	Average values for reach: Area (square feet)	Width (feet)	Velocity (feet per second)	Froude number	Friction slope	Water slope	Hydraulic radius (feet)	Hydraulic depth (feet)	Manning's *n*	Predicted *n* (equation 6)	Deviation of computed from observed value (percent)
16		South Fork Rio Grande at South Fork (lat 37°39'25", long 106°38'55") (Station 08219000)										
	70	48	49	1.51	0.27	0.009	0.009	0.98	0.98	0.087	0.064	-26
	800	157	64	5.12	.58	.007	.006	2.44	2.45	.043	.050	17
	[2]1,450	271	75	5.36	.50	.007	.007	3.52	3.61	.052	.048	-7
17		Trout Creek near Oak Creek (lat 40°18'44", long 107°00'34") (Miscellaneous site)										
	13	11	22	1.23	0.31	0.016	0.016	0.50	0.5	0.089	0.091	2
	29	14	23	2.11	.48	.017	.018	.60	.61	.065	.091	41
	57	19	25	2.97	.59	.016	.016	.80	.76	.053	.084	60
	164	31	26	5.36	.87	.013	.015	1.13	1.19	.033	.074	123
	[2]190	54	33	3.54	.49	.013	.014	1.57	1.64	.064	.070	10
18		Walton Creek near Steamboat Springs (lat 40°34'39", long 106°47'11") (Station 09238500)										
	234	73	46	3.27	0.45	0.027	0.027	1.63	1.59	0.103	0.091	-11
	590	110	51	5.46	.66	.031	.034	1.87	2.16	.074	.095	28
19		White River above Coal Creek, near Meeker (lat 40°00'18", long 107°49'29") (Station 09304200)										
	358	154	61	2.40	0.32	0.002	0.002	1.80	2.52	0.039	0.032	-18
	1,350	276	88	4.91	.49	.003	.003	3.10	3.14	.034	.034	0
	1,740	314	95	5.54	.54	.004	.004	3.25	3.31	.035	.038	8
20		Yampa River at Steamboat Springs (lat 40°29'01", long 106°49'54") (Station 09239500)										
	86	63	68	1.37	0.25	0.006	0.006	0.90	0.93	0.074	0.056	-24
	335	117	86	2.89	.44	.006	.006	1.30	1.36	.047	.052	11
	1,170	250	103	4.68	.53	.005	.005	2.40	2.43	.041	.046	11
	1,870	282	105	6.64	.71	.005	.006	2.66	2.69	.032	.045	44
21		Yampa River near Oak Creek (lat 40°16'47", long 106°50'50") (Miscellaneous site)										
	51	29	38	1.85	0.38	0.004	0.004	0.76	0.76	0.041	0.049	20
	119	44	42	2.74	.48	.004	.005	1.10	1.05	.034	.047	38
	135	50	42	2.72	.44	.004	.005	1.20	1.19	.038	.048	25
Range:												
Minimum	12	11	22	0.88	0.22	0.002	0.002	0.50	0.48	0.028	0.032	-44
Maximum	4,530	680	170	8.65	.97	.034	.039	5.51	6.58	.159	.106	123

[1]Discharge does not exactly equal the product of area and velocity because they are average values for the reach.
[2]Not used to develop prediction equation because bank vegetation was extremely dense.

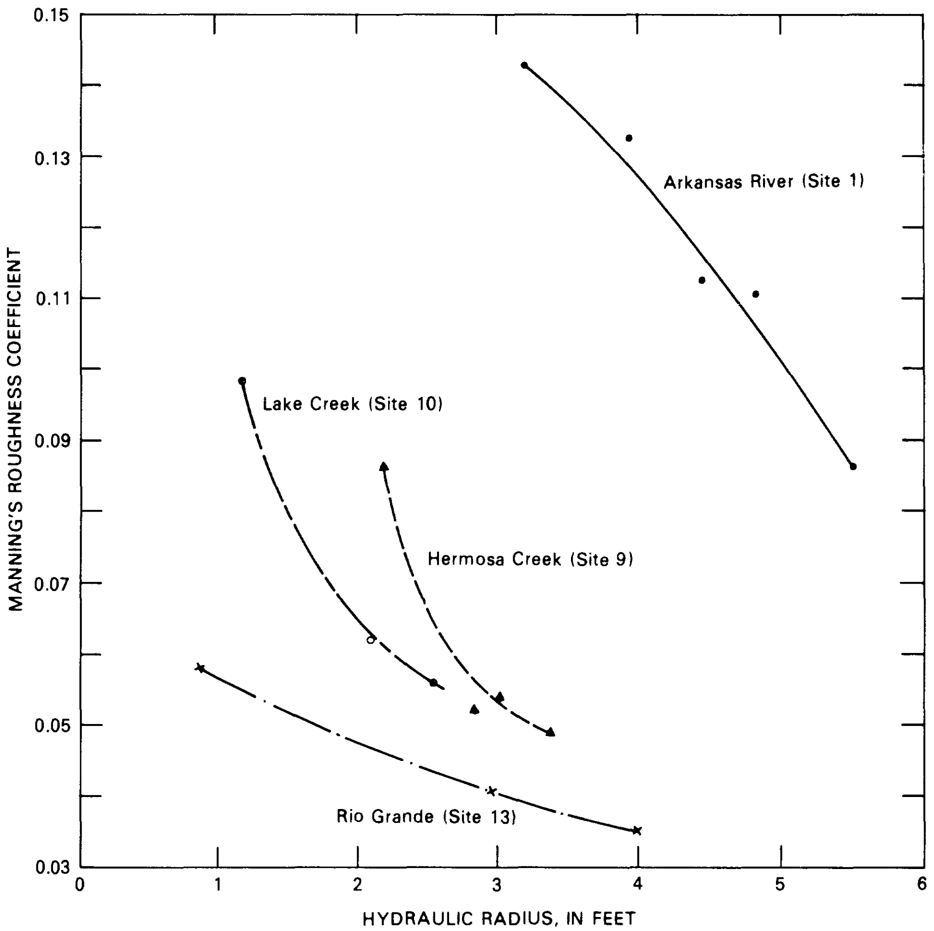


Figure 10.--Relation between Manning's roughness coefficient and hydraulic radius.

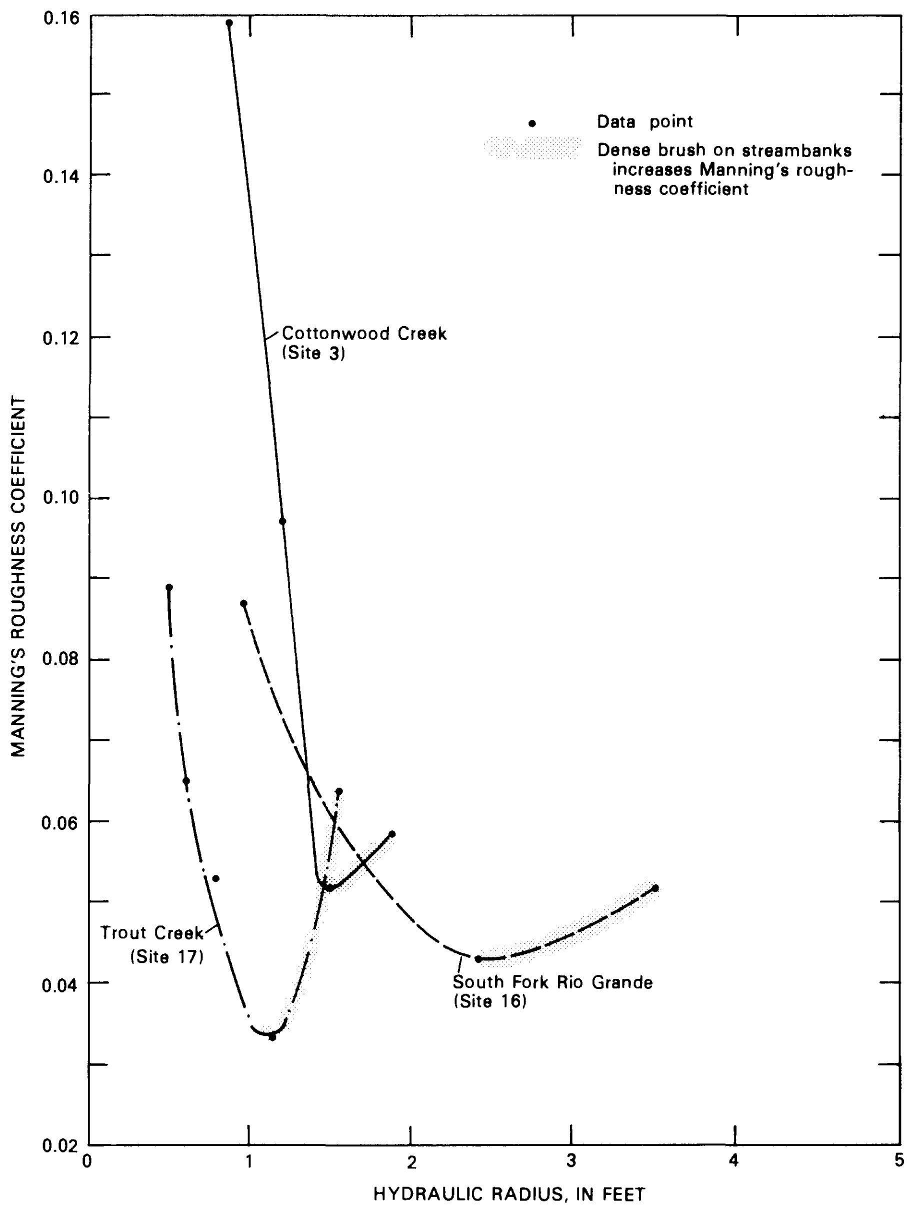


Figure 11.--Effect of streambank vegetation on the relation between Manning's roughness coefficient and hydraulic radius.

Table 4.--*Correlation coefficients for selected hydraulic characteristics*
[Coefficients were computed using untransformed data]

	Manning's coefficient, n	Friction slope, S_f	Water slope, S_w	Bed material size, d_{84}	Hydraulic radius, R	Hydraulic depth, D	Discharge, Q
n-----	1.00	0.71	0.68	0.64	-0.09	-0.04	-0.23
S_f----	----	1.00	.99	.66	.02	.07	-.12
S_w----	----	----	1.00	.62	-.02	.04	-.14
d_{84}---	----	----	----	1.00	.33	.39	.12
R-----	----	----	----	----	1.00	.99	.91
D-----	----	----	----	----	----	1.00	.88
Q-----	----	----	----	----	----	----	1.00

The method for predicting channel roughness uses *multiple-regression analysis*, which relates Manning's roughness coefficient to easily measured hydraulic characteristics of Colorado streams. The hydraulic characteristics used in the equation for predicting Manning's n for higher-gradient natural channels are defined below:

Energy gradient, S_f--The energy gradient or friction slope is the slope of the energy line of a body of flowing water. The Manning equation was developed for conditions of uniform flow in which the water and friction slopes are parallel. For these data, this condition was met because the two variables had approximately the same value. The correlation between the water and friction slopes was 0.99; therefore these two variables can be used interchangeably in the Manning equation provided the reach is reasonably uniform;

Hydraulic radius, R--Hydraulic radius is a measure of the boundary area causing friction per unit of flow and is computed as the cross-sectional area of a stream of water perpendicular to flow divided by the wetted perimeter. Cross-section area and wetted perimeter are obtained from onsite surveys. By standard practice, the wetted perimeter does not include surface irregularities of submersed stream-bed particles. Hydraulic depth, D, the cross-sectional area divided by top width, generally can be used in place of hydraulic radius in uniform reaches because the two variables had approximately the same value, and the correlation coefficient between them was 0.99.

The largest discharge measurements for Cottonwood Creek, South Fork Rio Grande, and Trout Creek were not used to develop the equation for predicting Manning's *n* because of the extreme effects of bank vegetation, as shown in figure 11. The resulting equation developed for predicting Manning's *n* for higher gradient natural channels is:

$$n = 0.39\, S_f^{0.38} R^{-0.16} \qquad (6)$$

and is graphically depicted in figure 12. The average ***standard error of estimate*** is 28 percent with a range of -24 to +32 percent. The predicted *n* value and deviation of computed from observed value is shown in table 3.

Barnes' (1967) and Limerinos' (1970) data were used to determine if equation 6 produced reasonable results and to determine its range of applicability. For slopes greater than 0.002 and a hydraulic radius less than 7 ft, the standard deviation of the percentage differences was 23 percent and ranged from -44 to +50 percent. An application of this equation is given later in the report in the section entitled, "Procedure for assigning *n* values."

The following limitations need to be observed when using the Manning *n* prediction equation as an aid in evaluating channel roughness:

1. The equation is applicable to natural main channels having relatively stable bed and bank material (cobble- and boulder-bed material), for average factors affecting roughness coefficients.

2. The equation is applicable within a range of slopes from 0.002 to 0.04 and for hydraulic radii from 0.5 to 7 ft. The upper limit on slope is due to a lack of verification data available for the slopes of high-gradient streams. Caution needs to be used in applying available hydraulic equations to streams with slopes greater than 0.04 because the applicability of the equations is questionable. Results of the regression analyses indicated that for a hydraulic radius greater than 7 ft, *n* did not vary significantly with depth; hence, extrapolation to large flow depths should not be too much in error as long as the bed and bank material remain fairly stable.

3. The energy loss coefficients due to acceleration or deceleration of velocity in a contracting reach were assumed to 0 and in an expanding reach were assumed to be 0.5. Analysis of the data indicates moderate to severe natural channel expansions caused large energy losses, and the expansion coefficient needs to be increased in these reaches.

4. The equation is not applicable in reaches of stream affected by backwater from downstream obstructions.

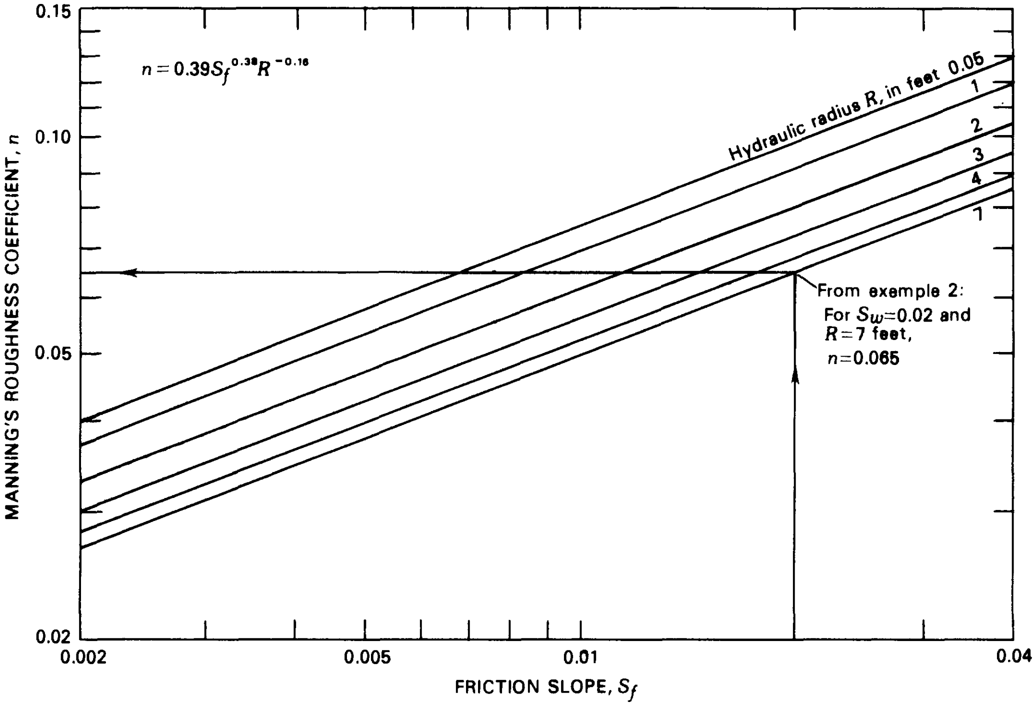


Figure 12.--Relation between Manning's roughness coefficient and friction slope and hydraulic radius.

Modified Channels

Flow resistance in modified channels can vary significantly depending on whether the stream is in its natural state or has been modified by man. The roughness characteristics of modified or constructed channels depend on the type of modification or construction. For those channels that retain some or most of their natural characteristics, all pertinent factors described in the preceding section need to be considered. The roughness coefficient for such stream channels needs to be selected according to the procedure described in that section.

Many streams have had their natural characteristics modified; channel designs are needed for modifying natural and existing conditions by realignment--straightening, dredging, and lining with natural or manmade materials. Generally, these channels are modified for esthetic reasons, for reduction of overbank flooding, for increasing conveyance within a limited right-of-way, or for prevention of erosion. Considerable verification data have been compiled for constructed channels, and the data from table 5 may be used to estimate the base *n* value. Minimum, normal, and maximum ranges of *n* values for each type of channel are included in table 5.

Table 5.--*Base values of n for modified channels*
[Modified from Aldridge and Garrett, 1973]

Type of channel and description	*n* value		
	Minimum	Normal	Maximum
A. Lined or built-up channels			
1. Concrete:			
a. Finished ----------------------	0.011	0.015	0.016
b. Unfinished --------------------	.014	.017	.020
2. Gravel bottom with sides of:			
a. Formed concrete ---------------	.017	.020	.025
b. Random stone in mortar---------	.020	.023	.026
c. Dry rubble or riprap-----------	.023	.033	.036
3. Vegetal lining --------------------	.030	-----	.500
B. Excavated or dredged channels			
1. Earth, straight and uniform:			
a. Clean, after weathering -------	.018	.022	.025
b. Gravel, uniform section, clean-	.022	.025	.030
c. With short grass, few weeds ---	.022	.027	.033

Table 5.--*Base values of n for modified channels*--Continued

Type of channel and description	n value		
	Minimum	Normal	Maximum
B. Excavated or dredged channels--Continued			
2. Earth, winding and sluggish:			
a. No vegetation -----------------	0.023	0.025	0.030
b. Grass, some weeds -------------	.025	.030	.033
c. Dense weeds or aquatic plants in deep channels ------------	.030	.035	.040
d. Earth bottom and rubble sides--	.028	.030	.035
e. Stony bottom and weedy banks --	.025	.035	.040
f. Cobble bottom and clean sides--	.030	.040	.050
3. Drag-line excavated or dredged:			
a. No vegetation -----------------	.025	.028	.033
b. Sparse brush on banks ---------	.035	.050	.060
4. Rock cuts:			
a. Smooth and uniform ------------	.025	.035	.040
b. Jagged and irregular ----------	.035	.040	.050
5. Channels not maintained, weeds and brush uncut:			
a. Dense weeds, high as depth of flow ------------------------	.050	.080	.120
b. Clean bottom, brush on sides --	.040	.050	.080
c. Dense brush, high stage -------	.080	.100	.140

An important aspect of selecting the base roughness coefficients for a constructed channel is a realistic appraisal of whether and how periodic maintenance will be done. While design values of *n* for newly constructed channels may be very small, the roughness may increase with time and may lead to significant changes in water-surface elevations, unless periodic maintenance such as mowing grass-lined channels, weed control, repair of broken concrete or rock linings, and removal of debris is done.

OVERBANK FLOW RESISTANCE

In general, overbank flow resistance is affected by factors similar to those affecting channel flow resistance, and an evaluation of the roughness characteristics should take all factors into consideration. The relative effect of these factors may, however, vary significantly between main channel and overbank roughness and between various types of overbanks. To some extent, roughness coefficients in overbanks can be evaluated in a manner similar to that of channel roughness. Generally, very little verified data are available for overbank roughness. Factors affecting overbank roughness and procedures for estimating roughness coefficients for natural, agricultural, and urban flood plains are described in the following sections.

Natural Overbanks

In general, the most significant factors affecting flow resistance in natural overbanks are the amount, type, and density of vegetation. Although other factors may have relatively little effect on roughness, they need to be evaluated as well.

Because very little verified *n* value data are available for overbank flow, considerable personal judgment is involved. General guidelines for estimating values of *n* for overbanks are given in table 6. The factors to be considered in evaluating roughness for minimum, normal, and maximum conditions on overbanks are discussed below.

Surface roughness and bed-material size generally are finer on the overbanks than in channels. Bed materials generally are sand and silt except along mountain streams where deposits may be similar to streambed deposits. If there is considerable vegetal cover, the bed materials may have little effect on the roughness values. If particle size seems to dominate overbank roughness, the procedure for determining the *n* values of natural channels needs to be used.

Most overbank surface irregularities are due to sediment ridges, old meander scars, and potholes. These irregularities increase turbulence and roughness. Flood-plain widths generally do not change rapidly within a reach, and expansion and contraction losses are not significant. Obstructions may be due to roads, fences, irrigation ditches, brush, debris, and downed trees. These obstructions increase turbulence and roughness.

Generally, the type, amount, and distribution of vegetation have the greatest effect on overbank roughness. A dense cover of grass can completely obscure the effects of surface materials; dense brush and trees can obstruct flows significantly, reducing overbank conveyance to a minimum. Seasonal changes in vegetation density and cover need to be considered. In general, Colorado streams flood in the spring and summer when vegetation growth and density are at their maximum.

No adjustments for meandering are taken for overbank flow, because flow generally is directly downvalley. The most significant factor to consider is whether the depth of flow and flow velocity are sufficient to bend the vegetation over. Generally, flows exceeding 1.0 ft in depth are capable of bending grass. Grass and brush that can be bent over offer greatly reduced resistance to flow. The velocity of flow will depend on the overbank roughness and channel gradient.

Values of *n* may exceed the maximum values shown in table 6. Petryk and Bosmajian (1977) reports that the *n* value may be as large as 0.40 in heavily vegetated flood plains. Arcement and Schneider (1984) have developed a guide, consisting of quantitative procedures and photographs, to help determine roughness coefficients for densely vegetated overbanks in tranquil flowing streams.

Table 6.--*Values of n for different types of vegetation on overbank areas*
[From Chow, 1959]

Overbank cover	*n* value		
	Minimum	Normal	Maximum
A. Pasture, no brush:[1]			
1. Short grass--------------------	0.025	0.030	0.035
2. High grass---------------------	.030	.035	.050
B. Cultivated areas:[1]			
1. No crop------------------------	.020	.030	.040
2. Mature row crops---------------	.025	.035	.045
3. Mature field crops-------------	.030	.040	.050
C. Brush:[1]			
1. Scattered brush, dense weeds---	.035	.050	.070
2. Sparse brush and trees, in winter----------------------	.035	.050	.060
3. Sparse brush and trees, in summer----------------------	.040	.060	.080
4. Medium to dense brush, in winter----------------------	.045	.070	.110
5. Medium to dense brush, in summer---------------------	.070	.100	.160
D. Trees			
1. Dense growth of willows, summer, straight--------------------	.110	.150	.200
2. Cleared land with tree stumps, no sprouts-------------------	.030	.040	.050
3. Same as above, but with dense growth of sprouts------------	.050	.060	.080
4. Dense stand of timber, a few down trees, little undergrowth, flood stage below branches---	.080	.100	.120
5. Same as above, but with flood stage reaching branches------	.100	.120	.160

[1]Shallow depths accompanied by an irregular ground surface in pastureland or brushland and by deep furrows perpendicular to the flow in cultivated fields can increase *n* values by as much as 0.02.

Agricultural Overbanks

When evaluating the roughness characteristics of agricultural overbanks, all the previously described factors except meandering need to be considered. Guidelines for estimating *n* values for agricultural overbanks are given in table 6. In evaluating overbank roughness with respect to minimum, normal, and maximum conditions, the following need to be considered. Removal of dense natural vegetation will decrease roughness. Leveling and regrading for cultivation, irrigation, and drainage may smooth out natural surface irregularities. Construction of roads, irrigation ditches, and laterals may obstruct flow. Type and orientation of crops with respect to the direction of flow can significantly affect *n* values. Row crops parallel to the direction of flow offer less resistance to flow than field crops or row crops planted transverse to the direction of flow. Roughness characteristics can be significantly affected by the depth of flow. General guidelines on changing *n* values with depth of flow are given in table 7.

It may be necessary to revise initial values after a preliminary hydraulic calculation has been made and depth of flow has been more accurately determined. Several computer models enable the user to input a varying *n* value with-depth relation. Probable flood-season, crop-growth conditions need to be considered when selecting n values.

Because it is difficult or impossible to predict farming practices--which fields will lie fallow, what types of crops will be planted--selection of roughness coefficients needs to be based on typical growing-season conditions.

Table 7.--*Sample values of n for agricultural overbank areas under various stages for the average growing season*
[From Chow, 1959]

Depth of water, in feet	Flood-plain cover[1]				
	Corn	Pasture	Meadow	Small grains	Brush and waste
Less than 1---	0.06	0.05	0.10	0.10	0.12
1 to 2--------	.06	.05	.08	.09	.11
2 to 3--------	.07	.04	.07	.08	.10
3 to 4--------	.07	.04	.06	.07	.09
More than 4---	.06	.04	.05	.06	.08

[1]From studies on the Nishnabotna River, Iowa.

Urban Overbanks

Urban development in overbank areas may significantly alter the roughness characteristics of natural areas. Removal of natural vegetation, grading, paving, construction of roads, streets with curbs and gutters, buildings, and fences may completely alter the natural roughness characteristics.

Generally, grading and paving, especially parallel to the direction of flow, will reduce turbulence and roughness. Conversely, construction of buildings, fences, and other obstructions can significantly reduce the total area of flow and increase turbulence and roughness.

Because there are little or no verified data for estimating roughness coefficients for urban areas containing buildings, two basic approaches have been used for calculating roughness coefficients for flow in urban areas. These approaches are: (1) Eliminating that part of the overbank cross section occupied by buildings and other obstructions, and selecting a roughness coefficient for the effective area of flow between the buildings; and (2) using the total area of the overbank cross section for estimating a roughness value that includes the effect of buildings and other obstructions (Hejl, 1977).

Using either approach, the following factors need to be considered. Buildings aligned with each other tend to produce less turbulence; rows of buildings and fences aligned parallel to the general direction of flow tend to produce less turbulence than the same structures at an angle to the direction of flow; chain link fences tend to catch debris resulting in decreased conveyance; and solid board fences at an angle to the flow can block flow completely unless they are pushed over by the force of the water. Both approaches need subjective judgment to evaluate all factors involved.

An objective method was developed by Hejl (1977) for determining the n values of flooded urban areas by considering the density of buildings on the overbank and using the n values of the open areas between the buildings. The steps needed to determine values of Manning's n for urban areas are as follows (Hejl, 1977):

1. Select cross section in the same manner as would be selected for nonurbanized areas. The cross sections are subdivided to separate the main-channel flow from the flow between the buildings on an overbank. The urban roughness coefficient, n_u, is applied only to the subsections that include buildings. The left and right overbanks are evaluated independently. A subdivided cross section is shown in figure 13.

2. Estimate the ratio of total width, W_T, to a summation of the widths of individual openings, W_O, for a cross section perpendicular to the direction of flow through a row of buildings of average density on the section of flood plain being evaluated, as shown in figure 13. This estimate can be made onsite, by aerial reconnaissance, or from a map.

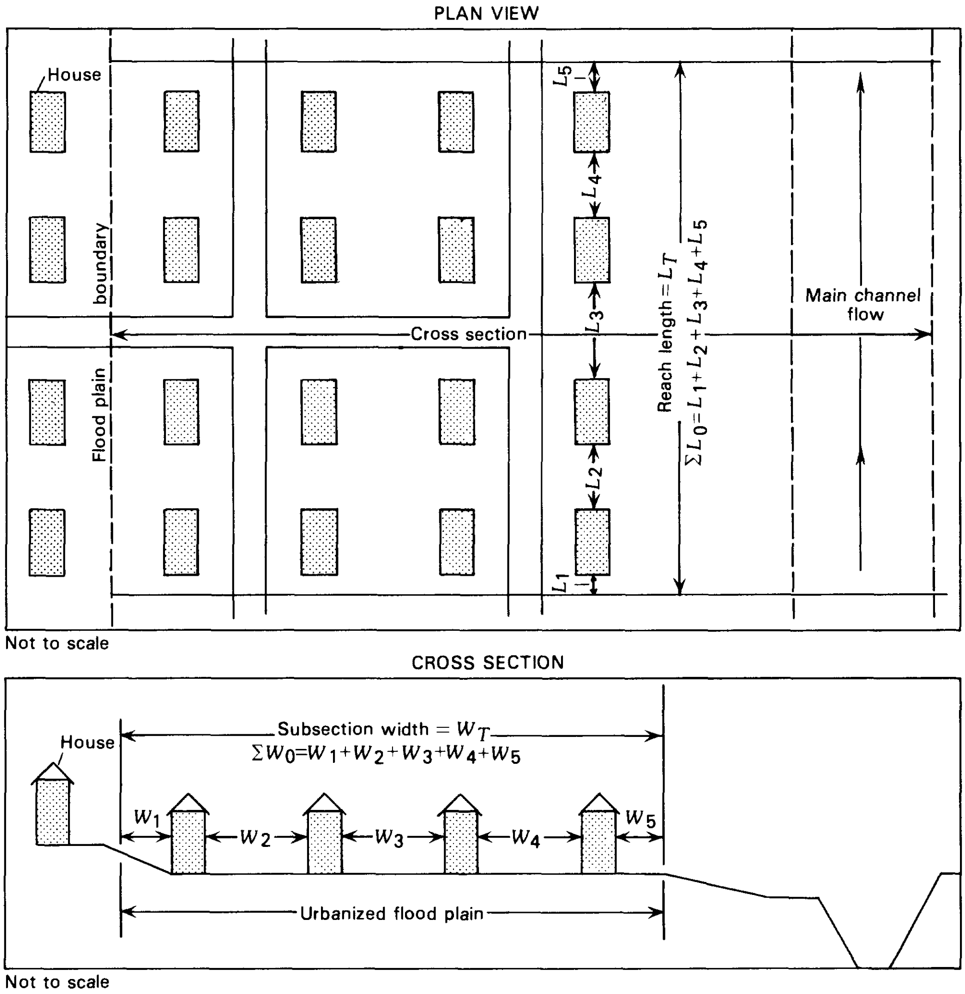


Figure 13.--Plan view and cross section of an urban area in which streets are either parallel or perpendicular to the direction of flow. Modified from Hejl (1977).

3. Estimate the ratio of the summation of distances between rows of buildings, ΣL_O, to the total length of reach, L_T, parallel to the direction of flow for the reach in step 2.

4. Select a Manning's roughness coefficient, n_O, for the open area between the buildings. Open areas include features such as trees, shrubbery, and streets.

5. Compute the urban roughness coefficient n_u from the following equation:

$$n_u = n_o \left[\frac{3}{2} \left(\frac{W_T}{\Sigma W_O} \right) + \left(1 - \frac{W_T}{\Sigma W_O} \right) \frac{\Sigma L_O}{L_T} - \frac{1}{2} \right], \tag{7}$$

where

n_u is the Manning's n value for urban areas used as part of the total cross-sectional area; n_O is the Manning's n value for the area between the buildings on the overbank; W_T is the total width of cross section, in feet; ΣW_O is the summation of individual widths between buildings of a cross section through a row of buildings perpendicular to the direction of flow, in feet; ΣL_O is the summation of longitudinal distances between rows of buildings, in feet; and L_T is the total length of the reach along a profile parallel to the direction of flow.

Use the roughness coefficient for the subsections including buildings directly in the hydraulic analyses, and use the total flow area of cross section.

In many cases, the idealized conditions described by Hejl (1977) and shown in figure 13 will not exist, and modifications such as the following will need to be made:

1. For buildings not in line with each other or not at a right angle to the direction of flow use approach number 1 on page 42.

2. Fences and other obstructions may need to be evaluated as part of ΣW_O and ΣL_O and;

3. Conditions may warrant computation of n values for different depths of flow.

PROCEDURE FOR ASSIGNING *n* VALUES

The procedure outlined in this section will enable the user to systematically evaluate the factors affecting channel and overbank roughness. Because of the interaction of the factors affecting roughness, sound experienced engineering judgment is needed in estimating *n* values.

The steps outlined are for one discharge or depth of flow. If *n* values are to encompass a range of flow depths, the procedure would be repeated at selected depths to account for changes in roughness with depth of flow. It is suggested the procedure be applied first to the channel and then to the overbank areas.

Following the procedure, four examples are shown for the hypothetical channel shown in figure 2. A roughness evaluation form similar to figure 14A and photographs of the stream are useful as documentation of stream roughness coefficients.

1. Determine the extent of the reach in which roughness seems uniform and to which *n* values are to apply. Conditions may not be uniform throughout the reach; however, *n* values need to be assigned for the average conditions. Use evidence of scour or deposition to determine whether the channel is sand bed, stable, or a combination of both. Determine if existing conditions are representative of flow conditions being considered.

2. Determine how the cross section will be subdivided. Usually, the section is subdivided by geometry into a channel and left and right overbank subareas. If roughness is not uniform across the channel, a composite *n* value needs to be computed. If distinct changes in roughness occur in the overbanks and are uniform throughout the reach, then separate *n* values need to be selected for each subarea.

3. Determine the type and size of material in each subarea of the channel. Tables 2 and 5 or the prediction equations 5 or 6 can be used to determine the base *n* values for each subarea of channel. In many cases, there only will be one subarea to describe the channel.

4. Determine the adjustment factors from table 1 that apply to the channel. Consider upstream conditions that may cause disturbances in the reach being studied. Add the adjustment factors to the base *n* value. Multiply the adjusted values by the meander coefficient. The value obtained is the overall *n* value for the channel, as selected in step 2.

5. Determine the type of material in each overbank segment. Tables 6 and 7 or the urban method outlined by Hejl (1977) can be used to determine the overbank roughness coefficients. In most cases, there only will be two segments to represent the left and right overbanks.

Stream and location:

Reach length:

Reach description:

Discharge and depth for the study period:

Channel computation of weighted n-value:

Factor	Value	Remarks
Base value (n_0)		
Cross section irregularity (n_1)		
Channel variation (n_2)		
Effects of obstructions (n_3)		
Channel vegetation (n_4)		
Degree of meandering (m)	L_m/L_s =	

$n = (n_0 + n_1 + n_2 + n_3 + n_4)\ m =$

Overbank n-values:

Subarea	Value	Remarks

Figure 14A.--Sample roughness-coefficient evaluation form.

6. Check the flow regime for sand-bed channels or overbanks (if they act as a movable bed). Use the *n* value estimated in step 4 or 5 in the Manning equation (eq. 1) to compute the velocity that then is used to compute stream power. The flow regime is evaluated from figure 5.

7. Make the hydraulic analyses and check the computed depth against the estimated flood in step 1. If the computed depth is substantially different from the estimated depth used to estimate the *n* values, the *n* values need to be reevaluated using the computed depth as the next estimated depth in step 1.

Example 1.--Natural Channel

Compute the roughness coefficient for reach *A* of figure 2 for low-flow conditions with a flow depth of 2 ft.

1. Cross section 1 represents the average conditions in the reach and is located 300 ft upstream from the initial reference point as measured along the main channel thalweg. The channel is stable and is composed of boulders, and the reach needs an average number of adjustment factors. There is no flow in the left or right overbanks (fig. 3). The flow depth of 2 ft is approximately equal to the hydraulic radius.

2. No subdivision is needed.

3. The channel is composed of boulders computed to have an intermediate diameter of 10 in. by the Wolman method (Wolman, 1954). The *n* values for boulders range from 0.04 to 0.07 (table 2). Surveyed water-surface levels indicate the water slope is 0.02 and is assumed equal to the friction slope. The slope and hydraulic radius are within the limits of the prediction equation 6 and figure 12. Using equation 6:

   then $$n = 0.39(0.02)^{0.38}\,(2)^{-0.16} = 0.079$$

   Use the *n* value from the prediction equation because it is based on data similar to the example problem.

4. The channel is average with respect to cross-section irregularities, channel variation, effect of obstructions, channel vegetation, and degrees of meandering, so that adjustments to the base *n* value are not needed because the prediction equation was used. The degree of meandering ratio (m) L_m to L_s equals 1.00 as the flow is within the main channel. The main channel *n* value is 0.079.

5. There is no overbank flow.

6. Flow regime criteria are not available and can not be made for a cobble-bed channel.

7. This step is not required because the flow depth was preselected.

Example 2.--Natural Flood Plain

1. Reach *A* in the natural flood plain shown in figure 2 extends from stations 0 to 570 ft measured along the flood plain. Cross-section 1 represents the average conditions in the reach and is located 285 ft upstream from the initial reference point. The channel is composed of boulders, and the reach needs an average number of adjustment factors. The left overbank is covered by sparse brush and trees, and the right overbank is overgrown with a dense stand of trees. Lack of channel scour or deposition indicates the channel is stable at most discharges. Existing channel conditions correspond to those for a 100-year discharge of 6,000 ft^3/s. The estimated 100-year flood depth of 7 ft is shown on section 1 of figure 3. A sample completed roughness evaluation form for a natural flood plain is shown in figure 14*B*.

2. The cross section is subdivided, based on shape, into the channel and a left and right overbank. Subarea 1, the left overbank, extends from stations 35 to 210 ft; subarea 2 the channel, from stations 210 to 280 ft; and subarea 3, the right overbank, from stations 280 to 400 ft; as shown in figure 3.

3. Moderate flow velocities during onsite inspection did not enable an actual particle size count; however, the average particle diameter of the boulders was estimated to be 12 in. The *n* for boulders ranges from 0.04 to 0.07 (table 2). Preliminary hydraulic computation indicates the 100-year friction slope is 0.02 and the hydraulic radius is 7 ft, which are within the limits of prediction equation 6 and figure 12. As indicated in figure 12, for a slope of 0.02 and a hydraulic radius of 7 ft, *n* is equal to 0.065.

4. The channel is average with respect to cross-section irregularities, channel variation, effect of obstructions, channel vegetation, and degree of meandering, so that adjustments to the base *n* value are not needed because the prediction equation was used. The degree of meandering ratio, L_m to L_s equals 580 ft divided by 570 ft or 1.02. No adjustment for meandering is required. The main channel *n* value is 0.065.

Stream and location: Hypothetical river in Colorado

Reach length: Station 0 to 570 feet. Section 1 in reach *A* is located at station 285 feet.

Reach description: The main channel is composed of boulders averaging 11 inches in diameter with average channel adjustment conditions. The left overbank consists of sparse brush and trees and the right bank consists of a dense stand of trees. Existing channel conditions are representative of study conditions. See figures 2 and 3 for the plan view and cross sections.

Discharge and depth for the study period: The 100-year discharge is 6,000 cubic feet per second, and the estimated flood depth is about 7 feet.

Channel computation of weighted *n*-value:

Factor	Value	Remarks
Base value (n_0)	0.065	Used prediction equation 6.
Cross section irregularity (n_1)	--	Average condition. Included in prediction equation.
Channel variation (n_2)	--	do.
Effects of obstructions (n_3)	--	do.
Channel vegetation (n_4)	--	do.
Degree of meandering (m)	1.0	$L_m/L_s = 1.06$

$n = (n_0 + n_1 + n_2 + n_3 + n_4)\ m = (0.065 + 0 + 0 + 0 + 0)\ 1.0 = 0.065$

Overbank *n*-values:

Subarea	Value	Remarks
Left overbank	0.08	Used table 6, item C5.
Right overbank	0.12	Used table 6, item D5.

Figure 14*B*.--Sample of a completed roughness-coefficient evaluation form for a natural flood plain.

5. Table 6 can be used to determine *n* for the overbanks. The left overbank covered with sparse brush and trees and many scattered boulders corresponds closest to the maximum *n* value for sparse brush and trees in summer (C3 in table 6), for which *n* equals 0.08. The right overbank covered with a dense stand of trees subject to flow in the branches corresponds closest to the normal *n* value for a dense stand of timber, a few downed trees, little undergrowth, and the flood stage reaching the branches (D5 in table 6), for which *n* equals 0.12.

6. Flow regime check criteria are not available and can not be made for a cobble-bed channels and densely vegetated overbanks.

7. Subsequent hydraulic analyses indicated the 100-year flood depth to be 7.5 ft, indicating the *n* values estimated for a depth of 7 ft can be considered valid and do not need to be recalculated.

Example 3.--Agricultural Flood Plain

1. Reach B in the agricultural flood plain shown in figure 2 extends from 0 to 720 ft upstream from the initial reference point measured along the flood plain. Cross-section 2 represents the average conditions in the reach and is at station 360 ft. The channel is composed of sand with sloughed banks, an alternating low-water channel, and is bordered by a few willows. The left overbank is pasture, and the right overbank is covered with corn. Existing channel conditions correspond to those for 100-year discharge of 6,000 ft^3/s. The estimated 100-year flood depth of 8 ft is shown on section 2 of figure 3.

2. The cross section is subdivided, based on shape, into the channel and a left and right overbank. Subarea 1, the left overbank, extends from stations 90 to 240 ft; subarea 2, the channel, from stations 240 to 280 ft; and subarea 3, the right overbank, from stations 280 to 410 ft; as shown in figure 3.

3. A sieve and particle-size analysis of a composite sample of sand from along the channel indicate a d_{50} of 0.024 in. (0.6 millimeter). Because channel conditions basically are natural, the channel is classed as a natural channel. For a d_{50} of 0.024 in. (0.6 millimeter), the base *n* value is 0.023 (table 2).

4. Table 1 can be used to determine adjustment factors for the base n_1 value. The *n* value adjustment for moderately eroded banks is two-thirds (Aldridge and Garrett, 1973) of 0.006, or 0.004. Two-thirds times the adjustment factor in table 1 is applied to the base *n* value given by Benson and Dalrymple (1967) in table 2. The n_2 value adjustment for occasionally alternating low-water channel is two-thirds of 0.003, or 0.002. There are no obstructions in the reach. The n_4 value adjustment for small willows is

two-thirds of 0.002, or 0.001. The degree of meandering (*m*) ratio L_m to L_s equals 720 ft divided by 570 ft, or 1.26. The multiplying factor used is 1.15. The main channel *n* value is (0.023 + 0.004 + 0.002 + 0.001) 1.15 = 0.034.

5. Table 7 can be used to evaluate overbank roughness. For an average left overbank depth of water of approximately 1 ft, the *n* value for pasture is 0.05. For an average right overbank depth of water of approximately 1 ft, the *n* value for corn is 0.06.

6. Subsequent hydraulic analyses indicated the channel hydraulic radius is 6 ft, the water slope 0.001, and the velocity 10 ft/s. The value of $62RS_wV$ is 62(6)(0.001)(10) = 3.72. Plot this value in figure 5 for a median particle size of 0.024 in. (0.6 millimeter). Because the flow is classified as upper regime, the *n* value of 0.034 is satisfactory. The flow-regime check is not needed for the overbanks because grass in the pasture and corn would prevent erosion at this shallow depth of flow and low velocity. For greater flow depths and higher velocities in the overbanks, the flow regime check would be needed if the vegetation were eroded.

7. Subsequent hydraulic analyses indicated the 100-year flood depth was 8.5 ft, indicating the *n* values estimated for a depth of 8 ft can be considered valid and do not need to be recalculated.

As discussed in the section "Cross Sections," "Location" (criteria 4), an additional cross section also would be required between the two subreaches. The same cross section 1 to 2 ft apart would be used with different roughness values.

Example 4.--Urban Flood Plain

1. Reach C in the urban flood plain shown in figure 2 extends from stations 0 to 460 ft upstream from the initial reference point measured along the flood plain. Cross-section 3 represents the average conditions through the reach and is at station 230 ft. The channel is trapezoidal and lined with concrete and does not need any adjustments. The left overbank consists of a grass-covered golf course with scattered trees, and the right overbank consists of a housing development. Existing channel conditions correspond to those for a 100-year discharge of 6,000 ft^3/s. The estimated 100-year flood depth of 8 ft is shown on section 3 of figure 3.

2. The cross section is subdivided, based on shape, into a channel and a left and right overbank. Subarea 1, the left overbank, extends from stations 15 to 120 ft; subarea 2, the channel, from stations 120 to 180 ft; and subarea 3, the right overbank, from stations 180 to 430 ft.

3. Table 5 can be used for the *n* values of modified channels. The channel has a finished concrete bottom and sides, and the base *n* value is 0.015 (A., 1., subsection a in table 5).

4. No adjustments are needed for this channel. The *n* value for the channel is 0.015.

5. The *n* value for the left overbank covered with short grass and a few trees corresponds most closely to an *n* value (0.033) between the normal and maximum *n* values for short grass (A., subsection 1. in table 6). The Hejl (1977) method can be used to evaluate the roughness of the right overbank. In this example W_T = 240 ft, ΣW_O = 125 ft (excludes houses and the solid wooden fences), ΣL_O = 210 ft, and L_T = 460 ft. The *n* value for the open area between buildings consisting of short grass and a few trees (the same as the left overbank) is 0.033. Because the width of the road is narrow relative to the total right overbank width and the *n* value for gravel is similar to grass, a composite *n* value was not computed. The urban-roughness coefficient for the right overbank is computed using equation 7 as

$$n_u = 0.033\left[\frac{3}{2}\left(\frac{240}{125}\right) + \left(1 - \frac{240}{125}\right)\frac{210}{460} - \frac{1}{2}\right] = 0.065$$

6. The flow regime check is not made for concrete channels nor for the grassed area in the overbanks as discussed in example 3.

7. Subsequent hydraulic analyses indicated the 100-year flow depth is 7.5 ft, indicating the *n* values estimated for a flow depth of 8 ft can be considered valid and do not need to be recalculated.

SUMMARY

Many investigations, such as those concerning flood plains and instream flow-requirement studies, need hydraulic analyses that in turn need an evaluation of flow resistance. Manning's roughness coefficient generally is used to describe flow resistance. The degree of roughness depends on many factors including the surface roughness of the bed material, cross-section geometry, channel variations, obstruction to flow, type and density of vegetation, and degree of channel meandering. There currently is no method that ensures that different users will obtain the same roughness coefficient for the given channel; thus, an evaluation of the roughness characteristics of channels and flood plains primarily depends on experience. A basic knowledge of the factors controlling flow resistance aids in the evaluation and determination of roughness coefficients.

This report summarizes and compares several methods of determining roughness coefficients. Additional *n*-verification data on higher-gradient streams also are included. A procedure for estimating roughness coefficients is outlined that also is applicable in other hydraulically similar stream environments. The procedure enables the user to systematically evaluate the factors affecting channel and overbank roughness. The procedure first provides guidelines for determining cross-section locations, subdivision, and reach lengths. Guidelines then are presented for factors affecting roughness coefficients and their selection in natural, agricultural, and urban channels and overbanks.

Two prediction equations are presented to aid in the calculation of *n* values in natural stable channels where roughness can change dramatically with depth of flow. Examples of the procedure are presented for different types of channels. Roughness coefficients can be determined for stages ranging from low- to high-flow conditions as long as the bed and banks remain fairly stable. An evaluation of available data on cobble- and boulder-bed mountain streams having slopes as great as 0.05 indicates the flow regime generally to be subcritical. The factors affecting channel roughness, particularly during large floods, create extreme turbulence and energy losses; hence roughness coefficients are very large, generally resulting in subcritical flow. For these conditions a limiting assumption of subcritical to critical flow seems to be a reasonable assumption in hydraulic analyses.

Roughness coefficients and hydraulic computations may not be applicable for sediment-laden flows, including mudflows and debris flows, on streams with slopes greater than 0.05, and in scoured reaches. If mudflow or debris-flow evidence is observed, for slopes greater than 0.05 or if scoured reaches are encountered in the study reach, alternative methods of analysis may need to be used.

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